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# **SAS/OR<sup>®</sup> 12.2 User's Guide Mathematical Programming Legacy Procedures**



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**SAS/OR® 12.2 User's Guide: Mathematical Programming Legacy Procedures**

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In the following list, the name of the developer(s) currently supporting the procedure is listed.

|          |                |
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The final responsibility for the SAS System lies with SAS Institute alone. We hope that you will always let us know your opinions about the SAS System and its documentation. It is through your participation that SAS software is continuously improved.

# Chapter 1

## What's New in SAS/OR 12.1 and 12.2

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## Overview

SAS/OR 12.1 delivers a broad range of new capabilities and enhanced features, encompassing optimization, constraint programming, and discrete-event simulation. SAS/OR 12.1 enhancements significantly improve performance and expand your tool set for building, analyzing, and solving operations research models.

In previous years, SAS/OR® software was updated only with new releases of Base SAS® software, but this is no longer the case. This means that SAS/OR software can be released to customers when enhancements are ready, and the goal is to update SAS/OR every 12 to 18 months. To mark this newfound independence, the release numbering scheme for SAS/OR is changing with this release. This new numbering scheme will be maintained when new versions of Base SAS and SAS/OR ship at the same time.

Note that SAS/OR 12.2 is a maintenance release. No new features have been added. The information in this chapter applies to both SAS/OR 12.1 and SAS/OR 12.2.

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## Highlights of Enhancements in SAS/OR 12.1

Highlights of the SAS/OR enhancements include the following:

- multithreading is used to improve performance in these three areas:
  - PROC OPTMODEL problem generation
  - multistart for nonlinear optimization
  - option tuning for mixed integer linear optimization
- concurrent solve capability (experimental) for linear programming (LP) and nonlinear programming (NLP)
- improvements to all simplex LP algorithms and mixed integer linear programming (MILP) solver
- new decomposition (DECOMP) algorithm for LP and MILP
- new option for controlling MILP cutting plane strategy
- new conflict search capability for MILP solver
- option tuning for PROC OPTMILP
- new procedure, PROC OPTNET, for network optimization and analysis
- new SUBMIT block for invoking SAS code within PROC OPTMODEL
- SAS Simulation Studio improvements:
  - one-click connection of remote blocks in large models
  - autoscrolling for navigating large models
  - new search capability for block types and label content
  - alternative Experiment window configuration for large experiments
  - selective animation capability
  - new submodel component (experimental)

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## The CLP Procedure

In SAS/OR 12.1, the CLP procedure adds two classes of constraints that expand its capabilities and can accelerate its solution process. The LEXICO statement imposes a lexicographic ordering between pairs of variable lists. Lexicographic order is essentially analogous to alphabetical order but expands the concept to include numeric values. One vector (list) of values is lexicographically less than another if the corresponding elements are equal up to a certain point and immediately after that point the next element of the first vector is numerically less than the second. Lexicographic ordering can be useful in eliminating certain types of symmetry that can arise among solutions to constraint satisfaction problems (CSPs). Imposing a lexicographic ordering eliminates many of the mutually symmetric solutions, reducing the number of permissible solutions to the problem and in turn shortening the solution process.

Another constraint class that is added to PROC CLP for SAS/OR 12.1 is the bin-packing constraint, imposed via the PACK statement. A bin-packing constraint directs that a specified number of items must be placed into a specified number of bins, subject to the capacities (expressed in numbers of items) of the bins. The PACK statement provides a compact way to express such constraints, which can often be useful components of larger CSPs or optimization problems.

---

## The DTREE, GANTT, and NETDRAW Procedures

In SAS/OR 12.1 the DTREE, GANTT, and NETDRAW procedures each add procedure-specific graph styles that control fonts, line colors, bar and node fill colors, and background images.

---

## Supporting Technologies for Optimization

The underlying improvements in optimization in SAS/OR 12.1 are chiefly related to multithreading, which denotes the use of multiple computational cores to enable computations to be executed in parallel rather than serially. Multithreading can provide dramatic performance improvements for optimization because these underlying computations are performed many times in the course of an optimization process.

The underlying linear algebra operations for the linear, quadratic, and nonlinear interior point optimization algorithms are now multithreaded. The LP, QP, and NLP solvers can be used by PROC OPTMODEL, PROC OPTLP, and PROC OPTQP in SAS/OR. For nonlinear optimization with PROC OPTMODEL, the evaluation of nonlinear functions is multithreaded for improved performance.

Finally, the process of creating an optimization model from PROC OPTMODEL statements has been multithreaded. PROC OPTMODEL contains powerful declarative and programming statements and is adept at enabling data-driven definition of optimization models, with the result that a rather small section of PROC OPTMODEL code can create a very large optimization model when it is executed. Multithreading can dramatically shorten the time that is needed to create an optimization model.

In SAS/OR 12.1 you can use the NTHREADS= option in the PERFORMANCE statement in PROC OPTMODEL and other SAS/OR optimization procedures to specify the number of cores to be used. Otherwise, SAS detects the number of cores available and uses them.

---

## PROC OPTMODEL: Nonlinear Optimization

The nonlinear optimization solver that PROC OPTMODEL uses builds on the introduction of multithreading for its two most significant improvements in SAS/OR 12.1. First, in addition to the nonlinear solver options ALGORITHM=ACTIVESET and ALGORITHM=INTERIORPOINT, SAS/OR 12.1 introduces the ALGORITHM=CONCURRENT option (experimental), with which you can invoke both the active set and interior point algorithms for the specified problem, running in parallel on separate threads. The solution process terminates when either of the algorithms terminates. For repeated solves of a number of similarly structured problems or simply for problems for which the best algorithm isn't readily apparent, ALGORITHM=CONCURRENT should prove useful and illuminating.

Second, multithreading is central to the nonlinear optimization solver's enhanced multistart capability, which now takes advantage of multiple threads to execute optimizations from multiple starting points in parallel. The multistart capability is essential for problems that feature nonconvex nonlinear functions in either or both of the objective and the constraints because such problems might have multiple locally optimal points. Starting optimization from several different starting points helps to overcome this difficulty, and multithreading this process helps to ensure that the overall optimization process runs as fast as possible.

---

## Linear Optimization with PROC OPTMODEL and PROC OPTLP

Extensive improvements to the primal and dual simplex linear optimization algorithms produce better performance and better integration with the crossover algorithm, which converts solutions that are found by the interior point algorithm into more usable basic optimal solutions. The crossover algorithm itself has undergone extensive enhancements that improve its speed and stability.

Paralleling developments in nonlinear optimization, SAS/OR 12.1 linear optimization introduces a concurrent algorithm, invoked with the `ALGORITHM=CONCURRENT` option, in the `SOLVE WITH LP` statement for PROC OPTMODEL or in the PROC OPTLP statement. The concurrent LP algorithm runs a selection of linear optimization algorithms in parallel on different threads, with settings to suit the problem at hand. The optimization process terminates when the first algorithm identifies an optimal solution. As with nonlinear optimization, the concurrent LP algorithm has the potential to produce significant reductions in the time needed to solve challenging problems and to provide insights that are useful when you solve a large number of similarly structured problems.

---

## Mixed Integer Linear Optimization with PROC OPTMODEL and PROC OPTMILP

Mixed integer linear optimization in SAS/OR 12.1 builds on and extends the advances in linear optimization. Overall, solver speed has increased by over 50% (on a library of test problems) compared to SAS/OR 9.3. The branch-and-bound algorithm has approximately doubled its ability to evaluate and solve component linear optimization problems (which are referred to as nodes in the branch-and-bound tree). These improvements have significantly reduced solution time for difficult problems.

---

## The Decomposition Algorithm

The most fundamental change to both linear and mixed integer linear optimization in SAS/OR 12.1 is the addition of the decomposition (DECOMP) algorithm, which is invoked with a specialized set of options in the `SOLVE WITH LP` and `SOLVE WITH MILP` statements for PROC OPTMODEL or in the `DECOMP` statement for PROC OPTLP and PROC OPTMILP. For many linear and mixed integer linear optimization problems, most of the constraints apply only to a small set of decision variables. Typically there are many such sets of constraints, complemented by a small set of linking constraints that apply to all or most of the decision variables. Optimization problems with these characteristics are said to have a “block-angular” structure, because it is easy to arrange the rows of the constraint matrix so that the nonzero values, which correspond to the local sets of constraints, appear as blocks along the main diagonal.

The DECOMP algorithm exploits this structure, decomposing the overall optimization problem into a set of component problems that can be solved in parallel on separate computational threads. The algorithm repeatedly solves these component problems and then cycles back to the overall problem to update key information that is used the next time the component problems are solved. This process repeats until it produces a solution to the complete problem, with the linking constraints present. The combination of

parallelized solving of the component problems and the iterative coordination with the solution of the overall problem can greatly reduce solution time for problems that were formerly regarded as too time-consuming to solve practically.

To use the DECOMP algorithm, you must either manually or automatically identify the blocks of the constraint matrix that correspond to component problems. The METHOD= option controls the means by which blocks are identified. METHOD=USER enables you to specify the blocks yourself, using the .block suffix to declare blocks. This is by far the most common method of defining blocks. If your problem has a significant or dominant network structure, you can use METHOD=NETWORK to identify the blocks in the problem automatically. Finally, if no linking constraints are present in your problem, then METHOD=AUTO identifies the blocks automatically.

The DECOMP algorithm uses a number of detailed options that specify how the solution processes for the component problems and the overall problem are configured and how they coordinate with each other. You can also specify the number of computational threads to make available for processing component problems and the level of detail in the information to appear in the SAS log. Options specific to the linear and mixed integer linear solvers that are used by the DECOMP algorithm are largely identical to those for the respective solvers.

---

## Setting the Cutting Plane Strategy

Cutting planes are a major component of the mixed integer linear optimization solver, accelerating its progress by removing fractional (not integer feasible) solutions. SAS/OR 12.1 adds the CUTSTRATEGY= option in the PROC OPTMILP statement and in the SOLVE WITH MILP statement for PROC OPTMODEL, enabling you to determine the aggressiveness of your overall cutting plane strategy. This option complements the individual cut class controls (CUTCLQUE=, CUTGOMORY=, CUTMIR=, and so on), with which you can enable or disable certain cut types, and the ALLCUTS= option, which enables or disables all cutting planes. In contrast, the CUTSTRATEGY= option controls cuts at a higher level, creating a profile for cutting plane use. As the cut strategy becomes more aggressive, more effort is directed toward creating cutting planes and more cutting planes are applied. The available values of the CUTSTRATEGY= option are AUTOMATIC, BASIC, MODERATE, and AGGRESSIVE; the default is AUTOMATIC. The precise cutting plane strategy that corresponds to each of these settings can vary from problem to problem, because the strategy is also tuned to suit the problem at hand.

---

## Conflict Search

Another means of accelerating the solution process for mixed integer linear optimization takes information from infeasible linear optimization problems that are encountered during an initial exploratory phase of the branch-and-bound process. This information is analyzed and ultimately is used to help the branch-and-bound process avoid combinations of decision variable values that are known to lead to infeasibility. This approach, known as conflict analysis or conflict search, influences presolve operations on branch-and-bound nodes, cutting planes, computation of decision variable bounds, and branching. Although the approach is complex, its application in SAS/OR 12.1 is straightforward. The CONFLICTSEARCH= option in the PROC OPTMILP statement or the SOLVE WITH MILP statement in PROC OPTMODEL enables you to specify

the level of conflict search to be performed. The available values for the CONFLICTSEARCH= option are NONE, AUTOMATIC, MODERATE, and AGGRESSIVE. A more aggressive search strategy explores more branch-and-bound nodes initially before the branch-and-bound algorithm is restarted with information from infeasible nodes included. The default value is AUTOMATIC, which enables the solver to choose the search strategy.

---

## PROC OPTMILP: Option Tuning

The final SAS/OR 12.1 improvement to the mixed integer linear optimization solver is option tuning, which helps you determine the best option settings for PROC OPTMILP. There are many options and settings available, including controls on the presolve process, branching, heuristics, and cutting planes. The TUNER statement enables you to investigate the effects of the many possible combinations of option settings on solver performance and determine which should perform best. The PROBLEMS= option enables you to submit several problems for tuning at once. The OPTIONMODE= option specifies the options to be tuned. OPTIONMODE=USER indicates that you will supply a set of options and initial values via the OPTIONVALUES= data set, OPTIONMODE=AUTO (the default) tunes a small set of predetermined options, and OPTIONMODE=FULL tunes a much more extensive option set.

Option tuning starts by using an initial set of option values to solve the problem. The problem is solved repeatedly with different option values, with a local search algorithm to guide the choices. When the tuning process terminates, the best option values are output to a data set specified by the SUMMARY= option. You can control the amount of time used by this process by specifying the MAXTIME= option. You can multithread this process by using the NTHREADS= option in the PERFORMANCE statement for PROC OPTMILP, permitting analyses of various settings to occur simultaneously.

---

## PROC OPTMODEL: The SUBMIT Block

In SAS/OR 12.1, PROC OPTMODEL adds the ability to execute other SAS code nested inside PROC OPTMODEL syntax. This code is executed immediately after the preceding PROC OPTMODEL syntax and before the syntax that follows. Thus you can use the SUBMIT block to, for example, invoke other SAS procedures to perform analyses, to display results, or for other purposes, as an integral part of the process of creating and solving an optimization model with PROC OPTMODEL. This addition makes it even easier to integrate the operation of PROC OPTMODEL with other SAS capabilities.

To create a SUBMIT block, use a SUBMIT statement (which must appear on a line by itself) followed by the SAS code to be executed, and terminate the SUBMIT block with an ENDSUBMIT statement (which also must appear on a line by itself). The SUBMIT statement enables you to pass PROC OPTMODEL parameters, constants, and evaluated expressions to the SAS code as macro variables.



---

## Network Optimization with PROC OPTNET

PROC OPTNET, new in SAS/OR 12.1, provides several algorithms for investigating the characteristics of networks and solving network-oriented optimization problems. A network, sometimes referred to as a graph, consists of a set of nodes that are connected by a set of arcs, edges, or links. There are many applications of network structures in real-world problems, including supply chain analysis, communications, transportation, and utilities problems. PROC OPTNET addresses the following classes of network problems:

- biconnected components
- maximal cliques
- connected components
- cycle detection
- weighted matching
- minimum-cost network flow
- minimum cut
- minimum spanning tree
- shortest path
- transitive closure
- traveling salesman

PROC OPTNET syntax provides a dedicated statement for each problem class in the preceding list.

The formats of PROC OPTNET input data sets are designed to fit network-structured data, easing the process of specifying network-oriented problems. The underlying algorithms are highly efficient and can successfully address problems of varying levels of detail and scale. PROC OPTNET is a logical destination for users who are migrating from some of the legacy optimization procedures in SAS/OR. Former users of PROC NETFLOW can turn to PROC OPTNET to solve shortest-path and minimum-cost network flow problems, and former users of PROC ASSIGN can instead use the LINEAR\_ASSIGNMENT statement in PROC OPTNET to solve assignment problems.

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## SAS Simulation Studio 12.1

SAS Simulation Studio 12.1, a component of SAS/OR 12.1 for Windows environments, adds several features that improve your ability to build, explore, and work with large, complex discrete-event simulation models. Large models present a number of challenges to a graphical user interface such as that of SAS Simulation Studio. Connection of model components, navigation within a model, identification of objects or areas of interest, and management of different levels of modeling are all tasks that can become more difficult as the model size grows significantly beyond what can be displayed on one screen. An indirect effect of model

growth is an increased number of factors and responses that are needed to parameterize and investigate the performance of the system being modeled.

Improvements in SAS Simulation Studio 12.1 address each of these issues. In SAS Simulation Studio, you connect blocks by dragging the cursor to create links between output and input ports on regular blocks and Connector blocks. SAS Simulation Studio 12.1 automatically scrolls the display of the Model window as you drag the link that is being created from its origin to its destination, thus enabling you to create a link between two blocks that are located far apart (additionally you can connect any two blocks by clicking on the OutEntity port of the first block and then clicking on the InEntity port of the second block). Automatic scrolling also enables you to navigate a large model more easily. To move to a new area in the Model window, you can simply hold down the left mouse button and drag the visible region of the model to the desired area. This works for simple navigation and for moving a block to a new, remote location in the model.

SAS Simulation Studio 12.1 also enables you to search among the blocks in a model and identify the blocks that have a specified type, a certain character string in their label, or both. From the listing of identified blocks, you can open the Properties dialog box for each identified block and edit its settings. Thus, if you can identify a set of blocks that need similar updates, then you can make these updates without manually searching through the model for qualifying blocks and editing them individually. For very large models, this capability not only makes the update process easier but also makes it more thorough because you can identify qualifying blocks centrally.

When you design experiments for large simulation models, you often need a large number of factors to parameterize the model and a large number of responses to track system performance in sufficient detail. This was a challenge prior to SAS Simulation Studio 12.1 because the Experiment window displayed factors and responses in the header row of a table, with design points and their replications' results displayed in the rows below. A very large number of factors and responses did not fit on one screen in this display scheme, and you had to scroll across the Experiment window to view all of them.

SAS Simulation Studio 12.1 provides you with two alternative configurations for the Experiment window. The Design Matrix tab presents the tabular layout described earlier. The Design Point tab presents each design point in its own display. Factors and responses (summarized over replications) are displayed in separate tables, each with the factor or response names appearing in one column and the respective values in a second column. This layout enables a large number of factors and responses to be displayed. Response values for each replication of the design point can be displayed in a separate window.

SAS Simulation Studio 12.1 enhances its multilevel model management features by introducing the submodel component (experimental). Like the compound block, the submodel encapsulates a group of SAS Simulation Studio blocks and their connections, but the submodel outpaces the compound block in some important ways. The submodel, when expanded, opens in its own window. This means a submodel in its collapsed form can be placed close to other blocks in the Model window without requiring space for its expanded form (as is needed for compound blocks). The most important property of the submodel is its ability to be copied and instantiated in several locations simultaneously, whether in the same model, in different models in the same project, or in different projects. Each such instance is a direct reference to the original submodel, not a disconnected copy. Thus you can edit the submodel by editing any of its instances; changes that are made to any instance are propagated to all current and future instances of the submodel. This feature enables you to maintain consistency across your models and projects.

Finally, SAS Simulation Studio 12.1 introduces powerful new animation controls that should prove highly useful in debugging simulation models. In the past, animation could be switched on or off and its speed controlled, but these choices were made for the entire model. If you needed to animate a particular segment of the model, perhaps during a specific time span for the simulation clock, you had to focus your attention

on that area and pay special attention when the time period of interest arrived. In SAS Simulation Studio 12.1 you can select both the area of the model to animate (by selecting a block or a compound block) and the time period over which animation should occur (by specifying the start and end times for animation). You can also control simulation speed for each such selection. Multiple selections are supported so that you can choose to animate several areas of the model, each during its defined time period and at its chosen speed.



## Chapter 2

# Introduction

This book contains all 24 examples from the classic book *Model Building in Mathematical Programming* by H. Paul Williams. For each example, the problem statement is first repeated verbatim from Williams' book.<sup>1</sup> Then the problem is solved using the OPTMODEL procedure in SAS/OR software.

The examples cover linear programming, mixed integer linear programming, and quadratic programming. In most cases, the problem is solved with a single call to one of the mathematical programming solvers available in PROC OPTMODEL. The purpose of this book is to supplement the *SAS/OR User's Guide: Mathematical Programming* with additional examples that demonstrate best practices.

Each chapter contains five sections, described as follows.

- **Problem Statement:**  
Repeats verbatim the problem description, including any tables and figures, from Williams' book.
- **Mathematical Programming Formulation:**  
Describes the index sets, parameters, decision variables, objectives, and constraints for one formulation of the problem.
- **Input Data:**  
Creates the input data sets and macro variables to be used by PROC OPTMODEL.
- **PROC OPTMODEL Statements and Output:**  
Shows and discusses the PROC OPTMODEL statements that declare sets and parameters, read the input data, formulate the mathematical programming problem, solve the problem, and output the solution. Also shows the output created by PROC OPTMODEL and occasionally other SAS procedures.
- **Features Demonstrated:**  
Lists the important PROC OPTMODEL features demonstrated in this example.

Although PROC OPTMODEL is case-insensitive, in the interest of clarity a few typographical conventions are observed regarding capitalization of names:

| <b>OPTMODEL Expression</b>                    | <b>Capitalization</b>     |
|---|---------------------------|
| Index set names                               | All uppercase             |
| Index set member names                        | All lowercase             |
| Parameter names                               | All lowercase             |
| Variable names (including implicit variables) | First letter of each word |
| Objective names                               | First letter of each word |
| Constraint names                              | First letter              |

<sup>1</sup> Figures and tables are numbered differently so that they match the chapter organization of this book. To be consistent with the verbatim problem statement, all other sections use British spelling. However, for clarity, large numbers and decimals are punctuated in American style (for example, 10,000 instead of 10 000 and 0.5 instead of 0.5), words are occasionally added or changed (with the changes shown inside square brackets), and punctuation is occasionally changed.

The examples shown here are small and not computationally challenging. Throughout, a separation between data and model is maintained so that you can solve larger or more difficult instances without modifying the PROC OPTMODEL statements. A user who learns the techniques demonstrated in these examples will be well-prepared to use PROC OPTMODEL to tackle similar modeling challenges that arise in real-world problems.

# Chapter 3

## Using This Book

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### Purpose

*SAS/OR User's Guide: Mathematical Programming Legacy Procedures* provides a complete reference for the older mathematical programming procedures in SAS/OR software. This book serves as the primary documentation for the INTPOINT, LP, NETFLOW, and NLP procedures. The OPTLP, OPTMILP, OPTMODEL, and OPTQP procedures, the various solvers used by PROC OPTMODEL, and the MPS-format SAS data set specification are documented in *SAS/OR User's Guide: Mathematical Programming*.

This chapter describes the organization of this book and the conventions used in the text and example code. To gain full benefit from using this book, you should familiarize yourself with the information presented in this section and refer to it when needed. The section “[Additional Documentation for SAS/OR Software](#)” on page 16 refers to other documents that contain related information.

### Organization

Chapter 4, “[Introduction to Optimization](#),” contains a brief overview of the legacy mathematical programming procedures in SAS/OR software and highlights the need to transition in the near future from these legacy procedures to the newer OPTMODEL family of SAS/OR mathematical programming procedures. This chapter also provides an introduction to optimization and the use of the legacy optimization tools in the SAS System; it describes how to build input SAS data sets (directly or by synthesizing multiple data sources), use the legacy procedures to identify optimal solutions, and construct reports to communicate optimal decisions. Following this introductory chapter, the next four chapters describe the LP, INTPOINT, NETFLOW, and NLP procedures.

The following list summarizes the types of information provided for each procedure:

**Overview** provides a general description of what the procedure does. It outlines major capabilities of the procedure and lists all input and output data sets that are used with it.

**Getting Started** illustrates simple uses of the procedure using a few short examples. It provides introductory *hands-on* information for the procedure.

**Syntax** constitutes the major reference section for the syntax of the procedure. First, the statement syntax is summarized. Next, a functional summary table lists all the statements and options in the procedure, classified by function. In addition, the online version includes a Dictionary of Options, which provides an alphabetical list of all options. Following these tables, the PROC statement is described, and then all other statements are described in alphabetical order.

**Details** describes the features of the procedure, including algorithmic details and computational methods. It also explains how the various options interact with each other. This section describes input and output data sets in greater detail, with definitions of the output variables, and explains the format of printed output, if any.

**Examples** consists of examples that are designed to illustrate the use of the procedure. Each example includes a description of the problem and lists the options that are highlighted by the example. The example shows the data and the SAS statements needed, and includes the output produced. You can duplicate the examples by copying the statements and data and running the SAS program. The SAS Sample Library contains the code used to run the examples shown in this book; consult your SAS Software representative for specific information about the Sample Library.

**References** lists references that are relevant to the chapter.

---

## Typographical Conventions

The printed version of *SAS/OR User's Guide: Mathematical Programming Legacy Procedures* uses various type styles, as explained by the following list:



|                       |  |
|-----------------------|--|
| <i>roman</i>          | is the standard type style used for most text.   |
| UPPERCASE ROMAN       | is used for SAS statements, options, and other SAS language elements when they appear in the text. However, you can enter these elements in your own SAS code in lowercase, uppercase, or a mixture of the two. This style is also used for identifying arguments and values (in the syntax specifications) that are literals (for example, to denote valid keywords for a specific option). |
| <b>UPPERCASE BOLD</b> | is used in the “Syntax” section to identify SAS keywords, such as the names of procedures, statements, and options.  |
| VariableName          | is used for the names of SAS variables and data sets when they appear in the text.   |
| <i>oblique</i>        | is used to indicate an option variable for which you must supply a value (for example, <code>DUPLICATE=dup</code> indicates that you must supply a value for <i>dup</i> ).   |
| <i>italic</i>         | is used for terms that are defined in the text, for emphasis, and for publication titles.  |
| <b>monospace</b>      | is used to show examples of SAS statements. In most cases, this book uses lowercase type for SAS code. You can enter your own SAS code in lowercase, uppercase, or a mixture of the two.   |

---

## Conventions for Examples

Most of the output shown in this book is produced with the following SAS System options:

```
options linesize=80 pagesize=60 nonumber nodate;
```

---

## Accessing the SAS/OR Sample Library

The SAS/OR sample library includes many examples that illustrate the use of SAS/OR software, including the examples used in this documentation. To access these sample programs from the SAS windowing environment, select **Help** from the main menu and then select **Getting Started with SAS Software**. On the **Contents** tab, expand the **Learning to Use SAS, Sample SAS Programs**, and **SAS/OR** items. Then click **Samples**.

---

## Online Documentation

This documentation is available online with the SAS System. To access SAS/OR documentation from the SAS windowing environment, select **Help** from the main menu and then select **SAS Help and Documentation**. On the **Contents** tab, expand the **SAS Products** and **SAS/OR** items. Then expand the book you want to view. You can search the documentation by using the **Search** tab.

You can also access the documentation by going to <http://support.sas.com/documentation>.

---

## Additional Documentation for SAS/OR Software

In addition to *SAS/OR User's Guide: Mathematical Programming Legacy Procedures*, you might find the following documents helpful when using SAS/OR software:

### ***SAS/OR User's Guide: Bill of Material Processing***

provides documentation for the BOM procedure and all bill of material postprocessing SAS macros. The BOM procedure and SAS macros provide the ability to generate different reports and to perform several transactions to maintain and update bills of material.

### ***SAS/OR User's Guide: Constraint Programming***

provides documentation for the constraint programming procedure in SAS/OR software. This book serves as the primary documentation for the CLP procedure.

### ***SAS/OR User's Guide: Local Search Optimization***

provides documentation for the local search optimization procedure in SAS/OR software. This book serves as the primary documentation for the GA procedure, which uses genetic algorithms to solve optimization problems.

### ***SAS/OR User's Guide: Mathematical Programming***

provides documentation for the mathematical programming procedures in SAS/OR software. This book serves as the primary documentation for the OPTLP, OPTMILP, OPTMODEL, and OPTQP procedures, the various solvers called by the OPTMODEL procedure, and the MPS-format SAS data set specification.

### ***SAS/OR User's Guide: Mathematical Programming Examples***

supplements the *SAS/OR User's Guide: Mathematical Programming* with additional examples that demonstrate best practices for building and solving linear programming, mixed integer linear programming, and quadratic programming problems. The problem statements are reproduced with permission from the book *Model Building in Mathematical Programming* by H. Paul Williams.

### ***SAS/OR User's Guide: Network Optimization Algorithms***

provides documentation for a set of algorithms that can be used to investigate the characteristics of networks and to solve network-oriented optimization problems. This book also documents PROC OPTNET, which invokes these algorithms and provides network-structured formats for input and output data.

***SAS/OR User's Guide: Project Management***

provides documentation for the project management procedures in SAS/OR software. This book serves as the primary documentation for the CPM, DTREE, GANTT, NETDRAW, and PM procedures, in addition to the PROJMAN Application, a graphical user interface for project management.

***SAS/OR Software: Project Management Examples, Version 6***

contains a series of examples that illustrate how to use SAS/OR software to manage projects. Each chapter contains a complete project management scenario and describes how to use PROC GANTT, PROC CPM, and PROC NETDRAW, in addition to other reporting and graphing procedures in the SAS System, to perform the necessary project management tasks.

***SAS Simulation Studio: User's Guide***

provides documentation about using SAS Simulation Studio, a graphical application for creating and working with discrete-event simulation models. This book describes in detail how to build and run simulation models and how to interact with SAS software for analysis and with JMP software for experimental design and analysis.



# Chapter 4

## Introduction to Optimization

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### Important Information Regarding the Legacy Procedures

This book documents four of the older SAS/OR mathematical programming procedures: the LP, INTPOINT, NETFLOW, and NLP procedures. These procedures are collectively referred to as the “legacy mathematical programming procedures.” All of these procedures and their attendant mathematical optimization solvers were developed several years before the introduction of the newer OPTMODEL family of procedures and their corresponding linear, mixed integer linear, quadratic, and general nonlinear optimization solvers. These newer optimization procedures and solvers deliver significant improvements on the older procedures and solvers in several areas:

- clarity and flexibility in optimization modeling, including more versatile use of input data

- flexibility in tailoring the solution process to the model, synthesizing standard and customized optimization methods as needed
- scalability and speed in the provided linear, mixed integer linear, quadratic, and general nonlinear optimization solvers

For these reasons the focus of research and development for mathematical optimization in SAS/OR software has shifted to the newer procedures and solvers. The LP, INTPOINT, NETFLOW, and NLP procedures are no longer under active development although these legacy procedures are still fully supported. At some point in the near future, support for the legacy procedures will be discontinued. Accordingly all SAS/OR users are urged to plan now to migrate from these older procedures to the corresponding newer SAS/OR optimization procedures:

- for linear optimization, from the LP procedure to the OPTLP or OPTMODEL procedure
- for mixed integer linear optimization, from the LP procedure to the OPTMILP or OPTMODEL procedure
- from the NETFLOW procedure to the OPTLP or OPTMODEL procedure
- from the NLP procedure to the OPTMODEL procedure
- from the INTPOINT procedure to the OPTLP or OPTMODEL procedure

---

## Migrating from the Legacy Procedures

The LP, INTPOINT, and NETFLOW procedures have recently added the MPSOUT= option which bypasses the procedure's solver and produces a SAS data set in a mathematical programming system (MPS) format that describes the problem that was to be solved with the older procedure. This data set can be supplied as an input data set to the OPTLP or OPTMILP procedure. It is preferable to model the problem using the algebraic modeling capabilities of PROC OPTMODEL, thus producing highly readable SAS code that transparently depicts the algebraic structure of the optimization model. You can find examples that demonstrate how to model linear and mixed integer linear problems in OPTMODEL in Chapter 6, "The Linear Programming Solver" (*SAS/OR User's Guide: Mathematical Programming*) and Chapter 7, "The Mixed Integer Linear Programming Solver" (*SAS/OR User's Guide: Mathematical Programming*).

Migration from the NLP procedure to the OPTMODEL procedure is not as simple as migration for linear optimization because of the more broadly defined structure of nonlinear optimization models. A brief guide to migration from PROC NLP to PROC OPTMODEL is included in the section "[Rewriting NLP Models for PROC OPTMODEL](#)" on page 708; it includes several examples.

---

## Overview

Operations research tools are directed toward the solution of resource management and planning problems. Models in operations research are representations of the structure of a physical object or a conceptual or business process. Using the tools of operations research involves the following:

- defining a structural model of the system under investigation
- collecting the data for the model
- solving the model
- interpreting the results

SAS/OR software is a set of procedures for exploring models of distribution networks, production systems, resource allocation problems, and scheduling problems using the tools of operations research.

The following list suggests some of the application areas in which optimization-based decision support systems have been used. In practice, models often contain elements of several applications listed here.

- **Product-mix problems** find the mix of products that generates the largest return when several products compete for limited resources.
- **Blending problems** find the mix of ingredients to be used in a product so that it meets minimum standards at minimum cost.
- **Time-staged problems** are models whose structure repeats as a function of time. Production and inventory models are classic examples of time-staged problems. In each period, production plus inventory minus current demand equals inventory carried to the next period.
- **Scheduling problems** assign people to times, places, or tasks so as to optimize people's preferences or performance while satisfying the demands of the schedule.
- **Multiple objective problems** have multiple, possibly conflicting, objectives. Typically, the objectives are prioritized and the problems are solved sequentially in a priority order.
- **Capital budgeting and project selection problems** ask for the project or set of projects that yield the greatest return.
- **Location problems** seek the set of locations that meets the distribution needs at minimum cost.
- **Cutting stock problems** find the partition of raw material that minimizes waste and fulfills demand.

A problem is formalized with the construction of a model to represent it. These models, called mathematical programs, are represented in SAS data sets when they are to be solved using the legacy SAS/OR procedures. The solution of mathematical programs is called mathematical programming. Since mathematical programs are represented in SAS data sets, they can be saved, changed, and solved again. The legacy SAS/OR procedures also output SAS data sets that contain the solutions. These output data sets can then be used to produce customized reports. In addition, this structure enables you to build decision support systems by using operations research and other analytic tools in the SAS System as building blocks. All of these steps are even easier and solution of the mathematical programs is more efficient when you use PROC OPTMODEL and the rest of the newer SAS/OR mathematical programming procedures.

The basic optimization problem is that of minimizing or maximizing an objective function subject to constraints imposed on the variables of that function. The objective function and constraints can be linear or nonlinear; the constraints can be bound constraints, equality or inequality constraints, or integer constraints. Traditionally, optimization problems are divided into linear programming (LP; all functions and constraints are linear) and nonlinear programming (NLP).

The data that describe the model are supplied to an optimizer (such as one of the procedures described in this book), an optimizing algorithm is used to determine the optimal values for the decision variables so the objective is either maximized or minimized, the optimal values assigned to decision variables are on or between allowable bounds, and the constraints are obeyed. Determining the optimal values is the process called *optimization*.

This chapter describes how to use the legacy SAS/OR mathematical programming procedures to solve a wide variety of optimization problems. It describes various types of optimization problems, indicates which legacy SAS/OR procedure you can use, and demonstrates how to provide data, run the procedure, and obtain optimal solutions.

The next section broadly classifies the legacy SAS/OR procedures based on the types of mathematical programming problems they can solve.

---

## Linear Programming Problems

---

### PROC LP

The LP procedure solves linear programs with a primal simplex solver. It can perform several types of post-optimality analysis, including range analysis, sensitivity analysis, and parametric programming. The procedure can also be used interactively.

PROC LP requires a problem data set that contains the model. In addition, a primal data set can be used for warm-starting a problem that has been partially solved previously.

The problem data that describe the model can be in one of two formats: dense or sparse. The dense format represents the model as a rectangular coefficient matrix. The sparse format, on the other hand, represents only the nonzero elements of a rectangular coefficient matrix.

For more details about the LP procedure, see Chapter 6, “[The LP Procedure](#).”

---

### PROC INTPOINT

The INTPOINT procedure solves linear programming problems by using the interior point algorithm.

The constraint data can be specified in either the sparse or dense input format. This is the same format that is used by PROC LP; therefore, any model-building techniques that apply to models for PROC LP also apply to PROC INTPOINT.

For more details about the INTPOINT procedure, see Chapter 5, “[The INTPOINT Procedure](#).”



---

## Mixed Integer Linear Programming Problems

---

### PROC LP

The LP procedure solves mixed integer linear programming problems (MILPs) with a primal simplex solver. To solve a MILP, you first need to identify the integer variables. You can do this with a row in the input data set that has the keyword `INTEGER` for the type variable. It is important to note that integer variables must have upper bounds explicitly defined.

As with linear programs, you can specify MILP problem data using either sparse or dense format. For more details, see Chapter 6, “[The LP Procedure](#).”

---

## Network Problems

---

### PROC NETFLOW

The NETFLOW procedure solves network flow problems with linear side constraints by using either a network simplex algorithm or an interior point algorithm.

#### The Network Simplex Algorithm

PROC NETFLOW’s network simplex algorithm solves pure network flow problems and network flow problems with linear side constraints. The procedure accepts the network specification in formats that are particularly suited to networks.

Network flow problems, such as finding the minimum cost flow in a network, benefit from model representation in a format that is specialized for network structures. The network is represented in two data sets: a node data set that names the nodes in the network and gives supply and demand information at them, and an arc data set that uses node names to define the arcs in the network and gives arc costs and capacities. In addition, a side-constraint data set is included that gives any side constraints that apply to the flow through the network. Examples of these are found later in this chapter.

The constraint data can be specified in either the sparse or dense input format. This is the same format that is used by PROC LP; therefore, any model-building techniques that apply to models for PROC LP also apply to network flow models that have side constraints.

#### The Interior Point Algorithm

When you solve a constrained network problem, you can specify the `INTPOINT` option to indicate that the interior point algorithm is to be used. The input data are the same whether the network simplex or interior point method is used. The interior point method is often faster when problems have many side constraints.

The constraint data can be specified in either the sparse or dense input format. This is the same format that is used by PROC LP; therefore, any model-building techniques that apply to models for PROC LP also apply to network flow models that have side constraints. For more information about the NETFLOW procedure, see Chapter 7, “[The NETFLOW Procedure](#).”

---

## Nonlinear Problems

---

### The NLP Procedure

The NLP procedure offers a set of optimization techniques for minimizing or maximizing a continuous nonlinear function subject to linear and nonlinear, equality and inequality, and lower and upper bound constraints. Problems of this type are found in many settings, ranging from optimal control to maximum likelihood estimation.

Nonlinear programs can be input into the NLP procedure in various ways. The objective, constraint, and derivative functions are specified using the programming statements of PROC NLP. In addition, information in SAS data sets can be used to define the structure of objectives and constraints and to specify constants that are used in objectives, constraints, and derivatives.

PROC NLP uses the following data sets to input various pieces of information:

- The DATA= data set enables you to specify data that is used to define one or more objective functions in a nonlinear programming problem.
- The INQUAD= data set contains the arrays that appear in a quadratic programming problem.
- The INEST= data set specifies initial values for the decision variables, the values of constants that are referred to in the program statements, and simple boundary and general linear constraints.
- The MODEL= data set specifies a model (functions, constraints, derivatives) saved at a previous execution of the NLP procedure.

As an alternative to supplying data in SAS data sets, some or all data for the model can be specified using SAS programming statements. These statements are similar to the statements used in the SAS DATA step.

For more information about the NLP procedure, refer to Chapter 8, “[The NLP Procedure](#).”

---

## Model Building

Model generation and maintenance are often difficult and expensive aspects of applying mathematical programming techniques. The flexible input formats for the optimization procedures in SAS/OR software simplify this task.

---

### The LP Procedure

A small product-mix problem serves as a starting point for a discussion of different types of model formats that are supported in SAS/OR software.

A candy manufacturer makes two products: chocolates and toffee. What combination of chocolates and toffee should be produced in a day in order to maximize the company's profit? Chocolates contribute \$0.25 per pound to profit, and toffee contributes \$0.75 per pound. The decision variables are *chocolates* and *toffee*.

Four processes are used to manufacture the candy:

1. Process 1 combines and cooks the basic ingredients for both chocolates and toffee.
2. Process 2 adds colors and flavors to the toffee, then cools and shapes the confection.
3. Process 3 chops and mixes nuts and raisins, adds them to the chocolates, and then cools and cuts the bars.
4. Process 4 is packaging: chocolates are placed in individual paper shells; toffee is wrapped in cellophane packages.

During the day, there are 7.5 hours (27,000 seconds) available for each process.

Firm time standards have been established for each process. For Process 1, mixing and cooking take 15 seconds for each pound of chocolate, and 40 seconds for each pound of toffee. Process 2 takes 56.25 seconds per pound of toffee. For Process 3, each pound of chocolate requires 18.75 seconds of processing. In packaging, a pound of chocolates can be wrapped in 12 seconds, whereas a pound of toffee requires 50 seconds. These data are summarized as follows:

| Process        | Available     | Required per Pound  |                 |
|----------------|---------------|---------------------|-----------------|
|                | Time<br>(sec) | chocolates<br>(sec) | toffee<br>(sec) |
| 1 Cooking      | 27,000        | 15                  | 40              |
| 2 Color/Flavor | 27,000        |                     | 56.25           |
| 3 Condiments   | 27,000        | 18.75               |                 |
| 4 Packaging    | 27,000        | 12                  | 50              |

The objective is to maximize the company's total profit, which is represented as:

$$\text{Maximize: } 0.25(\text{chocolates}) + 0.75(\text{toffee})$$

The production of the candy is limited by the time available for each process. The limits placed on production by Process 1 are expressed by the following inequality:

$$\text{Process 1: } 15(\text{chocolates}) + 40(\text{toffee}) \leq 27,000$$

Process 1 can handle any combination of chocolates and toffee that satisfies this inequality.

The limits on production by other processes generate constraints described by the following inequalities:

$$\text{Process 2: } 56.25(\text{toffee}) \leq 27,000$$

$$\text{Process 3: } 18.75(\text{chocolates}) \leq 27,000$$

$$\text{Process 4: } 12(\text{chocolates}) + 50(\text{toffee}) \leq 27,000$$

This sample linear program illustrates a product mix problem. The mix of products that maximizes the objective without violating the constraints is the solution. For input to PROC LP, this model can be represented in a SAS data set that uses either dense or sparse format.

## Dense Format

The following DATA step creates a SAS data set for this product mix problem. Notice that the values of CHOCO and TOFFEE in the data set are the coefficients of those variables in the objective function and constraints. The variable `_id_` contains a character string that names the rows in the data set. The variable `_type_` is a character variable that contains keywords that describe the type of each row in the problem data set. The variable `_rhs_` contains the right-hand-side values.

```
data factory;
  input _id_ $ CHOCO TOFFEE _type_ $ _rhs_;
  datalines;
object      0.25      0.75      MAX      .
process1    15.00     40.00      LE    27000
process2     0.00     56.25      LE    27000
process3    18.75      0.00      LE    27000
process4    12.00     50.00      LE    27000
;
```

To solve this problem by using PROC LP, specify the following:

```
proc lp data=factory;
run;
```

## Sparse Format

Typically, mathematical programming models are sparse; that is, few of the coefficients in the constraint matrix are nonzero. For this reason the LP procedure also accepts data in a sparse format SAS data set. In this format only the nonzero coefficients for the constraints and objective function must be specified.

An example of a sparse format data set is shown here. The following data set contains the data from the product mix problem of the preceding section.

```
data sp_factory;
  format _type_ $8. _row_ $10. _col_ $10.;
  input _type_ $ _row_ $ _col_ $ _coef_;
  datalines;
max    object      .      .
.      object      chocolate .25
.      object      toffee    .75
le     process1    .      .
.      process1    chocolate 15
.      process1    toffee    40
.      process1    _RHS_     27000
le     process2    .      .
.      process2    toffee    56.25
.      process2    _RHS_     27000
le     process3    .      .
.      process3    chocolate 18.75
.      process3    _RHS_     27000
le     process4    .      .
.      process4    chocolate 12
.      process4    toffee    50
.      process4    _RHS_     27000
;
```

To solve this problem by using PROC LP, specify the following:

```
proc lp data=sp_factory sparsedata;
run;
```

The “Solution Summary” table (shown in [Figure 4.1](#)) contains information about the solution that was found, including whether the optimizer terminated successfully after finding the optimum.

PROC LP uses an iterative process to solve problems. First, the procedure finds a feasible solution that satisfies the constraints. Second, it finds an optimal solution from the set of feasible solutions. The “Solution Summary” table lists information about the optimization process such as the number of iterations, the infeasibilities of the solution, and the time required to solve the problem.

**Figure 4.1** Solution Summary

| The LP Procedure                 |              |      |
|----------------------------------|--------------|------|
| Solution Summary                 |              |      |
| Terminated Successfully          |              |      |
| Objective Value                  |              | 475  |
| Phase 1 Iterations               |              | 0    |
| Phase 2 Iterations               |              | 3    |
| Phase 3 Iterations               |              | 0    |
| Integer Iterations               |              | 0    |
| Integer Solutions                |              | 0    |
| Initial Basic Feasible Variables |              | 6    |
| Time Used (seconds)              |              | 0    |
| Number of Inversions             |              | 3    |
| Epsilon                          |              | 1E-8 |
| Infinity                         | 1.797693E308 |      |
| Maximum Phase 1 Iterations       |              | 100  |
| Maximum Phase 2 Iterations       |              | 100  |
| Maximum Phase 3 Iterations       | 99999999     |      |
| Maximum Integer Iterations       |              | 100  |
| Time Limit (seconds)             |              | 120  |

## Separating the Data from the Model Structure

It is often desirable to keep the data separate from the structure of the model. This is useful for large models with numerous identifiable components. The data are best organized in rectangular tables that can be easily examined and modified. Then, before the problem is solved, the model is built using the stored data. This process of model building is known as *matrix generation*. In conjunction with the sparse format used by the legacy procedures, the SAS DATA step provides a good matrix generation language.

For example, consider the candy manufacturing example introduced previously. Suppose that, for the user interface, it is more convenient to organize the data so that each record describes the information related to each product (namely, the contribution to the objective function and the unit amount needed for each process). A DATA step for saving the data might look like this:

```

data manfg;
format product $12.;
input product $ object process1 - process4 ;
datalines;
chocolate      .25    15  0.00 18.75    12
toffee         .75    40 56.25  0.00    50
licorice       1.00    29 30.00 20.00    20
jelly_beans    .85    10  0.00 30.00    10
_RHS_          .    27000 27000 27000 27000
;

```

Notice that there is a special record at the end that has product `_RHS_`. This record gives the amounts of time available for each of the processes. This information could have been stored in another data set. The next example illustrates a model in which the data are stored in separate data sets.

Building the model involves adding the data to the structure. There are as many ways to add data as there are programmers and problems. The following DATA step shows one way to use the candy data to build a sparse format model to solve the product mix problem:

```

data model;
array process object process1-process4;
format _type_ $8. _row_ $12. _col_ $12. ;
keep _type_ _row_ _col_ _coef_;

set manfg;          /* read the manufacturing data */

/* build the object function */

if _n_=1 then do;
    _type_='max'; _row_='object'; _col_=' '; _coef_=.;
    output;
end;

/* build the constraints */

do over process;
    if _i_>1 then do;
        _type_='le'; _row_='process' || put(_i_-1,1.);
    end;
    else
        _row_='object';
    _col_=product; _coef_=process;
    output;
end;
run;

```

The sparse format data set is shown in Figure 4.2.

**Figure 4.2** Sparse Data Format

| Obs | _type_ | _row_    | _col_       | _coef_   |
|-----|--------|----------|-------------|----------|
| 1   | max    | object   |             | .        |
| 2   | max    | object   | chocolate   | 0.25     |
| 3   | 1e     | process1 | chocolate   | 15.00    |
| 4   | 1e     | process2 | chocolate   | 0.00     |
| 5   | 1e     | process3 | chocolate   | 18.75    |
| 6   | 1e     | process4 | chocolate   | 12.00    |
| 7   |        | object   | toffee      | 0.75     |
| 8   | 1e     | process1 | toffee      | 40.00    |
| 9   | 1e     | process2 | toffee      | 56.25    |
| 10  | 1e     | process3 | toffee      | 0.00     |
| 11  | 1e     | process4 | toffee      | 50.00    |
| 12  |        | object   | licorice    | 1.00     |
| 13  | 1e     | process1 | licorice    | 29.00    |
| 14  | 1e     | process2 | licorice    | 30.00    |
| 15  | 1e     | process3 | licorice    | 20.00    |
| 16  | 1e     | process4 | licorice    | 20.00    |
| 17  |        | object   | jelly_beans | 0.85     |
| 18  | 1e     | process1 | jelly_beans | 10.00    |
| 19  | 1e     | process2 | jelly_beans | 0.00     |
| 20  | 1e     | process3 | jelly_beans | 30.00    |
| 21  | 1e     | process4 | jelly_beans | 10.00    |
| 22  |        | object   | _RHS_       | .        |
| 23  | 1e     | process1 | _RHS_       | 27000.00 |
| 24  | 1e     | process2 | _RHS_       | 27000.00 |
| 25  | 1e     | process3 | _RHS_       | 27000.00 |
| 26  | 1e     | process4 | _RHS_       | 27000.00 |

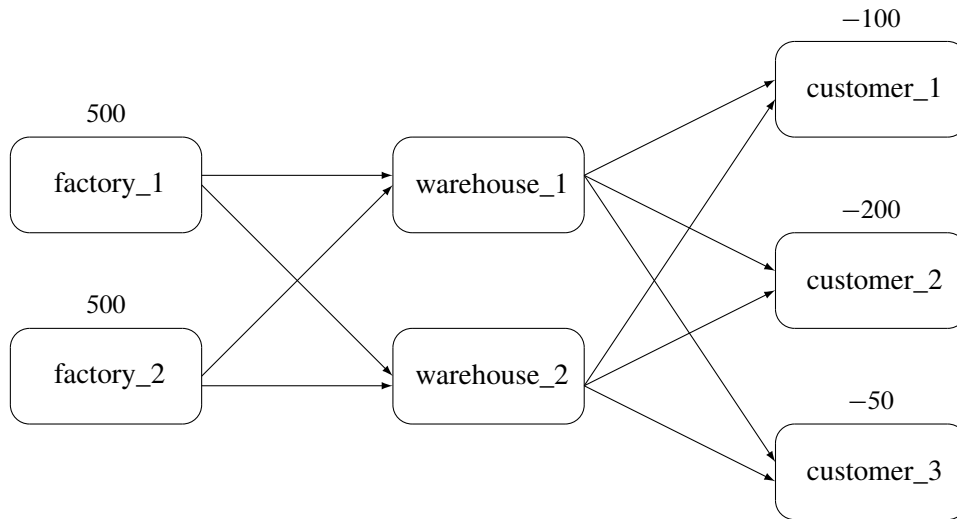
The model data set looks a little different from the sparse representation of the candy model shown earlier. It not only includes additional products (licorice and jelly beans), but it also defines the model in a different order. Since the sparse format is robust, the model can be generated in ways that are convenient for the DATA step program.

If the problem had more products, you could increase the size of the `manfg` data set to include the new product data. Also, if the problem had more than four processes, you could add the new process variables to the `manfg` data set and increase the size of the process array in the model data set. With these two simple changes and additional data, a product mix problem that has hundreds of processes and products can be modeled and solved.

---

## The NETFLOW Procedure

Network flow problems can be described by specifying the nodes in the network and their supplies and demands, specifying the arcs in the network and their costs, capacities, and lower flow bounds. Consider the simple transshipment problem in Figure 4.3 as an illustration.

**Figure 4.3** Transshipment Problem

Suppose the candy manufacturing company has two factories, two warehouses, and three customers for chocolate. The two factories each have a production capacity of 500 pounds per day. The three customers have demands of 100, 200, and 50 pounds per day, respectively.

The following data set describes the supplies (positive values for the `supdem` variable) and the demands (negative values for the `supdem` variable) for each of the customers and factories:

```

data nodes;
format node $10. ;
input node $ supdem;
datalines;
customer_1    -100
customer_2    -200
customer_3     -50
factory_1      500
factory_2      500
;

```

Suppose that two warehouses are used to store the chocolate before shipment to the customers, and that there are different costs for shipping between each factory, warehouse, and customer. What is the minimum cost routing for supplying the customers?

Arcs are described in another data set. Each observation defines a new arc in the network and gives data about the arc. For example, there is an arc between the node `factory_1` and the node `warehouse_1`. Each unit of flow on that arc costs 10. Although this example does not include it, lower and upper bounds on the flow across that arc can also be listed here.



```

data network;
    format from $12. to $12.;
    input from $ to $ cost ;
    datalines;
factory_1    warehouse_1    10
factory_2    warehouse_1     5
factory_1    warehouse_2     7
factory_2    warehouse_2     9
warehouse_1  customer_1     3
warehouse_1  customer_2     4
warehouse_1  customer_3     4
warehouse_2  customer_1     5
warehouse_2  customer_2     5
warehouse_2  customer_3     6
;

```

You can use PROC NETFLOW to find the minimum cost routing. This procedure takes the model as defined in the network and nodes data sets and finds the minimum cost flow.

```

proc netflow arcout=arc_sav
    arcdata=network nodedata=nodes;
    node node;      /* node data set information */
    supdem supdem;
    tail from;      /* arc data set information */
    head to;
    cost cost;
    run;

proc print;
    var from to cost _capac_ _lo_ _supply_ _demand_
        _flow_ _fcost_ _rcost_;
    sum _fcost_;
    run;

```

PROC NETFLOW produces the following messages in the SAS log:

```

NOTE: Number of nodes= 7 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 3 .
NOTE: Total supply= 1000 , total demand= 350 .
NOTE: Number of arcs= 10 .
NOTE: Number of iterations performed (neglecting any constraints)= 9 .
NOTE: Of these, 2 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= 3050 .
NOTE: The data set WORK.ARC_SAV has 10 observations and 13 variables.

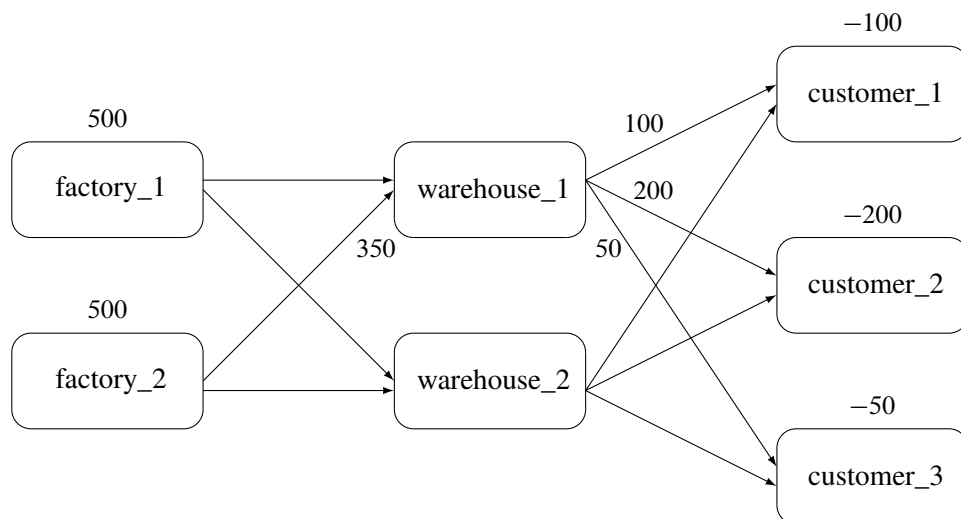
```

The solution (Figure 4.4) saved in the arc\_sav data set shows the optimal amount of chocolate to send across each arc (the amount to ship from each factory to each warehouse and from each warehouse to each customer) in the network per day.

**Figure 4.4** ARCOUT Data Set

| O<br>b<br>s | f<br>r<br>o<br>m | t<br>o      | c<br>o<br>s<br>t | — C — S — D — F — R |   |     |     |     |      |      |
|-------------|------------------|-------------|------------------|---------------------|---|-----|-----|-----|------|------|
|             |                  |             |                  | A                   | P | U   | M   | L   | O    | C    |
|             |                  |             |                  | P                   | — | P   | A   | —   | —    | —    |
|             |                  |             |                  | A                   | L | L   | N   | O   | S    | S    |
|             |                  |             |                  | C                   | O | Y   | D   | W   | T    | T    |
|             |                  |             |                  | —                   | — | —   | —   | —   | —    | —    |
| 1           | warehouse_1      | customer_1  | 3                | 99999999            | 0 | .   | 100 | 100 | 300  | .    |
| 2           | warehouse_2      | customer_1  | 5                | 99999999            | 0 | .   | 100 | 0   | 0    | 4    |
| 3           | warehouse_1      | customer_2  | 4                | 99999999            | 0 | .   | 200 | 200 | 800  | .    |
| 4           | warehouse_2      | customer_2  | 5                | 99999999            | 0 | .   | 200 | 0   | 0    | 3    |
| 5           | warehouse_1      | customer_3  | 4                | 99999999            | 0 | .   | 50  | 50  | 200  | .    |
| 6           | warehouse_2      | customer_3  | 6                | 99999999            | 0 | .   | 50  | 0   | 0    | 4    |
| 7           | factory_1        | warehouse_1 | 10               | 99999999            | 0 | 500 | .   | 0   | 0    | 5    |
| 8           | factory_2        | warehouse_1 | 5                | 99999999            | 0 | 500 | .   | 350 | 1750 | .    |
| 9           | factory_1        | warehouse_2 | 7                | 99999999            | 0 | 500 | .   | 0   | 0    | .    |
| 10          | factory_2        | warehouse_2 | 9                | 99999999            | 0 | 500 | .   | 0   | 0    | 2    |
|             |                  |             |                  |                     |   |     |     |     |      | ==== |
|             |                  |             |                  |                     |   |     |     |     |      | 3050 |

Notice which arcs have positive flow (`_FLOW_` is greater than 0). These arcs indicate the amount of chocolate that should be sent from `factory_2` to `warehouse_1` and from there to the three customers. The solution indicates no production at `factory_1` and no use of `warehouse_2`.

**Figure 4.5** Optimal Solution for the Transshipment Problem

## Matrix Generation

It is desirable to keep data in separate tables, and then to automate model building and reporting. This example illustrates a problem that has elements of both a product mix problem and a blending problem. Suppose four kinds of ties are made: all silk, all polyester, a 50-50 polyester-cotton blend, and a 70-30 cotton-polyester blend.

The data include cost and supplies of raw material, selling price, minimum contract sales, maximum demand of the finished products, and the proportions of raw materials that go into each product. The objective is to find the product mix that maximizes profit.

The data are saved in three SAS data sets. The following program demonstrates one way for these data to be saved:

```
data material;
  format descpt $20.;
  input descpt $ cost supply;
  datalines;
silk_material          .21    25.8
polyester_material     .6     22.0
cotton_material        .9     13.6
;

data tie;
  format descpt $20.;
  input descpt $ price contract demand;
  datalines;
all_silk               6.70    6.0    7.00
all_polyester          3.55    10.0   14.00
poly_cotton_blend      4.31    13.0   16.00
cotton_poly_blend      4.81    6.0    8.50
;

data manfg;
  format descpt $20.;
  input descpt $ silk poly cotton;
  datalines;
all_silk               100     0      0
all_polyester          0      100    0
poly_cotton_blend      0      50     50
cotton_poly_blend      0      30     70
;
```

The following program takes the raw data from the three data sets and builds a linear program model in the data set called model. Although it is designed for the three-resource, four-product problem described here, it can be extended to include more resources and products. The model-building DATA step remains essentially the same; all that changes are the dimensions of loops and arrays. Of course, the data tables must expand to accommodate the new data. Note that data-driven model creation as outlined here is far easier and more direct with the algebraic modeling capabilities of PROC OPTMODEL, the foremost of the newer SAS/OR mathematical programming procedures.

```

data model;
  array raw_mat {3} $ 20 ;
  array raw_comp {3} silk poly cotton;
  length _type_ $ 8 _col_ $ 20 _row_ $ 20 _coef_ 8 ;
  keep _type_ _col_ _row_ _coef_ ;

  /* define the objective, lower, and upper bound rows */

  _row_='profit'; _type_='max';      output;
  _row_='lower';  _type_='lowerbd';  output;
  _row_='upper';  _type_='upperbd';  output;
  _type_=' ' ;

  /* the object and upper rows for the raw materials */

  do i=1 to 3;
    set material;
    raw_mat[i]=descpt;  _col_=descpt;
    _row_='profit';     _coef_=-cost;  output;
    _row_='upper';      _coef_=supply; output;
  end;

  /* the object, upper, and lower rows for the products */

  do i=1 to 4;
    set tie;
    _col_=descpt;
    _row_='profit'; _coef_=price;      output;
    _row_='lower';  _coef_=contract;  output;
    _row_='upper';  _coef_=demand;     output;
  end;

  /* the coefficient matrix for manufacturing */

  _type_='eq';
  do i=1 to 4;          /* loop for each raw material */
    set manfg;
    do j=1 to 3;        /* loop for each product      */

      _col_=descpt;     /* % of material in product */
      _row_ = raw_mat[j];
      _coef_ = raw_comp[j]/100;
      output;

      _col_ = raw_mat[j]; _coef_ = -1;
      output;

    /* the right-hand side */

    if i=1 then do;
      _col_='_RHS_';
      _coef_=0;
      output;
    end;
  end;

```

```

        end;
    end;
    _type_='  ';
end;
stop;
run;

```

The model is solved using PROC LP, which saves the solution in the PRIMALOUT data set named solution. PROC PRINT displays the solution, shown in Figure 4.6.

```

proc lp sparsedata primalout=solution;
proc print ;
    id _var_;
    var _lbound_--_r_cost_;
run;

```

**Figure 4.6** Solution Data Set

| The LP Procedure   |                    |           |            |     |                  |
|--------------------|--------------------|-----------|------------|-----|------------------|
| Constraint Summary |                    |           |            |     |                  |
| Row                | Constraint Name    | Type      | S/S<br>Col | Rhs | Dual<br>Activity |
| 1                  | profit             | OBJECTIVE | .          | 0   | 168.708          |
| 2                  | silk_material      | EQ        | .          | 0   | 0                |
| 3                  | polyester_material | EQ        | .          | 0   | 0                |
| 4                  | cotton_material    | EQ        | .          | 0   | 0                |

| _VAR_              | _LBOUND_ | _VALUE_ | _UBOUND_   | _PRICE_ | _R_COST_ |
|--------------------|----------|---------|------------|---------|----------|
| all_polyester      | 10       | 11.800  | 14.0       | 3.55    | 0.000    |
| all_silk           | 6        | 7.000   | 7.0        | 6.70    | 6.490    |
| cotton_material    | 0        | 13.600  | 13.6       | -0.90   | 4.170    |
| cotton_poly_blend  | 6        | 8.500   | 8.5        | 4.81    | 0.196    |
| polyester_material | 0        | 22.000  | 22.0       | -0.60   | 2.950    |
| poly_cotton_blend  | 13       | 15.300  | 16.0       | 4.31    | 0.000    |
| silk_material      | 0        | 7.000   | 25.8       | -0.21   | 0.000    |
| PHASE_1_OBJECTIVE  | 0        | 0.000   | 0.0        | 0.00    | 0.000    |
| profit             | 0        | 168.708 | 1.7977E308 | 0.00    | 0.000    |

The solution shows that 11.8 units of polyester ties, 7 units of silk ties, 8.5 units of the cotton-polyester blend, and 15.3 units of the polyester-cotton blend should be produced. It also shows the amounts of raw materials that go into this product mix to generate a total profit of 168.708.

## Exploiting Model Structure

Another example helps to illustrate how the model can be simplified by exploiting the structure in the model when using the NETFLOW procedure.

Recall the chocolate transshipment problem discussed previously. The solution required no production at factory\_1 and no storage at warehouse\_2. Suppose this solution, although optimal, is unacceptable. An additional constraint that requires the production at the two factories to be balanced is needed. Now, the production at the two factories can differ by, at most, 100 units. Such a constraint might look like this:

$$-100 \leq (\text{factory\_1\_warehouse\_1} + \text{factory\_1\_warehouse\_2} - \text{factory\_2\_warehouse\_1} - \text{factory\_2\_warehouse\_2}) \leq 100$$

The network and supply and demand information are saved in the following two data sets:

```
data network;
    format from $12. to $12.;
    input from $ to $ cost ;
    datalines;
factory_1    warehouse_1  10
factory_2    warehouse_1   5
factory_1    warehouse_2   7
factory_2    warehouse_2   9
warehouse_1  customer_1   3
warehouse_1  customer_2   4
warehouse_1  customer_3   4
warehouse_2  customer_1   5
warehouse_2  customer_2   5
warehouse_2  customer_3   6
;

data nodes;
    format node $12. ;
    input node $ supdem;
    datalines;
customer_1   -100
customer_2   -200
customer_3    -50
factory_1     500
factory_2     500
;
```

The factory-balancing constraint is not a part of the network. It is represented in the sparse format in a data set for side constraints.

```
data side_con;
    format _type_ $8. _row_ $8. _col_ $21. ;
    input _type_ _row_ _col_ _coef_ ;
    datalines;
eq        balance      .                .
.         balance      factory_1_warehouse_1  1
```

```

.      balance  factory_1_warehouse_2      1
.      balance  factory_2_warehouse_1     -1
.      balance  factory_2_warehouse_2     -1
.      balance  diff                       -1
lo     lowerbd  diff                      -100
up     upperbd  diff                      100
;

```

This data set contains an equality constraint that sets the value of DIFF to be the amount that factory 1 production exceeds factory 2 production. It also contains bounds on the DIFF variable. Note that the DIFF variable is a nonarc variable.

You can use the following call to PROC NETFLOW to solve the problem:

```

proc netflow
  conout=con_sav
  arcdata=network nodedata=nodes condata=side_con
  sparsecondata ;
  node node;
  supdem supdem;
  tail from;
  head to;
  cost cost;
  run;

proc print;
  var from to _name_ cost _capac_ _lo_ _supply_ _demand_
      _flow_ _fcost_ _rcost_;
  sum _fcost_;
  run;

```

The solution is saved in the con\_sav data set, as displayed in Figure 4.7.

**Figure 4.7** CON\_SAV Data Set



## Report Writing

The reporting of the solution is also an important aspect of modeling. Since the optimization procedures save the solution in one or more SAS data sets, reports can be written using any of the tools in the SAS language.

### The DATA Step

Use of the DATA step and PROC PRINT is the most common way to produce reports. For example, from the data set solution shown in [Figure 4.6](#), a table that shows the revenue of the optimal production plan and a table of the cost of material can be produced with the following program:

```
data product(keep= _var_ _value_ _price_ revenue)
  material(keep=_var_ _value_ _price_ cost);
  set solution;
  if _price_>0 then do;
    revenue=_price*_value_; output product;
  end;
  else if _price_<0 then do;
    _price_=-_price_;
    cost = _price*_value_; output material;
  end;
run;

/* display the product report */

proc print data=product;
  id _var_;
  var _value_ _price_ revenue ;
  sum revenue;
  title 'Revenue Generated from Tie Sales';
run;

/* display the materials report */

proc print data=material;
  id _var_;
  var _value_ _price_ cost;
  sum cost;
  title 'Cost of Raw Materials';
run;
```

This DATA step reads the solution data set saved by PROC LP and segregates the records based on whether they correspond to materials or products—namely whether the contribution to profit is positive or negative. Each of these is then displayed to produce [Figure 4.9](#).

**Figure 4.9** Tie Problem: Revenues and Costs

| Revenue Generated from Tie Sales |         |         |         |
|----------------------------------|---------|---------|---------|
| _VAR_                            | _VALUE_ | _PRICE_ | revenue |
| all_polyester                    | 11.8    | 3.55    | 41.890  |
| all_silk                         | 7.0     | 6.70    | 46.900  |
| cotton_poly_blend                | 8.5     | 4.81    | 40.885  |
| poly_cotton_blend                | 15.3    | 4.31    | 65.943  |
|                                  |         |         | =====   |
|                                  |         |         | 195.618 |

| Cost of Raw Materials |         |         |       |
|-----------------------|---------|---------|-------|
| _VAR_                 | _VALUE_ | _PRICE_ | cost  |
| cotton_material       | 13.6    | 0.90    | 12.24 |
| polyester_material    | 22.0    | 0.60    | 13.20 |
| silk_material         | 7.0     | 0.21    | 1.47  |
|                       |         |         | ===== |
|                       |         |         | 26.91 |

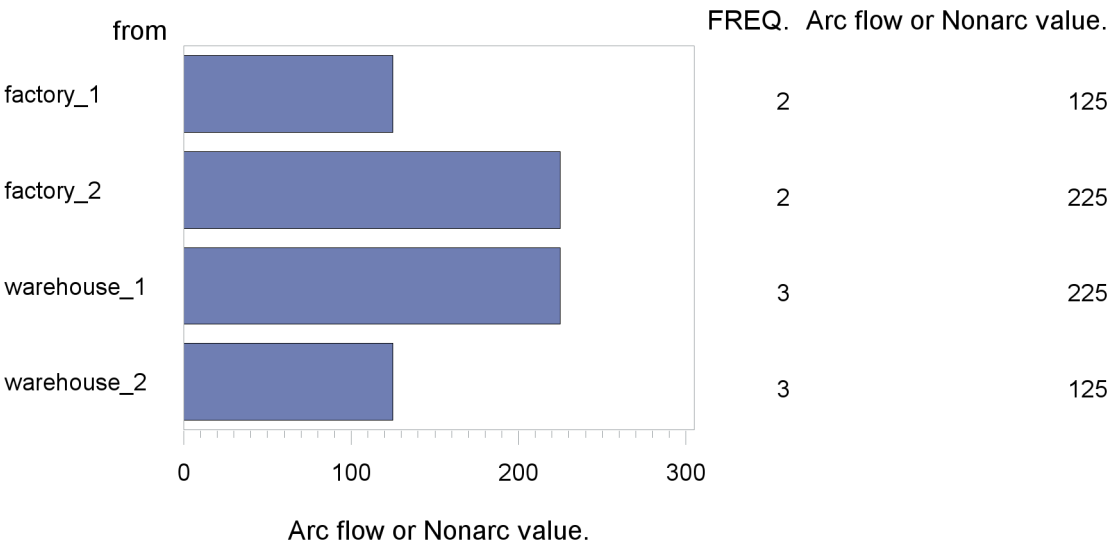
---

## Other Reporting Procedures

The GCHART procedure can be a useful tool for displaying the solution to mathematical programming models. The con\_solv data set that contains the solution to the balanced transshipment problem can be effectively displayed using PROC GCHART. In [Figure 4.10](#), the amount that is shipped from each factory and warehouse can be seen by submitting the following SAS statements:

```
title;
proc gchart data=con_sav;
  hbar from / sumvar=_flow_;
run;
```

Figure 4.10 Tie Problem: Throughputs

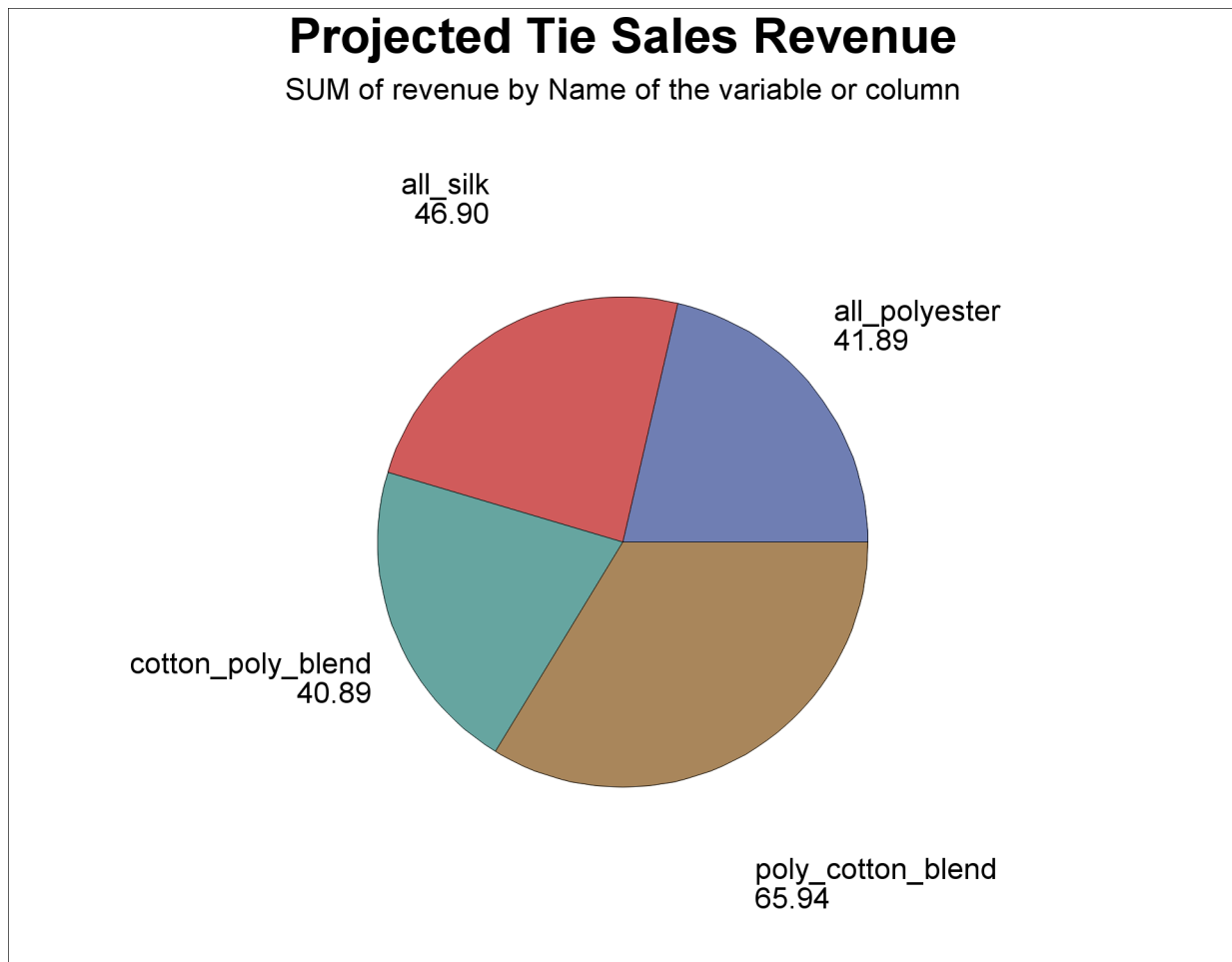


The horizontal bar chart is just one way of displaying the solution to a mathematical program. The solution to the tie product mix problem that was solved using PROC LP can also be illustrated using PROC GCHART.

```
proc gchart data=product;  
  pie _var_ / sumvar=revenue;  
  title h=2.5 'Projected Tie Sales Revenue';  
run;
```

The pie chart in Figure 4.11 shows the relative contribution of each product to total revenues.

**Figure 4.11** Tie Problem: Projected Tie Sales Revenue



The TABULATE procedure can also help automate solution reporting. Several examples in Chapter 6, “[The LP Procedure](#),” illustrate its use.

# Chapter 5

## The INTPOINT Procedure

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---

## Overview: INTPOINT Procedure

The INTPOINT procedure solves the Network Program with Side Constraints (NPSC) problem (defined in the section “[Mathematical Description of NPSC](#)” on page 45) and the more general Linear Programming (LP) problem (defined in the section “[Mathematical Description of LP](#)” on page 47). NPSC and LP models can be used to describe a wide variety of real-world applications ranging from production, inventory, and distribution problems to financial applications.

Whether your problem is NPSC or LP, PROC INTPOINT uses the same optimization algorithm, the interior point algorithm. This algorithm is outlined in the section “[The Interior Point Algorithm](#)” on page 47.

While many of your problems may best be formulated as LP problems, there may be other instances when your problems are better formulated as NPSC problems. The section “[Network Models](#)” on page 54 describes typical models that have a network component and suggests reasons why NPSC may be preferable to LP. The section “[Getting Started: NPSC Problems](#)” on page 61 outlines how you supply data of any NPSC problem to PROC INTPOINT and call the procedure. After it reads the NPSC data, PROC INTPOINT converts the problem into an equivalent LP problem, performs interior point optimization, then converts the solution it finds back into a form you can use as the optimum to the original NPSC model.

If your model is an LP problem, the way you supply the data to PROC INTPOINT and run the procedure is described in the section “[Getting Started: LP Problems](#)” on page 68.

You can also solve LP problems by using the OPTLP procedure. The OPTLP procedure requires a linear program to be specified by using a SAS data set that adheres to the MPS format, a widely accepted format

in the optimization community. You can use the `MPSOUT=` option in the INTPOINT procedure to convert typical PROC INTPOINT format data sets into MPS-format SAS data sets.

The remainder of this chapter is organized as follows:

- The section “[Typical PROC INTPOINT Run](#)” on page 75 describes how to use this procedure.
- The section “[Syntax: INTPOINT Procedure](#)” on page 77 describes all the statements and options of PROC INTPOINT.
- The section “[Functional Summary](#)” on page 77 lists the statements and options that can be used to control PROC INTPOINT.
- The section “[Details: INTPOINT Procedure](#)” on page 106 contains detailed explanations, descriptions, and advice on the use and behavior of the procedure.
- PROC INTPOINT is demonstrated by solving several examples in the section “[Examples: INTPOINT Procedure](#)” on page 132.

---

## Mathematical Description of NPSC

A network consists of a collection of nodes joined by a collection of arcs. The arcs connect nodes and convey flow of one or more commodities that are supplied at supply nodes and demanded at demand nodes in the network. Each arc has a cost per unit of flow, a flow capacity, and a lower flow bound associated with it. An important concept in network modeling is *conservation of flow*. Conservation of flow means that the total flow in arcs directed toward a node, plus the supply at the node, minus the demand at the node, equals the total flow in arcs directed away from the node.

Often all the details of a problem cannot be specified in a network model alone. In many of these cases, these details can be represented by the addition of side constraints to the model. Side constraints are linear functions of arc variables (variables containing flow through an arc) and nonarc variables (variables that are not part of the network). The data for a side constraint consist of coefficients of arcs and coefficients of nonarc variables, a constraint type (that is,  $\leq$ ,  $=$ , or  $\geq$ ) and a right-hand-side value (rhs). A nonarc variable has a name, an objective function coefficient analogous to an arc cost, an upper bound analogous to an arc capacity, and a lower bound analogous to an arc lower flow bound.

If a network component of NPSC is removed by merging arcs and nonarc variables into a single set of variables, and if the flow conservation constraints and side constraints are merged into a single set of constraints, the result is an LP problem. PROC INTPOINT will automatically transform an NPSC problem into an equivalent LP problem, perform the optimization, then transform the problem back into its original form. By doing this, PROC INTPOINT finds the flow through the network and the values of any nonarc variables that minimize the total cost of the solution. Flow conservation is met, flow through each arc is on or between the arc’s lower flow bound and capacity, the value of each nonarc variable is on or between the nonarc’s lower and upper bounds, and the side constraints are satisfied.

Note that, since many LPs have large embedded networks, PROC INTPOINT is an attractive alternative to the LP procedure in many cases. Rather than formulating all problems as LPs, network models remain conceptually easy since they are based on network diagrams that represent the problem pictorially. PROC INTPOINT accepts the network specification in a format that is particularly suited to networks. This not only

simplifies problem description but also aids in the interpretation of the solution. The conversion to and from the equivalent LP is done “behind the scenes” by the procedure.

If a network programming problem with side constraints has  $n$  nodes,  $a$  arcs,  $g$  nonarc variables, and  $k$  side constraints, then the formal statement of the problem solved by PROC INTPOINT is

$$\begin{array}{ll} \text{minimize} & c^T x + d^T z \\ \text{subject to} & Fx = b \\ & Hx + Qz \{ \geq, =, \leq \} r \\ & l \leq x \leq u \\ & m \leq z \leq v \end{array}$$

where

- $c$  is the  $a \times 1$  arc variable objective function coefficient vector (the cost vector)
- $x$  is the  $a \times 1$  arc variable value vector (the flow vector)
- $d$  is the  $g \times 1$  nonarc variable objective function coefficient vector
- $z$  is the  $g \times 1$  nonarc variable value vector
- $F$  is the  $n \times a$  node-arc incidence matrix of the network, where

$$F_{i,j} = \begin{cases} -1, & \text{if arc } j \text{ is directed from node } i \\ 1, & \text{if arc } j \text{ is directed toward node } i \\ 0, & \text{otherwise} \end{cases}$$

- $b$  is the  $n \times 1$  node supply/demand vector, where

$$b_i = \begin{cases} s, & \text{if node } i \text{ has supply capability of } s \text{ units of flow} \\ -d, & \text{if node } i \text{ has demand of } d \text{ units of flow} \\ 0, & \text{if node } i \text{ is a transshipment node} \end{cases}$$

- $H$  is the  $k \times a$  side constraint coefficient matrix for arc variables, where  $H_{i,j}$  is the coefficient of arc  $j$  in the  $i$ th side constraint
- $Q$  is the  $k \times g$  side constraint coefficient matrix for nonarc variables, where  $Q_{i,j}$  is the coefficient of nonarc  $j$  in the  $i$ th side constraint
- $r$  is the  $k \times 1$  side constraint right-hand-side vector
- $l$  is the  $a \times 1$  arc lower flow bound vector
- $u$  is the  $a \times 1$  arc capacity vector
- $m$  is the  $g \times 1$  nonarc variable lower bound vector
- $v$  is the  $g \times 1$  nonarc variable upper bound vector

The INTPOINT procedure can also be used to solve an unconstrained network problem, that is, one in which  $H$ ,  $Q$ ,  $d$ ,  $r$ , and  $z$  do not exist. It can also be used to solve a network problem with side constraints but no nonarc variables, in which case  $Q$ ,  $d$ , and  $z$  do not exist.



## Mathematical Description of LP

A linear programming (LP) problem has a linear objective function and a collection of linear constraints. PROC INTPOINT finds the values of variables that minimize the total cost of the solution. The value of each variable is on or between the variable's lower and upper bounds, and the constraints are satisfied.

If an LP has  $g$  variables and  $k$  constraints, then the formal statement of the problem solved by PROC INTPOINT is

$$\begin{array}{ll} \text{minimize} & d^T z \\ \text{subject to} & Qz \{ \geq, =, \leq \} r \\ & m \leq z \leq v \end{array}$$

where

- $d$  is the  $g \times 1$  variable objective function coefficient vector
- $z$  is the  $g \times 1$  variable value vector
- $Q$  is the  $k \times g$  constraint coefficient matrix for the variables, where  $Q_{i,j}$  is the coefficient of variable  $j$  in the  $i$ th constraint
- $r$  is the  $k \times 1$  side constraint right-hand-side vector
- $m$  is the  $g \times 1$  variable lower bound vector
- $v$  is the  $g \times 1$  variable upper bound vector

## The Interior Point Algorithm

The simplex algorithm, developed shortly after World War II, was for many years the main method used to solve linear programming problems. Over the last fifteen years, however, the interior point algorithm has been developed. This algorithm also solves linear programming problems. From the start it showed great theoretical promise, and considerable research in the area resulted in practical implementations that performed competitively with the simplex algorithm. More recently, interior point algorithms have evolved to become superior to the simplex algorithm, in general, especially when the problems are large.

There are many variations of interior point algorithms. PROC INTPOINT uses the Primal-Dual with Predictor-Corrector algorithm. More information on this particular algorithm and related theory can be found in the texts by Roos, Terlaky, and Vial (1997), Wright (1996), and Ye (1996).

## Interior Point Algorithmic Details

After preprocessing, the linear program to be solved is

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0 \end{array}$$

This is the *primal* problem. The matrices  $d$ ,  $z$ , and  $Q$  of NPSC have been renamed  $c$ ,  $x$ , and  $A$ , respectively, as these symbols are by convention used more, the problem to be solved is different from the original because of *preprocessing*, and there has been a change of primal variable to transform the LP into one whose variables have zero lower bounds. To simplify the algebra here, assume that variables have infinite upper bounds, and constraints are equalities. (Interior point algorithms do efficiently handle finite upper bounds, and it is easy to introduce primal slack variables to change inequalities into equalities.) The problem has  $n$  variables;  $i$  is a variable number;  $k$  is an iteration number, and if used as a subscript or superscript it denotes “of iteration  $k$ ”.

There exists an equivalent problem, the *dual* problem, stated as

$$\begin{array}{ll} \text{maximize} & b^T y \\ \text{subject to} & A^T y + s = c \\ & s \geq 0 \end{array}$$

where  $y$  are dual variables, and  $s$  are dual constraint slacks.

The interior point algorithm solves the system of equations to satisfy the Karush-Kuhn-Tucker (KKT) conditions for optimality:

$$\begin{aligned} Ax &= b \\ A^T y + s &= c \\ XSe &= 0 \\ x &\geq 0 \\ s &\geq 0 \end{aligned}$$

where

$$\begin{aligned} S &= \text{diag}(s) \text{ (that is, } S_{i,j} = s_i \text{ if } i = j, S_{i,j} = 0 \text{ otherwise)} \\ X &= \text{diag}(x) \\ e_i &= 1 \ \forall i \end{aligned}$$

These are the conditions for feasibility, with the *complementarity* condition  $XSe = 0$  added. Complementarity forces the optimal objectives of the primal and dual to be equal,  $c^T x_{opt} = b^T y_{opt}$ , as

$$\begin{aligned} 0 &= x_{opt}^T s_{opt} = s_{opt}^T x_{opt} = (c - A^T y_{opt})^T x_{opt} = \\ &= c^T x_{opt} - y_{opt}^T (Ax_{opt}) = c^T x_{opt} - b^T y_{opt} \end{aligned}$$

Before the optimum is reached, a solution  $(x, y, s)$  may not satisfy the KKT conditions:

- Primal constraints may be violated,  $\text{infeas}_c = b - Ax \neq 0$ .
- Dual constraints may be violated,  $\text{infeas}_d = c - A^T y - s \neq 0$ .
- Complementarity may not be satisfied,  $x^T s = c^T x - b^T y \neq 0$ . This is called the *duality gap*.

The interior point algorithm works by using Newton’s method to find a direction to move  $(\Delta x^k, \Delta y^k, \Delta s^k)$  from the current solution  $(x^k, y^k, s^k)$  toward a better solution:

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

where  $\alpha$  is the *step length* and is assigned a value as large as possible but not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  is “too close” to zero. The direction in which to move is found using

$$\begin{aligned} A\Delta x^k &= \text{infeas}_c \\ A^T \Delta y^k + \Delta s^k &= \text{infeas}_d \\ S^k \Delta x^k + X^k \Delta s^k &= -X^k S^k e \end{aligned}$$

To greatly improve performance, the third equation is changed to

$$S^k \Delta x^k + X^k \Delta s^k = -X^k S^k e + \sigma_k \mu_k e$$

where  $\mu_k = (x^k)^T s^k / n$ , the average complementarity, and  $0 \leq \sigma_k \leq 1$ .

The effect now is to find a direction in which to move to reduce infeasibilities and to reduce the complementarity toward zero, but if any  $x_i^k s_i^k$  is too close to zero, it is “nudged out” to  $\mu$ , and any  $x_i^k s_i^k$  that is larger than  $\mu$  is “nudged into”  $\mu$ . A  $\sigma_k$  close to or equal to 0.0 biases a direction toward the optimum, and a value of  $\sigma_k$  close to or equal to 1.0 “centers” the direction toward a point where all pairwise products  $x_i^k s_i^k = \mu$ . Such points make up the *central path* in the interior. Although centering directions make little, if any, progress in reducing  $\mu$  and moving the solution closer to the optimum, substantial progress toward the optimum can usually be made in the next iteration.

The central path is crucial to why the interior point algorithm is so efficient. As  $\mu$  is decreased, this path “guides” the algorithm to the optimum through the interior of feasible space. Without centering, the algorithm would find a series of solutions near each other close to the boundary of feasible space. Step lengths along the direction would be small and many more iterations would probably be required to reach the optimum.

That in a nutshell is the primal-dual interior point algorithm. Varieties of the algorithm differ in the way  $\alpha$  and  $\sigma_k$  are chosen and the direction adjusted during each iteration. A wealth of information can be found in the texts by Roos, Terlaky, and Vial (1997), Wright (1996), and Ye (1996).

The calculation of the direction is the most time-consuming step of the interior point algorithm. Assume the  $k$ th iteration is being performed, so the subscript and superscript  $k$  can be dropped from the algebra:

$$\begin{aligned} A\Delta x &= \text{infeas}_c \\ A^T \Delta y + \Delta s &= \text{infeas}_d \\ S\Delta x + X\Delta s &= -XSe + \sigma\mu e \end{aligned}$$

Rearranging the second equation,

$$\Delta s = \text{infeas}_d - A^T \Delta y$$

Rearranging the third equation,

$$\begin{aligned} \Delta s &= X^{-1}(-S\Delta x - XSe + \sigma\mu e) \\ \Delta s &= -\Theta\Delta x - Se + X^{-1}\sigma\mu e \end{aligned}$$

where  $\Theta = SX^{-1}$ .

Equating these two expressions for  $\Delta s$  and rearranging,

$$\begin{aligned} -\Theta\Delta x - Se + X^{-1}\sigma\mu e &= infeas_d - A^T\Delta y \\ -\Theta\Delta x &= Se - X^{-1}\sigma\mu e + infeas_d - A^T\Delta y \\ \Delta x &= \Theta^{-1}(-Se + X^{-1}\sigma\mu e - infeas_d + A^T\Delta y) \\ \Delta x &= \rho + \Theta^{-1}A^T\Delta y \end{aligned}$$

where  $\rho = \Theta^{-1}(-Se + X^{-1}\sigma\mu e - infeas_d)$ .

Substituting into the first direction equation,

$$\begin{aligned} A\Delta x &= infeas_c \\ A(\rho + \Theta^{-1}A^T\Delta y) &= infeas_c \\ A\Theta^{-1}A^T\Delta y &= infeas_c - A\rho \\ \Delta y &= (A\Theta^{-1}A^T)^{-1}(infeas_c - A\rho) \end{aligned}$$

$\Theta$ ,  $\rho$ ,  $\Delta y$ ,  $\Delta x$ , and  $\Delta s$  are calculated in that order. The hardest term is the factorization of the  $(A\Theta^{-1}A^T)$  matrix to determine  $\Delta y$ . Fortunately, although the *values* of  $(A\Theta^{-1}A^T)$  are different for each iteration, the *locations* of the nonzeros in this matrix remain fixed; the nonzero locations are the same as those in the matrix  $(AA^T)$ . This is because  $\Theta^{-1} = XS^{-1}$  is a diagonal matrix that has the effect of merely scaling the columns of  $(AA^T)$ .

The fact that the nonzeros in  $A\Theta^{-1}A^T$  have a constant pattern is exploited by all interior point algorithms and is a major reason for their excellent performance. Before iterations begin,  $AA^T$  is examined and its rows and columns are symmetrically permuted so that during Cholesky factorization, the number of *fill-ins* created is smaller. A list of arithmetic operations to perform the factorization is saved in concise computer data structures (working with memory locations rather than actual numerical values). This is called *symbolic factorization*. During iterations, when memory has been initialized with numerical values, the operations list is performed sequentially. Determining how the factorization should be performed again and again is unnecessary.

## The Primal-Dual Predictor-Corrector Interior Point Algorithm

The variant of the interior point algorithm implemented in PROC INTPOINT is a Primal-Dual Predictor-Corrector interior point algorithm. At first, Newton's method is used to find a direction  $(\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k)$  to move, but calculated as if  $\mu$  is zero, that is, as a step with no centering, known as an *affine* step:

$$\begin{aligned} A\Delta x_{aff}^k &= infeas_c \\ A^T\Delta y_{aff}^k + \Delta s_{aff}^k &= infeas_d \\ S^k\Delta x_{aff}^k + X^k\Delta s_{aff}^k &= -X^kS^ke \\ (x_{aff}^k, y_{aff}^k, s_{aff}^k) &= (x^k, y^k, s^k) + \alpha(\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k) \end{aligned}$$

where  $\alpha$  is the *step length* as before.

Complementarity  $x^T s$  is calculated at  $(x_{aff}^k, y_{aff}^k, s_{aff}^k)$  and compared with the complementarity at the starting point  $(x^k, y^k, s^k)$ , and the success of the affine step is gauged. If the affine step was successful in reducing the complementarity by a substantial amount, the need for centering is not great, and  $\sigma_k$  in the following linear system is assigned a value close to zero. If, however, the affine step was unsuccessful, centering would be beneficial, and  $\sigma_k$  in the following linear system is assigned a value closer to 1.0. The value of  $\sigma_k$  is therefore adaptively altered depending on the progress made toward the optimum.

A second linear system is solved to determine a centering vector  $(\Delta x_c^k, \Delta y_c^k, \Delta s_c^k)$  from  $(x_{aff}^k, y_{aff}^k, s_{aff}^k)$ :

$$\begin{aligned} A \Delta x_c^k &= 0 \\ A^T \Delta y_c^k + \Delta s_c^k &= 0 \\ S^k \Delta x_c^k + X^k \Delta s_c^k &= -X_{aff}^k S_{aff}^k e + \sigma_k \mu_k e \end{aligned}$$

Then

$$\begin{aligned} (\Delta x^k, \Delta y^k, \Delta s^k) &= (\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k) + (\Delta x_c^k, \Delta y_c^k, \Delta s_c^k) \\ (x^{k+1}, y^{k+1}, s^{k+1}) &= (x^k, y^k, s^k) + \alpha (\Delta x^k, \Delta y^k, \Delta s^k) \end{aligned}$$

where, as before,  $\alpha$  is the *step length* assigned a value as large as possible but not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  is “too close” to zero.

Although the Predictor-Corrector variant entails solving two linear systems instead of one, fewer iterations are usually required to reach the optimum. The additional overhead of calculating the second linear system is small, as the factorization of the  $(A\Theta^{-1}A^T)$  matrix has already been performed to solve the first linear system.

## Interior Point: Upper Bounds

If the LP had upper bounds ( $0 \leq x \leq u$  where  $u$  is the upper bound vector), then the primal and dual problems, the duality gap, and the KKT conditions would have to be expanded.

The primal linear program to be solved is

$$\begin{aligned} \text{minimize} \quad & c^T x \\ \text{subject to} \quad & Ax = b \\ & 0 \leq x \leq u \end{aligned}$$

where  $0 \leq x \leq u$  is split into  $x \geq 0$  and  $x \leq u$ . Let  $z$  be primal slack so that  $x + z = u$ , and associate dual variables  $w$  with these constraints. The interior point algorithm solves the system of equations to satisfy the Karush-Kuhn-Tucker (KKT) conditions for optimality:

$$\begin{aligned} Ax &= b \\ x + z &= u \\ A^T y + s - w &= c \\ XSe &= 0 \end{aligned}$$

$$ZWe = 0$$

$$x, s, z, w \geq 0$$

These are the conditions for feasibility, with the *complementarity* conditions  $XSe = 0$  and  $ZWe = 0$  added. Complementarity forces the optimal objectives of the primal and dual to be equal,  $c^T x_{opt} = b^T y_{opt} - u^T w_{opt}$ , as

$$0 = z_{opt}^T w_{opt} = (u - x_{opt})^T w_{opt} = u^T w_{opt} - x_{opt}^T w_{opt}$$

$$0 = x_{opt}^T s_{opt} = s_{opt}^T x_{opt} = (c - A^T y_{opt} + w_{opt})^T x_{opt} =$$

$$c^T x_{opt} - y_{opt}^T (Ax_{opt}) + w_{opt}^T x_{opt} = c^T x_{opt} - b^T y_{opt} + u^T w_{opt}$$

Before the optimum is reached, a solution  $(x, y, s, z, w)$  might not satisfy the KKT conditions:

- Primal bound constraints may be violated,  $infeas_b = u - x - z \neq 0$ .
- Primal constraints may be violated,  $infeas_c = b - Ax \neq 0$ .
- Dual constraints may be violated,  $infeas_d = c - A^T y - s + w \neq 0$ .
- Complementarity conditions may not be satisfied,  $x^T s \neq 0$  or  $z^T w \neq 0$ .

The calculations of the interior point algorithm can easily be derived in a fashion similar to calculations for when an LP has no upper bounds. See the paper by Lustig, Marsten, and Shanno (1992).

In some iteration  $k$ , the *affine* step system that must be solved is

$$\Delta x_{aff} + \Delta z_{aff} = infeas_b$$

$$A \Delta x_{aff} = infeas_c$$

$$A^T \Delta y_{aff} + \Delta s_{aff} - \Delta w_{aff} = infeas_d$$

$$S \Delta x_{aff} + X \Delta s_{aff} = -XSe$$

$$Z \Delta w_{aff} + W \Delta z_{aff} = -ZWe$$

Therefore, the computations involved in solving the affine step are

$$\Theta = SX^{-1} + WZ^{-1}$$

$$\rho = \Theta^{-1}(infeas_d + (S - W)e - Z^{-1}W infeas_b)$$

$$\Delta y_{aff} = (A\Theta^{-1}A^T)^{-1}(infeas_c + A\rho)$$

$$\Delta x_{aff} = \Theta^{-1}A^T \Delta y_{aff} - \rho$$

$$\Delta z_{aff} = infeas_b - \Delta x_{aff}$$

$$\Delta w_{aff} = -We - Z^{-1}W \Delta z_{aff}$$

$$\Delta s_{aff} = -Se - X^{-1}S \Delta x_{aff}$$

$$(x_{aff}, y_{aff}, s_{aff}, z_{aff}, w_{aff}) = (x, y, s, z, w) +$$

$$\alpha(\Delta x_{aff}, \Delta y_{aff}, \Delta s_{aff}, \Delta z_{aff}, \Delta w_{aff})$$

and  $\alpha$  is the *step length* as before.

A second linear system is solved to determine a centering vector  $(\Delta x_c, \Delta y_c, \Delta s_c, \Delta z_c, \Delta w_c)$  from  $(x_{\text{aff}}, y_{\text{aff}}, s_{\text{aff}}, z_{\text{aff}}, w_{\text{aff}})$ :

$$\begin{aligned}\Delta x_c + \Delta z_c &= 0 \\ A\Delta x_c &= 0 \\ A^T \Delta y_c + \Delta s_c - \Delta w_c &= 0 \\ S\Delta x_c + X\Delta s_c &= -X_{\text{aff}}S_{\text{aff}}e + \sigma\mu e \\ Z\Delta w_c + W\Delta z_c &= -Z_{\text{aff}}W_{\text{aff}}e + \sigma\mu e\end{aligned}$$

where

$$\begin{aligned}\zeta_{\text{start}} &= x^T s + z^T w, \text{ complementarity at the start of the iteration} \\ \zeta_{\text{aff}} &= x_{\text{aff}}^T s_{\text{aff}} + z_{\text{aff}}^T w_{\text{aff}}, \text{ the affine complementarity} \\ \mu &= \zeta_{\text{aff}} / 2n, \text{ the average complementarity} \\ \sigma &= (\zeta_{\text{aff}} / \zeta_{\text{start}})^3\end{aligned}$$

Therefore, the computations involved in solving the centering step are

$$\begin{aligned}\rho &= \Theta^{-1}(\sigma\mu(X^{-1} - Z^{-1})e - X^{-1}X_{\text{aff}}S_{\text{aff}}e + Z^{-1}Z_{\text{aff}}W_{\text{aff}}e) \\ \Delta y_c &= (A\Theta^{-1}A^T)^{-1}A\rho \\ \Delta x_c &= \Theta^{-1}A^T\Delta y_c - \rho \\ \Delta z_c &= -\Delta x_c \\ \Delta w_c &= \sigma\mu Z^{-1}e - Z^{-1}Z_{\text{aff}}W_{\text{aff}}e - Z^{-1}W_{\text{aff}}\Delta z_c \\ \Delta s_c &= \sigma\mu X^{-1}e - X^{-1}X_{\text{aff}}S_{\text{aff}}e - X^{-1}S_{\text{aff}}\Delta x_c\end{aligned}$$

Then

$$\begin{aligned}(\Delta x, \Delta y, \Delta s, \Delta z, \Delta w) &= \\ &(\Delta x_{\text{aff}}, \Delta y_{\text{aff}}, \Delta s_{\text{aff}}, \Delta z_{\text{aff}}, \Delta w_{\text{aff}}) \\ &+ (\Delta x_c, \Delta y_c, \Delta s_c, \Delta z_c, \Delta w_c) \\ (x^{k+1}, y^{k+1}, s^{k+1}, z^{k+1}, w^{k+1}) &= \\ &(x^k, y^k, s^k, z^k, w^k) \\ &+ \alpha(\Delta x, \Delta y, \Delta s, \Delta z, \Delta w)\end{aligned}$$

where, as before,  $\alpha$  is the *step length* assigned a value as large as possible but not so large that an  $x_i^{k+1}$ ,  $s_i^{k+1}$ ,  $z_i^{k+1}$ , or  $w_i^{k+1}$  is “too close” to zero.

The algebra in this section has been simplified by assuming that *all* variables have finite upper bounds. If the number of variables with finite upper bounds  $n_u < n$ , you need to change the algebra to reflect that the  $Z$  and  $W$  matrices have dimension  $n_u \times 1$  or  $n_u \times n_u$ . Other computations need slight modification. For example, the average complementarity is

$$\mu = x_{aff}^T s_{aff} / n + z_{aff}^T w_{aff} / n_u$$

An important point is that any upper bounds can be handled by specializing the algorithm and *not* by generating the constraints  $x \leq u$  and adding these to the main primal constraints  $Ax = b$ .

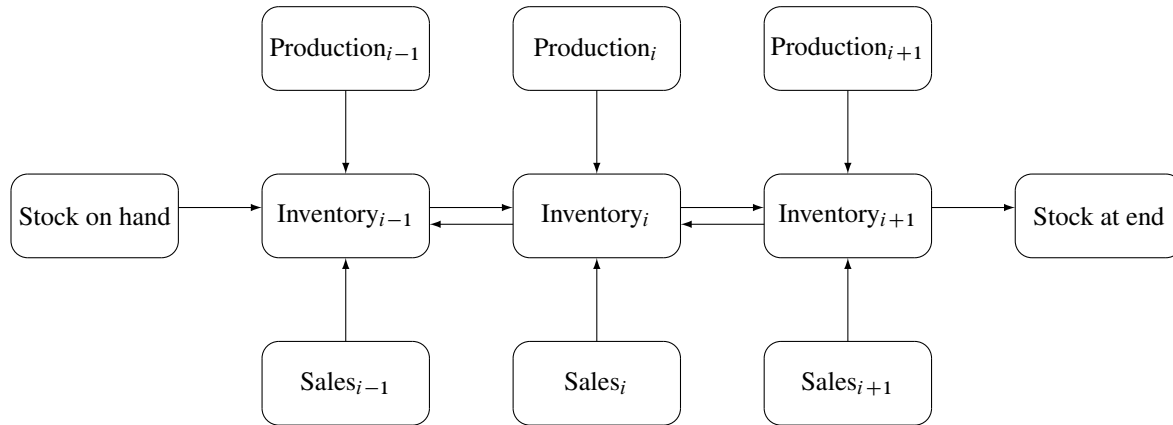
## Network Models

The following are descriptions of some typical NPSC models.

### Production, Inventory, and Distribution (Supply Chain) Problems

One common class of network models is the production-inventory-distribution or supply-chain problem. The diagram in Figure 5.1 illustrates this problem. The subscripts on the Production, Inventory, and Sales nodes indicate the time period. By replicating sections of the model, the notion of time can be included.

**Figure 5.1** Production-Inventory-Distribution Problem



In this type of model, the nodes can represent a wide variety of facilities. Several examples are suppliers, spot markets, importers, farmers, manufacturers, factories, parts of a plant, production lines, waste disposal facilities, workstations, warehouses, coolstores, depots, wholesalers, export markets, ports, rail junctions, airports, road intersections, cities, regions, shops, customers, and consumers. The diversity of this selection demonstrates how rich the potential applications of this model are.

Depending upon the interpretation of the nodes, the objectives of the modeling exercise can vary widely. Some common types of objectives are

- to reduce collection or purchase costs of raw materials
- to reduce inventory holding or backorder costs. Warehouses and other storage facilities sometimes have capacities, and there can be limits on the amount of goods that can be placed on backorder.
- to decide where facilities should be located and what the capacity of these should be. Network models have been used to help decide where factories, hospitals, ambulance and fire stations, oil and water wells, and schools should be sited.



- to determine the assignment of resources (machines, production capability, workforce) to tasks, schedules, classes, or files
- to determine the optimal distribution of goods or services. This usually means minimizing transportation costs and reducing transit time or distances covered.
- to find the shortest path from one location to another
- to ensure that demands (for example, production requirements, market demands, contractual obligations) are met
- to maximize profits from the sale of products or the charge for services
- to maximize production by identifying bottlenecks

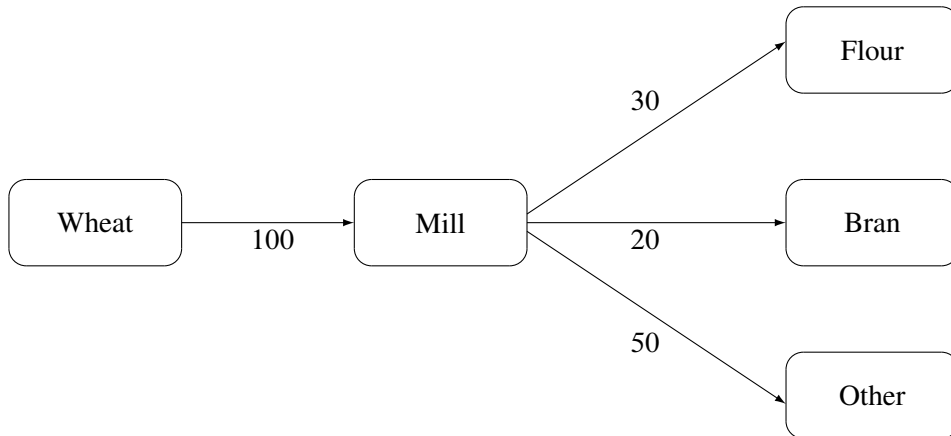
Some specific applications are

- car distribution models. These help determine which models and numbers of cars should be manufactured in which factories and where to distribute cars from these factories to zones in the United States in order to meet customer demand at least cost.
- models in the timber industry. These help determine when to plant and mill forests, schedule production of pulp, paper, and wood products, and distribute products for sale or export.
- military applications. The nodes can be theaters, bases, ammunition dumps, logistical suppliers, or radar installations. Some models are used to find the best ways to mobilize personnel and supplies and to evacuate the wounded in the least amount of time.
- communications applications. The nodes can be telephone exchanges, transmission lines, satellite links, and consumers. In a model of an electrical grid, the nodes can be transformers, powerstations, watersheds, reservoirs, dams, and consumers. The effect of high loads or outages might be of concern.

## Proportionality Constraints

In many models, you have the characteristic that a flow through an arc must be proportional to the flow through another arc. Side constraints are often necessary to model that situation. Such constraints are called *proportionality constraints* and are useful in models where production is subject to refining or modification into different materials. The amount of each output, or any waste, evaporation, or reduction can be specified as a proportion of input.

Typically, the arcs near the supply nodes carry raw materials and the arcs near the demand nodes carry refined products. For example, in a model of the milling industry, the flow through some arcs may represent quantities of wheat. After the wheat is processed, the flow through other arcs might be flour. For others it might be bran. The side constraints model the relationship between the amount of flour or bran produced as a proportion of the amount of wheat milled. Some of the wheat can end up as neither flour, bran, nor any useful product, so this waste is drained away via arcs to a waste node.

**Figure 5.2** Proportionality Constraints

In order for arcs to be specified in side constraints, they must be named. By default, PROC INTPOINT names arcs using the names of the nodes at the head and tail of the arc. An arc is named with its tail node name followed by an underscore and its head node name. For example, an arc from node *from* to node *to* is called *from\_to*.

Consider the network fragment in Figure 5.2. The arc *Wheat\_Mill* conveys the wheat milled. The cost of flow on this arc is the milling cost. The capacity of this arc is the capacity of the mill. The lower flow bound on this arc is the minimum quantity that must be milled for the mill to operate economically. The constraints

$$0.3 \text{ Wheat\_Mill} - \text{Mill\_Flour} = 0.0$$

$$0.2 \text{ Wheat\_Mill} - \text{Mill\_Bran} = 0.0$$

force every unit of wheat that is milled to produce 0.3 units of flour and 0.2 units of bran. Note that it is not necessary to specify the constraint

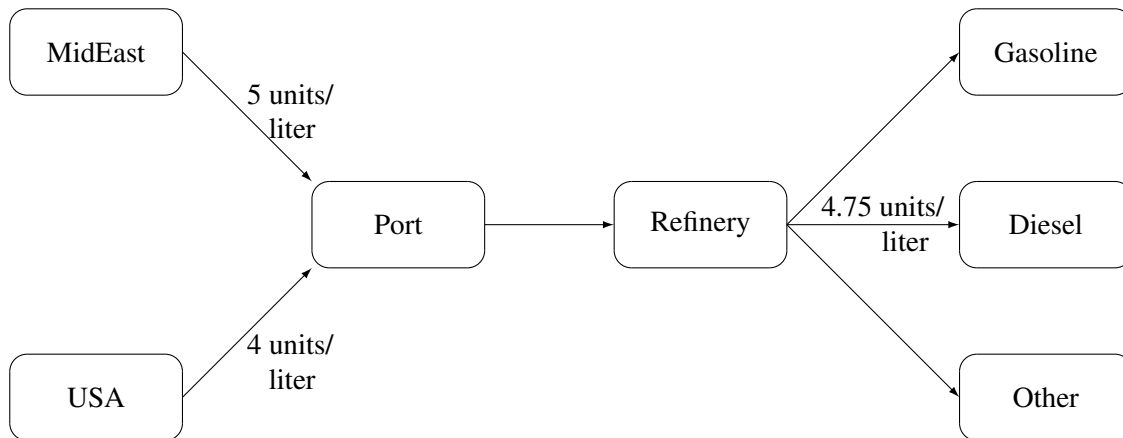
$$0.5 \text{ Wheat\_Mill} - \text{Mill\_Other} = 0.0$$

since flow conservation implies that any flow that does not traverse through *Mill\_Flour* or *Mill\_Bran* must be conveyed through *Mill\_Other*. And, computationally, it is better if this constraint is not specified, since there is one less side constraint and fewer problems with numerical precision. Notice that the sum of the proportions must equal 1.0 exactly; otherwise, flow conservation is violated.

## Blending Constraints

Blending or quality constraints can also influence the recipes or proportions of ingredients that are mixed. For example, different raw materials can have different properties. In an application of the oil industry, the amount of products that are obtained could be different for each type of crude oil. Furthermore, fuel might have a minimum octane requirement or limited sulphur or lead content, so that a blending of crudes is needed to produce the product.

The network fragment in Figure 5.3 shows an example of this.

**Figure 5.3** Blending Constraints

The arcs MidEast\_Port and USA\_Port convey crude oil from the two sources. The arc Port\_Refinery represents refining while the arcs Refinery\_Gasoline and Refinery\_Diesel carry the gas and diesel produced. The proportionality constraints

$$0.4 \text{ Port\_Refinery} - \text{Refinery\_Gasoline} = 0.0$$

$$0.2 \text{ Port\_Refinery} - \text{Refinery\_Diesel} = 0.0$$

capture the restrictions for producing gasoline and diesel from crude. Suppose that only crude from the Middle East is used, then the resulting diesel would contain 5 units of sulphur per liter. If only crude from the U.S.A. is used, the resulting diesel would contain 4 units of sulphur per liter. Diesel can have at most 4.75 units of sulphur per liter. Some crude from the U.S.A. must be used if Middle East crude is used in order to meet the 4.75 sulphur per liter limit. The side constraint to model this requirement is

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 4.75 \text{ Port\_Refinery} \leq 0.0$$

Since  $\text{Port\_Refinery} = \text{MidEast\_Port} + \text{USA\_Port}$ , flow conservation allows this constraint to be simplified to

$$1 \text{ MidEast\_Port} - 3 \text{ USA\_Port} \leq 0.0$$

If, for example, 120 units of crude from the Middle East is used, then at least 40 units of crude from the U.S.A. must be used. The preceding constraint is simplified because you assume that the sulphur concentration of diesel is proportional to the sulphur concentration of the crude mix. If this is not the case, the relation

$$0.2 \text{ Port\_Refinery} = \text{Refinery\_Diesel}$$

is used to obtain

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 4.75 (1.0/0.2 \text{ Refinery\_Diesel}) \leq 0.0$$

which equals

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 23.75 \text{ Refinery\_Diesel} \leq 0.0$$

An example similar to this oil industry problem is solved in the section “[Introductory NPSC Example](#)” on page 62.

## Multicommodity Problems

Side constraints are also used in models in which there are capacities on transportation or some other shared resource, or there are limits on overall production or demand in multicommodity, multidivisional, or multiperiod problems. Each commodity, division, or period can have a separate network coupled to one main system by the side constraints. Side constraints are used to combine the outputs of subdivisions of a problem (either commodities, outputs in distinct time periods, or different process streams) to meet overall demands or to limit overall production or expenditures. This method is more desirable than doing separate *local* optimizations for individual commodity, process, or time networks and then trying to establish relationships between each when determining an overall policy if the *global* constraint is not satisfied. Of course, to make models more realistic, side constraints may be necessary in the local problems.

**Figure 5.4** Multicommodity Problem

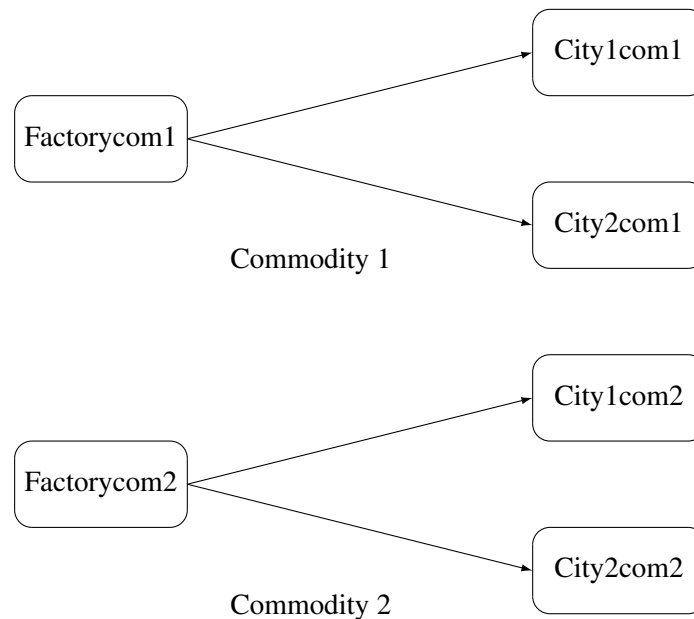


Figure 5.4 shows two network fragments. They represent identical production and distribution sites of two different commodities. Suffix *com1* represents commodity 1 and suffix *com2* represents commodity 2. The nodes *Factorycom1* and *Factorycom2* model the same factory, and nodes *City1com1* and *City1com2* model the same location, city 1. Similarly, *City2com1* and *City2com2* are the same location, city 2. Suppose that commodity 1 occupies 2 cubic meters, commodity 2 occupies 3 cubic meters, the truck dispatched to city 1 has a capacity of 200 cubic meters, and the truck dispatched to city 2 has a capacity of 250 cubic meters. How much of each commodity can be loaded onto each truck? The side constraints for this case are

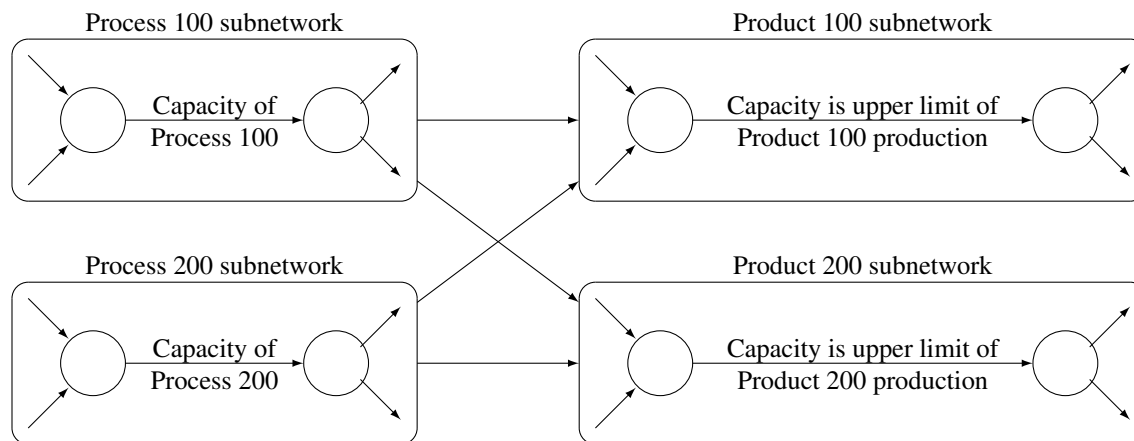
$$2 \text{ Factorycom1\_City1com1} + 3 \text{ Factorycom2\_City1com2} \leq 200$$

$$2 \text{ Factorycom1\_City2com1} + 3 \text{ Factorycom2\_City2com2} \leq 250$$

## Large Modeling Strategy

In many cases, the flow through an arc might actually represent the flow or movement of a commodity from place to place or from time period to time period. However, sometimes an arc is included in the network as a method of capturing some aspect of the problem that you would not normally think of as part of a network model. There is no commodity movement associated with that arc. For example, in a multiprocess, multiproduct model (Figure 5.5), there might be subnetworks for each process and each product. The subnetworks can be joined together by a set of arcs that have flows that represent the amount of product  $j$  produced by process  $i$ . To model an upper-limit constraint on the total amount of product  $j$  that can be produced, direct all arcs carrying product  $j$  to a single node and from there through a single arc. The capacity of this arc is the upper limit of product  $j$  production. It is preferable to model this structure in the network rather than to include it in the side constraints because the efficiency of the optimizer may be less affected by a reasonable increase in the size of the network rather than increasing the number or complicating side constraints.

**Figure 5.5** Multiprocess, Multiproduct Example



When starting a project, it is often a good strategy to use a small network formulation and then use that model as a framework upon which to add detail. For example, in the multiprocess, multiproduct model, you might start with the network depicted in Figure 5.5. Then, for example, the process subnetwork can be enhanced to include the distribution of products. Other phases of the operation could be included by adding more subnetworks. Initially, these subnetworks can be single nodes, but in subsequent studies they can be expanded to include greater detail.

## Advantages of Network Models over LP Models

Many linear programming problems have large embedded network structures. Such problems often result when modeling manufacturing processes, transportation or distribution networks, or resource allocation, or when deciding where to locate facilities. Often, some commodity is to be moved from place to place, so the more natural formulation in many applications is that of a constrained network rather than a linear program.

Using a network diagram to visualize a problem makes it possible to capture the important relationships in an easily understood picture form. The network diagram aids the communication between model builder and

model user, making it easier to comprehend how the model is structured, how it can be changed, and how results can be interpreted.

If a network structure is embedded in a linear program, the problem is an NPSC (see the section “[Mathematical Description of NPSC](#)” on page 45). When the network part of the problem is large compared to the nonnetwork part, especially if the number of side constraints is small, it is worthwhile to exploit this structure to describe the model. Rather than generating the data for the flow conservation constraints, generate instead the data for the nodes and arcs of the network.

## Flow Conservation Constraints

The constraints  $Fx = b$  in NPSC (see the section “[Mathematical Description of NPSC](#)” on page 45) are referred to as the nodal flow conservation constraints. These constraints algebraically state that the sum of the flow through arcs directed toward a node plus that node’s supply, if any, equals the sum of the flow through arcs directed away from that node plus that node’s demand, if any. The flow conservation constraints are implicit in the network model and should not be specified explicitly in side constraint data when using PROC INTPOINT to solve NPSC problems.

## Nonarc Variables

Nonarc variables can be used to simplify side constraints. For example, if a sum of flows appears in many constraints, it may be worthwhile to equate this expression with a nonarc variable and use this in the other constraints. This keeps the constraint coefficient matrix sparse. By assigning a nonarc variable a nonzero objective function, it is then possible to incur a cost for using resources above some lowest feasible limit. Similarly, a profit (a negative objective function coefficient value) can be made if all available resources are not used.

In some models, nonarc variables are used in constraints to absorb excess resources or supply needed resources. Then, either the excess resource can be used or the needed resource can be supplied to another component of the model.

For example, consider a multicommodity problem of making television sets that have either 19- or 25-inch screens. In their manufacture, three and four chips, respectively, are used. Production occurs at two factories during March and April. The supplier of chips can supply only 2,600 chips to factory 1 and 3,750 chips to factory 2 each month. The names of arcs are in the form  $\text{Prod}_n\_s\_m$ , where  $n$  is the factory number,  $s$  is the screen size, and  $m$  is the month. For example,  $\text{Prod1\_25\_Apr}$  is the arc that conveys the number of 25-inch TVs produced in factory 1 during April. You might have to determine similar systematic naming schemes for your application.

As described, the constraints are

$$3 \text{ Prod1\_19\_Mar} + 4 \text{ Prod1\_25\_Mar} \leq 2600$$

$$3 \text{ Prod2\_19\_Mar} + 4 \text{ Prod2\_25\_Mar} \leq 3750$$

$$3 \text{ Prod1\_19\_Apr} + 4 \text{ Prod1\_25\_Apr} \leq 2600$$

$$3 \text{ Prod2\_19\_Apr} + 4 \text{ Prod2\_25\_Apr} \leq 3750$$

If there are chips that could be obtained for use in March but not used for production in March, why not keep these unused chips until April? Furthermore, if the March excess chips at factory 1 could be used either at factory 1 or factory 2 in April, the model becomes

$$3 \text{ Prod1\_19\_Mar} + 4 \text{ Prod1\_25\_Mar} + \text{F1\_Unused\_Mar} = 2600$$

$$3 \text{ Prod2\_19\_Mar} + 4 \text{ Prod2\_25\_Mar} + \text{F2\_Unused\_Mar} = 3750$$

$$3 \text{ Prod1\_19\_Apr} + 4 \text{ Prod1\_25\_Apr} - \text{F1\_Kept\_Since\_Mar} = 2600$$

$$3 \text{ Prod2\_19\_Apr} + 4 \text{ Prod2\_25\_Apr} - \text{F2\_Kept\_Since\_Mar} = 3750$$

$$\text{F1\_Unused\_Mar} + \text{F2\_Unused\_Mar} \text{ (continued)}$$

$$- \text{F1\_Kept\_Since\_Mar} - \text{F2\_Kept\_Since\_Mar} \geq 0.0$$

where  $\text{F1\_Kept\_Since\_Mar}$  is the number of chips used during April at factory 1 that were obtained in March at either factory 1 or factory 2, and  $\text{F2\_Kept\_Since\_Mar}$  is the number of chips used during April at factory 2 that were obtained in March. The last constraint ensures that the number of chips used during April that were obtained in March does not exceed the number of chips not used in March. There may be a cost to hold chips in inventory. This can be modeled having a positive objective function coefficient for the nonarc variables  $\text{F1\_Kept\_Since\_Mar}$  and  $\text{F2\_Kept\_Since\_Mar}$ . Moreover, nonarc variable upper bounds represent an upper limit on the number of chips that can be held in inventory between March and April.

See [Example 5.1](#) through [Example 5.5](#), which use this TV problem. The use of nonarc variables as described previously is illustrated.

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## Introduction

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### Getting Started: NPSC Problems

To solve NPSC problems using PROC INTPOINT, you save a representation of the network and the side constraints in three SAS data sets. These data sets are then passed to PROC INTPOINT for solution. There are various forms that a problem's data can take. You can use any one or a combination of several of these forms.

The `NODEDATA=` data set contains the names of the supply and demand nodes and the supply or demand associated with each. These are the elements in the column vector  $b$  in the NPSC problem (see the section “[Mathematical Description of NPSC](#)” on page 45).

The `ARCDATA=` data set contains information about the variables of the problem. Usually these are arcs, but there can also be data related to nonarc variables in the `ARCDATA=` data set.

An arc is identified by the names of its tail node (where it originates) and head node (where it is directed). Each observation can be used to identify an arc in the network and, optionally, the cost per flow unit across

the arc, the arc's capacity, lower flow bound, and name. These data are associated with the matrix  $F$  and the vectors  $c$ ,  $l$ , and  $u$  in the NPSC problem (see the section “[Mathematical Description of NPSC](#)” on page 45).

**NOTE:** Although  $F$  is a node-arc incidence matrix, it is specified in the [ARCDATA=](#) data set by arc definitions. Do not explicitly specify these flow conservation constraints as constraints of the problem.

In addition, the [ARCDATA=](#) data set can be used to specify information about nonarc variables, including objective function coefficients, lower and upper value bounds, and names. These data are the elements of the vectors  $d$ ,  $m$ , and  $v$  in the NPSC problem (see the section “[Mathematical Description of NPSC](#)” on page 45). Data for an arc or nonarc variable can be given in more than one observation.

Supply and demand data also can be specified in the [ARCDATA=](#) data set. In such a case, the [NODEDATA=](#) data set may not be needed.

The [CONDATA=](#) data set describes the side constraints and their right-hand sides. These data are elements of the matrices  $H$  and  $Q$  and the vector  $r$ . Constraint types are also specified in the [CONDATA=](#) data set. You can include in this data set upper bound values or capacities, lower flow or value bounds, and costs or objective function coefficients. It is possible to give all information about some or all nonarc variables in the [CONDATA=](#) data set.

An arc is identified in this data set by its name. If you specify an arc's name in the [ARCDATA=](#) data set, then this name is used to associate data in the [CONDATA=](#) data set with that arc. Each arc also has a default name that is the name of the tail and head node of the arc concatenated together and separated by an underscore character; `tail_head`, for example.

If you use the [dense](#) side constraint input format (described in the section “[CONDATA= Data Set](#)” on page 107), and want to use the default arc names, these arc names are names of SAS variables in the [VAR](#) list of the [CONDATA=](#) data set.

If you use the [sparse](#) side constraint input format (see the section “[CONDATA= Data Set](#)” on page 107) and want to use the default arc names, these arc names are values of the [COLUMN](#) list variable of the [CONDATA=](#) data set.

PROC INTPOINT reads the data from the [NODEDATA=](#) data set, the [ARCDATA=](#) data set, and the [CONDATA=](#) data set. Error checking is performed, and the model is converted into an equivalent LP. This LP is [preprocessed](#). Preprocessing is optional but highly recommended. [Preprocessing](#) analyzes the model and tries to determine before optimization whether variables can be “fixed” to their optimal values. Knowing that, the model can be modified and these variables dropped out. It can be determined that some constraints are redundant. Sometimes, [preprocessing](#) succeeds in reducing the size of the problem, thereby making the subsequent optimization easier and faster.

The optimal solution to the equivalent LP is then found. This LP is converted back to the original NPSC problem, and the optimum for this is derived from the optimum of the equivalent LP. If the problem was [preprocessed](#), the model is now post-processed, where fixed variables are reintroduced. The solution can be saved in the [CONOUT=](#) data set.

## Introductory NPSC Example

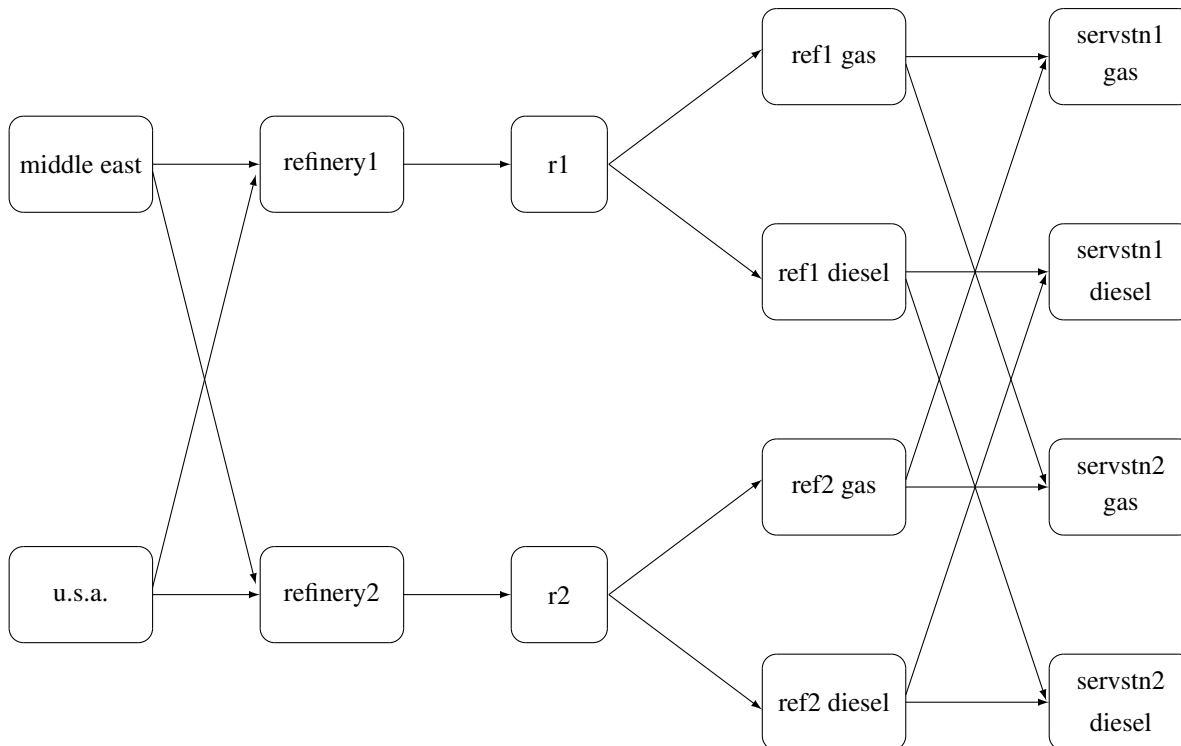
Consider the following transshipment problem for an oil company. Crude oil is shipped to refineries where it is processed into gasoline and diesel fuel. The gasoline and diesel fuel are then distributed to service stations. At each stage, there are shipping, processing, and distribution costs. Also, there are lower flow bounds and capacities.



In addition, there are two sets of side constraints. The first set is that two times the crude from the Middle East cannot exceed the throughput of a refinery plus 15 units. (The phrase “plus 15 units” that finishes the last sentence is used to enable some side constraints in this example to have a nonzero rhs.) The second set of constraints are necessary to model the situation that one unit of crude mix processed at a refinery yields three-fourths of a unit of gasoline and one-fourth of a unit of diesel fuel.

Because there are two products that are not independent in the way in which they flow through the network, an NPSC is an appropriate model for this example (see Figure 5.6). The side constraints are used to model the limitations on the amount of Middle Eastern crude that can be processed by each refinery and the conversion proportions of crude to gasoline and diesel fuel.

**Figure 5.6** Oil Industry Example



To solve this problem with PROC INTPOINT, save a representation of the model in three SAS data sets. In the **NODEDATA=** data set, you name the supply and demand nodes and give the associated supplies and demands. To distinguish demand nodes from supply nodes, specify demands as negative quantities. For the oil example, the NODEDATA= data set can be saved as follows:

```

title 'Oil Industry Example';
title3 'Setting Up Nodedata = Noded For PROC INTPOINT';
data noded;
    input _node_&$15. _sd_;
    datalines;
middle east      100
u.s.a.           80
servstn1 gas     -95
servstn1 diesel  -30
  
```

```
servstn2 gas      -40
servstn2 diesel   -15
;
```

The **ARC**DATA= data set contains the rest of the information about the network. Each observation in the data set identifies an arc in the network and gives the cost per flow unit across the arc, the capacities of the arc, the lower bound on flow across the arc, and the name of the arc.

```
title3 'Setting Up Arcdata = Arcd1 For PROC INTPOINT';
data arc1;
  input _from_&$11. _to_&$15. _cost_ _capac_ _lo_ _name_ $;
  datalines;
middle east refinery 1      63      95      20      m_e_ref1
middle east refinery 2      81      80      10      m_e_ref2
u.s.a.      refinery 1      55      .      .      .
u.s.a.      refinery 2      49      .      .      .
refinery 1   r1              200     175     50      thrupt1
refinery 2   r2              220     100     35      thrupt2
r1           ref1 gas        .      140     .      r1_gas
r1           ref1 diesel     .      75     .      .
r2           ref2 gas        .      100     .      r2_gas
r2           ref2 diesel     .      75     .      .
ref1 gas     servstn1 gas    15      70     .      .
ref1 gas     servstn2 gas    22      60     .      .
ref1 diesel  servstn1 diesel 18      .      .      .
ref1 diesel  servstn2 diesel 17      .      .      .
ref2 gas     servstn1 gas    17      35     5      .
ref2 gas     servstn2 gas    31      .      .      .
ref2 diesel  servstn1 diesel 36      .      .      .
ref2 diesel  servstn2 diesel 23      .      .      .
;
```

Finally, the **CON**DATA= data set contains the side constraints for the model:

```
title3 'Setting Up Condata = Cond1 For PROC INTPOINT';
data cond1;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
-2   .   1   .   .   .   >=  -15
.   -2   .   .   1   .   GE  -15
.   .   -3  4   .   .   EQ   0
.   .   .   .   -3  4   =    0
;
```

Note that the SAS variable names in the **CON**DATA= data set are the names of arcs given in the **ARC**DATA= data set. These are the arcs that have nonzero constraint coefficients in side constraints. For example, the proportionality constraint that specifies that one unit of crude at each refinery yields three-fourths of a unit of gasoline and one-fourth of a unit of diesel fuel is given for refinery 1 in the third observation and for refinery 2 in the last observation. The third observation requires that each unit of flow on the arc thrupt1 equals three-fourths of a unit of flow on the arc r1\_gas. Because all crude processed at refinery 1 flows through thrupt1 and all gasoline produced at refinery 1 flows through r1\_gas, the constraint models the situation. It proceeds similarly for refinery 2 in the last observation.

To find the minimum cost flow through the network that satisfies the supplies, demands, and side constraints, invoke PROC INTPOINT as follows:

```
proc intpoint
  bytes=1000000
  nodedata=noded      /* the supply and demand data */
  arcdata=arcd1       /* the arc descriptions      */
  condata=cond1       /* the side constraints     */
  conout=solution;    /* the solution data set   */
run;
```

The following messages, which appear on the SAS log, summarize the model as read by PROC INTPOINT and note the progress toward a solution.

```
NOTE: Number of nodes= 14 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 180 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of side constraint coefficients= 8 .
NOTE: The following messages relate to the equivalent Linear Programming
      problem solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 16 .
NOTE: Number of >= constraints= 2 .
NOTE: Number of constraint coefficients= 44 .
NOTE: Number of variables= 18 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 3.
NOTE: After preprocessing, number of >= constraints= 2.
NOTE: The preprocessor eliminated 13 constraints from the problem.
NOTE: The preprocessor eliminated 33 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 5.
NOTE: The preprocessor eliminated 13 variables from the problem.
NOTE: 4 columns, 0 rows and 4 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 10 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 5 factor nodes make up 1 supernodes
NOTE: There are 0 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
NOTE: Bound feasibility attained by iteration 1.
NOTE: Dual feasibility attained by iteration 1.
NOTE: Constraint feasibility attained by iteration 1.
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 6
      iterations.
NOTE: Optimum reached.
NOTE: Objective= 50875.
NOTE: The data set WORK.SOLUTION has 18 observations and 10 variables.
NOTE: There were 18 observations read from the data set WORK.ARC1.
NOTE: There were 6 observations read from the data set WORK.NODED.
NOTE: There were 4 observations read from the data set WORK.COND1.
```

The first set of messages shows the size of the problem. The next set of messages provides statistics on the size of the equivalent LP problem. The number of variables may not equal the number of arcs if the problem has nonarc variables. This example has none. To convert a network to the equivalent LP problem, a flow conservation constraint must be created for each node (including an excess or bypass node, if required). This explains why the number of equality constraints and the number of constraint coefficients differ from the number of equality side constraints and the number of coefficients in all side constraints.

If the [preprocessor](#) was successful in decreasing the problem size, some messages will report how well it did. In this example, the model size was cut approximately in half!

The next set of messages describes aspects of the interior point algorithm. Of particular interest are those concerned with the Cholesky factorization of  $AA^T$  where  $A$  is the coefficient matrix of the final LP. It is crucial to preorder the rows and columns of this matrix to prevent *fill-in* and reduce the number of row operations to undertake the factorization. See the section “[Interior Point Algorithmic Details](#)” on page 47 for a more extensive explanation.

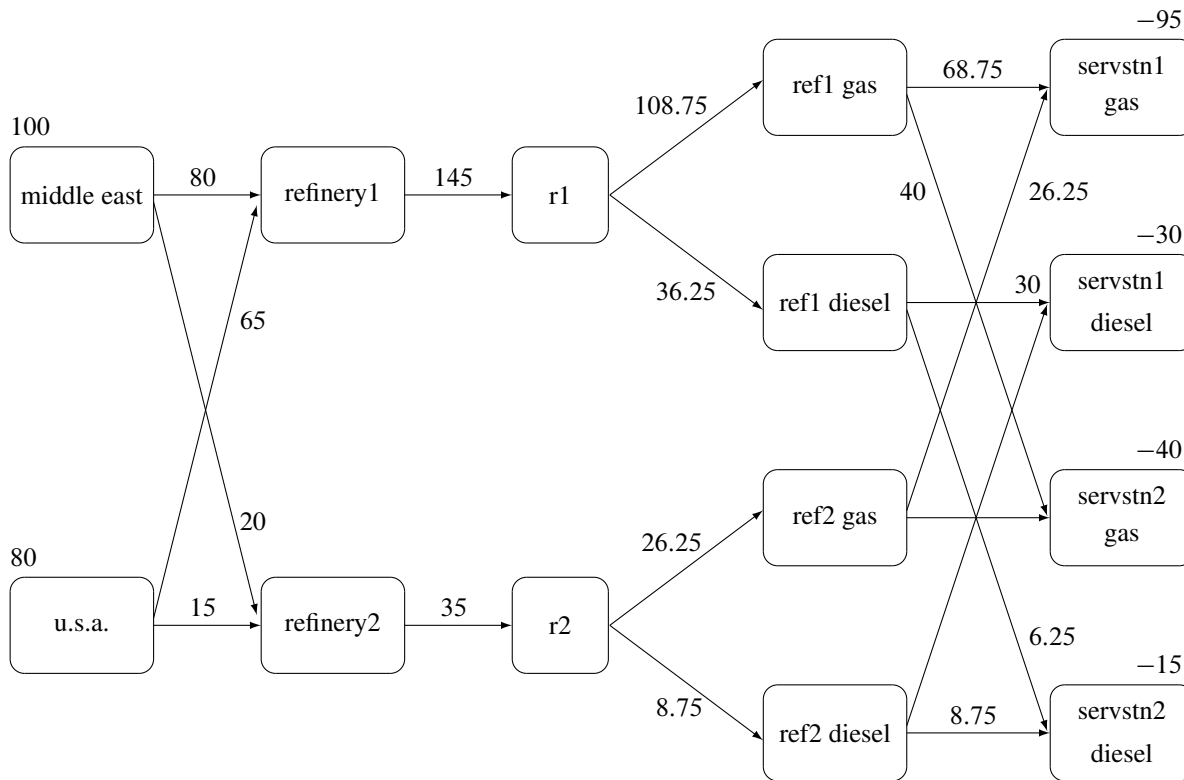
Unlike PROC LP, which displays the solution and other information as output, PROC INTPOINT saves the optimum in the output SAS data set that you specify. For this example, the solution is saved in the SOLUTION data set. It can be displayed with the PRINT procedure as

```
title3 'Optimum';
proc print data=solution;
  var _from_ _to_ _cost_ _capac_ _lo_ _name_
      _supply_ _demand_ _flow_ _fcost_;
  sum _fcost_;
run;
```

**Figure 5.7** CONOUT=SOLUTION

| Optimum        |                 |   |     |          |    |          |     |    |         |          |
|----------------|-----------------|---|-----|----------|----|----------|-----|----|---------|----------|
|                |                 |   |     |          |    |          | S   | D  |         |          |
|                | f               |   | c   | a        |    | n        | U   | E  |         | F        |
|                | r               |   | o   | p        |    | a        | P   | M  | F       | C        |
| O              | o               | t | s   | a        | l  | m        | L   | N  | O       | S        |
| b              | m               | o | t   | c        | o  | e        | Y   | D  | W       | T        |
| s              |                 |   |     |          |    |          |     |    |         |          |
| 1 refinery 1   | r1              |   | 200 | 175      | 50 | thruput1 | .   | .  | 145.000 | 29000.00 |
| 2 refinery 2   | r2              |   | 220 | 100      | 35 | thruput2 | .   | .  | 35.000  | 7700.00  |
| 3 r1           | ref1 diesel     |   | 0   | 75       | 0  |          | .   | .  | 36.250  | 0.00     |
| 4 r1           | ref1 gas        |   | 0   | 140      | 0  | r1_gas   | .   | .  | 108.750 | 0.00     |
| 5 r2           | ref2 diesel     |   | 0   | 75       | 0  |          | .   | .  | 8.750   | 0.00     |
| 6 r2           | ref2 gas        |   | 0   | 100      | 0  | r2_gas   | .   | .  | 26.250  | 0.00     |
| 7 middle east  | refinery 1      |   | 63  | 95       | 20 | m_e_ref1 | 100 | .  | 80.000  | 5040.00  |
| 8 u.s.a.       | refinery 1      |   | 55  | 99999999 | 0  |          | 80  | .  | 65.000  | 3575.00  |
| 9 middle east  | refinery 2      |   | 81  | 80       | 10 | m_e_ref2 | 100 | .  | 20.000  | 1620.00  |
| 10 u.s.a.      | refinery 2      |   | 49  | 99999999 | 0  |          | 80  | .  | 15.000  | 735.00   |
| 11 ref1 diesel | servstn1 diesel |   | 18  | 99999999 | 0  |          | .   | 30 | 30.000  | 540.00   |
| 12 ref2 diesel | servstn1 diesel |   | 36  | 99999999 | 0  |          | .   | 30 | 0.000   | 0.00     |
| 13 ref1 gas    | servstn1 gas    |   | 15  | 70       | 0  |          | .   | 95 | 68.750  | 1031.25  |
| 14 ref2 gas    | servstn1 gas    |   | 17  | 35       | 5  |          | .   | 95 | 26.250  | 446.25   |
| 15 ref1 diesel | servstn2 diesel |   | 17  | 99999999 | 0  |          | .   | 15 | 6.250   | 106.25   |
| 16 ref2 diesel | servstn2 diesel |   | 23  | 99999999 | 0  |          | .   | 15 | 8.750   | 201.25   |
| 17 ref1 gas    | servstn2 gas    |   | 22  | 60       | 0  |          | .   | 40 | 40.000  | 880.00   |
| 18 ref2 gas    | servstn2 gas    |   | 31  | 99999999 | 0  |          | .   | 40 | 0.000   | 0.00     |
| =====          |                 |   |     |          |    |          |     |    |         |          |
| 50875.00       |                 |   |     |          |    |          |     |    |         |          |

Notice that, in CONOUT=SOLUTION (Figure 5.7), the optimal flow through each arc in the network is given in the variable named `_FLOW_`, and the cost of flow through each arc is given in the variable `_FCOST_`.

**Figure 5.8** Oil Industry Solution

## Getting Started: LP Problems

Data for an LP problem resembles the data for side constraints and nonarc variables supplied to PROC INTPOINT when solving an NPSC problem. It is also very similar to the data required by the LP procedure.

To solve LP problems using PROC INTPOINT, you save a representation of the LP variables and the constraints in one or two SAS data sets. These data sets are then passed to PROC INTPOINT for solution. There are various forms that a problem's data can take. You can use any one or a combination of several of these forms.

The **ARCDATA=** data set contains information about the LP variables of the problem. Although this data set is called ARCDATA, it contains data for no arcs. Instead, all data in this data set are related to LP variables. This data set has no SAS variables containing values that are node names.

The **ARCDATA=** data set can be used to specify information about LP variables, including objective function coefficients, lower and upper value bounds, and names. These data are the elements of the vectors  $d$ ,  $m$ , and  $v$  in problem (LP). Data for an LP variable can be given in more than one observation.

The **CONDATA=** data set describes the constraints and their right-hand sides. These data are elements of the matrix  $Q$  and the vector  $r$ .

Constraint types are also specified in the **CONDATA=** data set. You can include in this data set LP variable data such as upper bound values, lower value bounds, and objective function coefficients. It is possible to give all information about some or all LP variables in the **CONDATA=** data set.

Because PROC INTPOINT evolved from PROC NETFLOW, another procedure in SAS/OR software that was originally designed to solve models with networks, the `ARCdata=` data set is always expected. If the `ARCdata=` data set is not specified, by default the last data set created before PROC INTPOINT is invoked is assumed to be the `ARCdata=` data set. However, these characteristics of PROC INTPOINT are not helpful when an LP problem is being solved and all data are provided in a single data set specified by the `CONDdata=` data set, and that data set is not the last data set created before PROC INTPOINT starts. In this case, you must specify that the `ARCdata=` data set and the `CONDdata=` data set are both equal to the input data set. PROC INTPOINT then knows that an LP problem is to be solved and that the data reside in one data set.

An LP variable is identified in this data set by its name. If you specify an LP variable's name in the `ARCdata=` data set, then this name is used to associate data in the `CONDdata=` data set with that LP variable.

If you use the `dense` constraint input format (described in the section “`CONDdata= Data Set`” on page 107), these LP variable names are names of SAS variables in the `VAR` list of the `CONDdata=` data set.

If you use the `sparse` constraint input format (described in the section “`CONDdata= Data Set`” on page 107), these LP variable names are values of the SAS variables in the `COLUMN` list of the `CONDdata=` data set.

PROC INTPOINT reads the data from the `ARCdata=` data set (if there is one) and the `CONDdata=` data set. Error checking is performed, and the LP is `preprocessed`. Preprocessing is optional but highly recommended. The `preprocessor` analyzes the model and tries to determine before optimization whether LP variables can be “fixed” to their optimal values. Knowing that, the model can be modified and these LP variables dropped out. Some constraints may be found to be redundant. Sometimes, `preprocessing` succeeds in reducing the size of the problem, thereby making the subsequent optimization easier and faster.

The optimal solution is then found for the resulting LP. If the problem was `preprocessed`, the model is now post-processed, where fixed LP variables are reintroduced. The solution can be saved in the `CONOUT=` data set.

## Introductory LP Example

Consider the linear programming problem in the section “An Introductory Example” on page 177. The SAS data set in that section is created the same way here:

```

title 'Linear Programming Example';
title3 'Setting Up Condata = dcon1 For PROC INTPOINT';
data dcon1;
  input _id_ $17.
        a_light a_heavy brega naphthal naphthai
        heatingo jet_1 jet_2
        _type_ $ _rhs_;
  datalines;
profit          -175 -165 -205  0  0  0 300 300 max      .
naphtha_1_conv   .035 .030 .045 -1  0  0  0  0  eq      0
naphtha_i_conv   .100 .075 .135  0 -1  0  0  0  eq      0
heating_o_conv   .390 .300 .430  0  0 -1  0  0  eq      0
recipe_1         0    0    0  0 .3 .7 -1  0  eq      0
recipe_2         0    0    0 .2  0 .8  0 -1  eq      0
available        110  165   80  .  .  .  .  . upperbd .
;

```

To solve this problem, use

```
proc intpoint
  bytes=1000000
  condata=dcon1
  conout=solutn1;
run;
```

Note how it is possible to use an input SAS data set of PROC LP and, without requiring any changes to be made to the data set, to use that as an input data set for PROC INTPOINT.

The following messages that appear on the SAS log summarize the model as read by PROC INTPOINT and note the progress toward a solution

```
NOTE: Number of variables= 8 .
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 5 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 18 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 0.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 5 constraints from the problem.
NOTE: The preprocessor eliminated 18 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 0.
NOTE: The preprocessor eliminated 8 variables from the problem.
NOTE: The optimum has been determined by the Preprocessor.
NOTE: Objective= 1544.
NOTE: The data set WORK.SOLUTN1 has 8 observations and 6 variables.
NOTE: There were 7 observations read from the data set WORK.DCON1.
```

Notice that the [preprocessor](#) succeeded in fixing *all* LP variables to their optimal values, eliminating the need to do any actual optimization.

Unlike PROC LP, which displays the solution and other information as output, PROC INTPOINT saves the optimum in the output SAS data set you specify. For this example, the solution is saved in the SOLUTION data set. It can be displayed with PROC PRINT as

```
title3 'LP Optimum';
proc print data=solutn1;
  var _name_ _objfn_ _upperbd _lowerbd _value_ _fcost_;
  sum _fcost_;
run;
```

Notice that in the CONOUT=SOLUTION (Figure 5.9) the optimal value through each variable in the LP is given in the variable named `_VALUE_`, and that the cost of value for each variable is given in the variable `_FCOST_`.



Figure 5.9 CONOUT=SOLUTN1

| LP Optimum |          |         |          |          |         |         |
|------------|----------|---------|----------|----------|---------|---------|
| Obs        | _NAME_   | _OBJFN_ | _UPPERBD | _LOWERBD | _VALUE_ | _FCOST_ |
| 1          | a_heavy  | -165    | 165      | 0        | 0.00    | 0       |
| 2          | a_light  | -175    | 110      | 0        | 110.00  | -19250  |
| 3          | brega    | -205    | 80       | 0        | 80.00   | -16400  |
| 4          | heatingo | 0       | 99999999 | 0        | 77.30   | 0       |
| 5          | jet_1    | 300     | 99999999 | 0        | 60.65   | 18195   |
| 6          | jet_2    | 300     | 99999999 | 0        | 63.33   | 18999   |
| 7          | naphthai | 0       | 99999999 | 0        | 21.80   | 0       |
| 8          | naphthal | 0       | 99999999 | 0        | 7.45    | 0       |
|            |          |         |          |          |         | =====   |
|            |          |         |          |          |         | 1544    |

The same model can be specified in the [sparse](#) format as in the following scon2 data set. This format enables you to omit the zero coefficients.

```

title3 'Setting Up Condata = scon2 For PROC INTPOINT';
data scon2;
  format _type_ $8. _col_ $8. _row_ $16.;
  input _type_ $ _col_ $ _row_ $ _coef_;
  datalines;
max      .                profit                .
eq       .                napha_l_conv           .
eq       .                napha_i_conv           .
eq       .                heating_oil_conv        .
eq       .                recipe_1                .
eq       .                recipe_2                .
upperbd  .                available              .
.        a_light          profit                  -175
.        a_light          napha_l_conv            .035
.        a_light          napha_i_conv            .100
.        a_light          heating_oil_conv        .390
.        a_light          available              110
.        a_heavy          profit                  -165
.        a_heavy          napha_l_conv            .030
.        a_heavy          napha_i_conv            .075
.        a_heavy          heating_oil_conv        .300
.        a_heavy          available              165
.        brega            profit                  -205
.        brega            napha_l_conv            .045
.        brega            napha_i_conv            .135
.        brega            heating_oil_conv        .430
.        brega            available              80
.        naphthal         napha_l_conv            -1
.        naphthal         recipe_2                .2
.        naphthai         napha_i_conv            -1
.        naphthai         recipe_1                .3
.        heatingo         heating_oil_conv        -1

```

```

.      heatingo      recipe_1      .7
.      heatingo      recipe_2      .8
.      jet_1         profit        300
.      jet_1         recipe_1      -1
.      jet_2         profit        300
.      jet_2         recipe_2      -1
;

```

To find the minimum cost solution, invoke PROC INTPOINT (note the [SPARSECONDATA](#) option which must be specified) as follows:

```

proc intpoint
  bytes=1000000
  sparsecondata
  condata=scon2
  conout=solutn2;
run;

```

A data set that can be used as the [ARCDATA=](#) data set can be initialized as follows:

```

data vars3;
  input _name_ $ profit available;
  datalines;
a_heavy -165 165
a_light -175 110
brega -205 80
heatingo 0 .
jet_1 300 .
jet_2 300 .
naphthai 0 .
naphthal 0 .
;

```

The following [CONDATA=](#) data set is the original [dense](#) format [CONDATA=](#) dcon1 data set after the LP variable's nonconstraint information has been removed. (You could have left some or all of that information in CONDATA as PROC INTPOINT “merges” data, but doing that and checking for consistency takes time.)

```

data dcon3;
  input _id_ $17.
         a_light a_heavy brega naphthal naphthai
         heatingo jet_1 jet_2
         _type_ $ _rhs_;
  datalines;
naphtha_l_conv .035 .030 .045 -1 0 0 0 0 eq 0
naphtha_i_conv .100 .075 .135 0 -1 0 0 0 eq 0
heating_o_conv .390 .300 .430 0 0 -1 0 0 eq 0
recipe_1       0    0    0 0 .3 .7 -1 0 eq 0
recipe_2       0    0    0 .2 0 .8 0 -1 eq 0
;

```

**NOTE:** You must now specify the [MAXIMIZE](#) option; otherwise, PROC INTPOINT will optimize to the minimum (which, incidentally, has a total objective = -3539.25). You must indicate that the SAS variable profit in the [ARCDATA=vars3](#) data set has values that are objective function coefficients, by specifying the

**OBJFN** statement. The **UPPERBD** must be specified as the SAS variable available that has as values upper bounds:

```
proc intpoint
  maximize          /* ***** necessary ***** */
  bytes=1000000
  arcdata=vars3
  condata=dcon3
  conout=solutn3;
  objfn profit;
  upperbd available;
run;
```

The **ARCdata=vars3** data set can become more concise by noting that the model variables heatingo, naphthai, and naphthal have zero objective function coefficients (the default) and default upper bounds, so those observations need not be present:

```
data vars4;
  input _name_ $ profit available;
  datalines;
a_heavy  -165 165
a_light  -175 110
brega    -205 80
jet_1     300 .
jet_2     300 .
;
```

The **CONdata=dcon3** data set can become more concise by noting that all the constraints have the same type (eq) and zero (the default) rhs values. This model is a good candidate for using the **DEFCONTYPE=** option.

The **DEFCONTYPE=** option can be useful not only when *all* constraints have the same type as is the case here, but also when *most* constraints have the same type and you want to change the default type from  $\leq$  to  $=$  or  $\geq$ . The essential constraint type data in the **CONdata=** data set is that which overrides the **DEFCONTYPE=** type you specified.

```
data dcon4;
  input _id_ $17.
         a_light a_heavy brega naphthal naphthai
         heatingo jet_1 jet_2;
  datalines;
naphtha_l_conv  .035 .030 .045 -1 0 0 0 0
naphtha_i_conv  .100 .075 .135 0 -1 0 0 0
heating_o_conv  .390 .300 .430 0 0 -1 0 0
recipe_1        0 0 0 0 .3 .7 -1 0
recipe_2        0 0 0 .2 0 .8 0 -1
;
```

```
proc intpoint
  maximize defcontype=eq
  bytes=1000000
  arcdata=vars3
  condata=dcon3
  conout=solutn3;
```

```

objfn profit;
upperbd available;
run;

```

Here are several different ways of using the `ARCDATA=` data set and a `sparse` format `CONDATA=` data set for this LP. The following `CONDATA=` data set is the result of removing the profit and available data from the original `sparse` format `CONDATA=scon2` data set.

```

data scon5;
  format _type_ $8. _col_ $8. _row_ $16. ;
  input _type_ $ _col_ $ _row_ $ _coef_;
  datalines;
eq      .      napha_l_conv      .
eq      .      napha_i_conv      .
eq      .      heating_oil_conv  .
eq      .      recipe_1          .
eq      .      recipe_2          .
.      a_light  napha_l_conv      .035
.      a_light  napha_i_conv      .100
.      a_light  heating_oil_conv  .390
.      a_heavy  napha_l_conv      .030
.      a_heavy  napha_i_conv      .075
.      a_heavy  heating_oil_conv  .300
.      brega    napha_l_conv      .045
.      brega    napha_i_conv      .135
.      brega    heating_oil_conv  .430
.      naphthal napha_l_conv      -1
.      naphthal recipe_2          .2
.      naphthai napha_i_conv      -1
.      naphthai recipe_1          .3
.      heatingo heating_oil_conv  -1
.      heatingo recipe_1          .7
.      heatingo recipe_2          .8
.      jet_1    recipe_1          -1
.      jet_2    recipe_2          -1
;

proc intpoint
  maximize
  bytes=1000000
  sparsesecondata
  arcdata=vars3      /* or arcdata=vars4 */
  conddata=scon5
  conout=solutn5;
  objfn profit;
  upperbd available;
run;

```

The `CONDATA=scon5` data set can become more concise by noting that all the constraints have the same type (eq) and zero (the default) rhs values. Use the `DEFCONTYPE=` option again. Once the first five observations of the `CONDATA=scon5` data set are removed, the `_type_` variable has values that are missing in all of the remaining observations. Therefore, this variable can be removed.

```

data scon6;
    input _col_ $ _row_&$16. _coef_;
    datalines;
a_light  napha_l_conv      .035
a_light  napha_i_conv      .100
a_light  heating_oil_conv  .390
a_heavy  napha_l_conv      .030
a_heavy  napha_i_conv      .075
a_heavy  heating_oil_conv  .300
brega    napha_l_conv      .045
brega    napha_i_conv      .135
brega    heating_oil_conv  .430
naphthal napha_l_conv      -1
naphthal recipe_2         .2
naphthai napha_i_conv      -1
naphthai recipe_1         .3
heatingo heating_oil_conv  -1
heatingo recipe_1         .7
heatingo recipe_2         .8
jet_1    recipe_1         -1
jet_2    recipe_2         -1
;

proc intpoint
    maximize
    bytes=1000000
    defcontype=eq
    sparsesecondata
    arcdata=vars4
    condata=scon6
    conout=solutn6;
objfn profit;
upperbd available;
run;

```

---

## Typical PROC INTPOINT Run

You start PROC INTPOINT by giving the [PROC INTPOINT](#) statement. You can specify many options in the PROC INTPOINT statement to control the procedure, or you can rely on default settings and specify very few options. However, there are some options you must specify:

- You must specify the [BYTES=](#) parameter indicating the size of the working memory that the procedure is allowed to use. This option has no default.
- In many instances (and certainly when solving NPSC problems), you need to specify the [ARCDATA=](#) data set. This option has a default (which is the SAS data set that was created last before PROC INTPOINT began running), but that may need to be overridden.
- The [CONDATA=](#) data set must also be specified if the problem is NPSC and has side constraints, or if it is an LP problem.

- When solving a network problem, you have to specify the **NODEDATA=** data set, if some model data are given in such a data set.

Some options, while optional, are frequently required. To have the optimal solution output to a SAS data set, you have to specify the **CONOUT=** data set. You may want to indicate reasons why optimization should stop (for example, you can indicate the maximum number of iterations that can be performed), or you might want to alter stopping criteria so that optimization does not stop prematurely. Some options enable you to control other aspects of the interior point algorithm. Specifying certain values for these options can reduce the time it takes to solve a problem.

The SAS variable lists should be given next. If you have SAS variables in the input data sets that have special names (for example, a SAS variable in the **ARCdata=** data set named **\_TAIL\_** that has tail nodes of arcs as values), it may not be necessary to have many or any variable lists. If you do not specify a **TAIL** variable list, PROC INTPOINT will search the **ARCdata=** data set for a SAS variable named **\_TAIL\_**.

What usually follows is a **RUN** statement, which indicates that all information that you, the user, need to supply to PROC INTPOINT has been given, and the procedure is to start running. This also happens if you specify a statement in your SAS program that PROC INTPOINT does not recognize as one of its own, the next **DATA** step or procedure.

The **QUIT** statement indicates that PROC INTPOINT must immediately finish.

For example, a PROC INTPOINT run might look something like this:

```
proc intpoint
  bytes=    /* working memory size */
  arcdata= /* data set */
  condata= /* data set */
  /* other options */
;
variable list specifications; /* if necessary */
run;      /* start running, read data, */
          /* and do the optimization. */
```

## Syntax: INTPOINT Procedure

Below are statements used in PROC INTPOINT, listed in alphabetical order as they appear in the text that follows.

```

PROC INTPOINT options ;
  CAPACITY variable ;
  COEF variables ;
  COLUMN variable ;
  COST variable ;
  DEMAND variable ;
  HEADNODE variable ;
  ID variables ;
  LO variable ;
  NAME variable ;
  NODE variable ;
  QUIT ; ;
  RHS variable ;
  ROW variables ;
  RUN ; ;
  SUPDEM variable ;
  SUPPLY variable ;
  TAILNODE variable ;
  TYPE variable ;
  VAR variables ;

```

## Functional Summary

Table 5.1 outlines the options that can be specified in the INTPOINT procedure. All options are specified in the PROC INTPOINT statement.

**Table 5.1** Functional Summary

| Description   | Statement     | Option        |
|---|---------------|---------------|
| <b>Input Data Set Options:</b>  |               |               |
| Arcs input data set   | PROC INTPOINT | ARCDATA=      |
| Nodes input data set  | PROC INTPOINT | NODEDATA=     |
| Constraint input data set   | PROC INTPOINT | CONDATA=      |
| <b>Output Data Set Options:</b>   |               |               |
| Constrained solution data set   | PROC INTPOINT | CONOUT=       |
| Convert sparse or dense format input data set into MPS-format output data set | PROC INTPOINT | MPSOUT=       |
| <b>Data Set Read Options:</b>   |               |               |
| CONDATA has <i>sparse</i> data format   | PROC INTPOINT | SPARSECONDATA |

| Description  | Statement     | Option            |
|--|---------------|-------------------|
| Default constraint type                              | PROC INTPOINT | DEFCONTYPE=       |
| Special <b>COLUMN</b> variable value                 | PROC INTPOINT | TYPEOBS=          |
| Special <b>COLUMN</b> variable value                 | PROC INTPOINT | RHSOBS=           |
| Used to interpret arc and variable names             | PROC INTPOINT | NAMECTRL=         |
| No nonarc data in <b>ARCDATA</b>                     | PROC INTPOINT | ARCS_ONLY_ARCDATA |
| Data for an arc found once in <b>ARCDATA</b>         | PROC INTPOINT | ARC_SINGLE_OBS    |
| Data for a constraint found once in <b>CONDATA</b>   | PROC INTPOINT | CON_SINGLE_OBS    |
| Data for a coefficient found once in <b>CONDATA</b>  | PROC INTPOINT | NON_REPLIC=       |
| Data are grouped, exploited during data read         | PROC INTPOINT | GROUPED=          |
| <b>Problem Size Specification Options:</b>           |               |                   |
| Approximate number of nodes                          | PROC INTPOINT | NNODES=           |
| Approximate number of arcs                           | PROC INTPOINT | NARCS=            |
| Approximate number of variables                      | PROC INTPOINT | NNAS=             |
| Approximate number of coefficients                   | PROC INTPOINT | NCOEFS=           |
| Approximate number of constraints                    | PROC INTPOINT | NCONS=            |
| <b>Network Options:</b>                              |               |                   |
| Default arc cost, objective function coefficient     | PROC INTPOINT | DEFCOST=          |
| Default arc capacity, variable upper bound           | PROC INTPOINT | DEFCAPACITY=      |
| Default arc flow and variable lower bound            | PROC INTPOINT | DEFMINFLOW=       |
| Network's only supply node                           | PROC INTPOINT | SOURCE=           |
| <b>SOURCE</b> 's supply capability                   | PROC INTPOINT | SUPPLY=           |
| Network's only demand node                           | PROC INTPOINT | SINK=             |
| <b>SINK</b> 's demand                                | PROC INTPOINT | DEMAND=           |
| Convey excess supply/demand through network          | PROC INTPOINT | THRUNET           |
| Find max flow between <b>SOURCE</b> and <b>SINK</b>  | PROC INTPOINT | MAXFLOW           |
| Cost of bypass arc, <b>MAXFLOW</b> problem           | PROC INTPOINT | BYPASSDIVIDE=     |
| Find shortest path from <b>SOURCE</b> to <b>SINK</b> | PROC INTPOINT | SHORTPATH         |
| <b>Interior Point Algorithm Options:</b>             |               |                   |
| Factorization method                                 | PROC INTPOINT | FACT_METHOD=      |
| Allowed amount of dual infeasibility                 | PROC INTPOINT | TOLDINF=          |
| Allowed amount of primal infeasibility               | PROC INTPOINT | TOLPINF=          |
| Allowed total amount of dual infeasibility           | PROC INTPOINT | TOLTOTDINF=       |
| Allowed total amount of primal infeasibility         | PROC INTPOINT | TOLTOTPINF=       |
| Cut-off tolerance for Cholesky factorization         | PROC INTPOINT | CHOLTINYTOL=      |
| Density threshold for Cholesky processing            | PROC INTPOINT | DENSETHR=         |
| Step-length multiplier                               | PROC INTPOINT | PDSTEPMULT=       |
| Preprocessing type                                   | PROC INTPOINT | PRSLTYPE=         |
| Print optimization progress on SAS log               | PROC INTPOINT | PRINTLEVEL2=      |
| Ratio test zero tolerance                            | PROC INTPOINT | RTTOL=            |



| Description  | Statement     | Option            |
|--|---------------|-------------------|
| <b>Interior Point Algorithm Stopping Criteria:</b> |               |                   |
| maximum number of interior point iterations        | PROC INTPOINT | MAXITERB=         |
| primal-dual (duality) gap tolerance                | PROC INTPOINT | PDGAPTOL=         |
| Stop because of complementarity                    | PROC INTPOINT | STOP_C=           |
| Stop because of duality gap                        | PROC INTPOINT | STOP_DG=          |
| Stop because of <i>infeas<sub>b</sub></i>          | PROC INTPOINT | STOP_IB=          |
| Stop because of <i>infeas<sub>c</sub></i>          | PROC INTPOINT | STOP_IC=          |
| Stop because of <i>infeas<sub>d</sub></i>          | PROC INTPOINT | STOP_ID=          |
| Stop because of complementarity                    | PROC INTPOINT | AND_STOP_C=       |
| Stop because of duality gap                        | PROC INTPOINT | AND_STOP_DG=      |
| Stop because of <i>infeas<sub>b</sub></i>          | PROC INTPOINT | AND_STOP_IB=      |
| Stop because of <i>infeas<sub>c</sub></i>          | PROC INTPOINT | AND_STOP_IC=      |
| Stop because of <i>infeas<sub>d</sub></i>          | PROC INTPOINT | AND_STOP_ID=      |
| Stop because of complementarity                    | PROC INTPOINT | KEEPGOING_C=      |
| Stop because of duality gap                        | PROC INTPOINT | KEEPGOING_DG=     |
| Stop because of <i>infeas<sub>b</sub></i>          | PROC INTPOINT | KEEPGOING_IB=     |
| Stop because of <i>infeas<sub>c</sub></i>          | PROC INTPOINT | KEEPGOING_IC=     |
| Stop because of <i>infeas<sub>d</sub></i>          | PROC INTPOINT | KEEPGOING_ID=     |
| Stop because of complementarity                    | PROC INTPOINT | AND_KEEPGOING_C=  |
| Stop because of duality gap                        | PROC INTPOINT | AND_KEEPGOING_DG= |
| Stop because of <i>infeas<sub>b</sub></i>          | PROC INTPOINT | AND_KEEPGOING_IB= |
| Stop because of <i>infeas<sub>c</sub></i>          | PROC INTPOINT | AND_KEEPGOING_IC= |
| Stop because of <i>infeas<sub>d</sub></i>          | PROC INTPOINT | AND_KEEPGOING_ID= |
| <b>Memory Control Options:</b>                     |               |                   |
| Issue memory usage messages to SAS log             | PROC INTPOINT | MEMREP            |
| Number of bytes to use for main memory             | PROC INTPOINT | BYTES=            |
| <b>Miscellaneous Options:</b>                      |               |                   |
| Infinity value                                     | PROC INTPOINT | INFINITY=         |
| Maximization instead of minimization               | PROC INTPOINT | MAXIMIZE          |
| Zero tolerance - optimization                      | PROC INTPOINT | ZERO2=            |
| Zero tolerance - real number comparisons           | PROC INTPOINT | ZEROTOL=          |
| Suppress similar SAS log messages                  | PROC INTPOINT | VERBOSE=          |
| Scale problem data                                 | PROC INTPOINT | SCALE=            |
| Write optimization time to SAS log                 | PROC INTPOINT | OPTIM_TIMER       |

## PROC INTPOINT Statement

**PROC INTPOINT** *options* ;

This statement invokes the procedure. The following options can be specified in the PROC INTPOINT statement.

## Data Set Options

This section briefly describes all the input and output data sets used by PROC INTPOINT. The **ARC DATA=** data set, the **NODE DATA=** data set, and the **CON DATA=** data set can contain SAS variables that have special names, for instance **\_CAPAC\_**, **\_COST\_**, and **\_HEAD\_**. PROC INTPOINT looks for such variables if you do not give explicit variable list specifications. If a SAS variable with a special name is found and that SAS variable is not in another variable list specification, PROC INTPOINT determines that values of the SAS variable are to be interpreted in a special way. By using SAS variables that have special names, you may not need to have any variable list specifications.

### **ARC DATA=SAS-data-set**

names the data set that contains arc and, optionally, nonarc variable information and nodal supply/demand data. The **ARC DATA=** data set must be specified in all PROC INTPOINT statements when solving NPSC problems.

If your problem is an LP, the **ARC DATA=** data set is optional. You can specify LP variable information such as objective function coefficients, and lower and upper bounds.

### **CON DATA=SAS-data-set**

names the data set that contains the side constraint data. The data set can also contain other data such as arc costs, capacities, lower flow bounds, nonarc variable upper and lower bounds, and objective function coefficients. PROC INTPOINT needs a **CON DATA=** data set to solve a constrained problem. See the section “**CON DATA= Data Set**” on page 107 for more information.

If your problem is an LP, this data set contains the constraint data, and can also contain other data such as objective function coefficients, and lower and upper bounds. PROC INTPOINT needs a **CON DATA=** data set to solve an LP.

### **CON OUT=SAS-data-set**

### **COUT=SAS-data-set**

names the output data set that receives an optimal solution. See the section “**CON OUT= Data Set**” on page 115 for more information.

If PROC INTPOINT is outputting observations to the output data set and you want this to stop, press the keys used to stop SAS procedures.

### **MPS OUT=SAS-data-set**

names the SAS data set that contains converted sparse or dense format input data in MPS format. Invoking this option directs the INTPOINT procedure to halt before attempting optimization. For more information about the **MPS OUT=** option, see the section “**Converting Any PROC INTPOINT Format to an MPS-Format SAS Data Set**” on page 116. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*).

### **NODE DATA=SAS-data-set**

names the data set that contains the node supply and demand specifications. You do not need observations in the **NODE DATA=** data set for transshipment nodes. (Transshipment nodes neither supply nor demand flow.) All nodes are assumed to be transshipment nodes unless supply or demand data indicate otherwise. It is acceptable for some arcs to be directed toward supply nodes or away from demand nodes.

This data set is used only when you are solving network problems (not when solving LP problems), in which case the use of the NODEDATA= data set is optional provided that, if the NODEDATA= data set is not used, supply and demand details are specified by other means. Other means include using the **MAXFLOW** or **SHORTPATH** option, **SUPPLY** or **DEMAND** variable list (or both) in the **ARCDATA=** data set, and the **SOURCE=**, **SUPPLY=**, **SINK=**, or **DEMAND=** option in the PROC INTPOINT statement.

## General Options

The following is a list of options you can use with PROC INTPOINT. The options are listed in alphabetical order.

### ARCS\_ONLY\_ARCDATA

indicates that data for arcs only are in the **ARCDATA=** data set. When PROC INTPOINT reads the data in the **ARCDATA=** data set, memory would not be wasted to receive data for nonarc variables. The read might then be performed faster. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

### ARC\_SINGLE\_OBS

indicates that for all arcs and nonarc variables, data for each arc or nonarc variable is found in only one observation of the **ARCDATA=** data set. When reading the data in the **ARCDATA=** data set, PROC INTPOINT knows that the data in an observation is for an arc or a nonarc variable that has not had data previously read and that needs to be checked for consistency. The read might then be performed faster.

When solving an LP, specifying the **ARC\_SINGLE\_OBS** option indicates that for all LP variables, data for each LP variable is found in only one observation of the **ARCDATA=** data set. When reading the data in the **ARCDATA=** data set, PROC INTPOINT knows that the data in an observation is for an LP variable that has not had data previously read and that needs to be checked for consistency. The read might then be performed faster.

If you specify **ARC\_SINGLE\_OBS**, PROC INTPOINT automatically works as if **GROUPED=ARCDATA** is also specified.

See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

### BYPASSDIVIDE=*b*

### BYPASSDIV=*b*

### BPD=*b*

should be used only when the **MAXFLOW** option has been specified; that is, PROC INTPOINT is solving a maximal flow problem. PROC INTPOINT prepares to solve maximal flow problems by setting up a bypass arc. This arc is directed from the **SOURCE=** to the **SINK=** and will eventually convey flow equal to **INFINITY** minus the maximal flow through the network. The cost of the bypass arc must be great enough to drive flow through the network, rather than through the bypass arc. Also, the cost of the bypass arc must be greater than the eventual total cost of the maximal flow, which can be nonzero if some network arcs have nonzero costs. The cost of the bypass is set to the value of the **INFINITY=** option. Valid values for the **BYPASSDIVIDE=** option must be greater than or equal to 1.1.

If there are no nonzero costs of arcs in the **MAXFLOW** problem, the cost of the bypass arc is set to 1.0 (-1.0 if maximizing) if you do not specify the **BYPASSDIVIDE=** option. The default value for the **BYPASSDIVIDE=** option (in the presence of nonzero arc costs) is 100.0.

**BYTES=*b***

indicates the size of the main working memory (in bytes) that PROC INTPOINT will allocate. Specifying this option is mandatory. The working memory is used to store all the arrays and buffers used by PROC INTPOINT. If this memory has a size smaller than what is required to store all arrays and buffers, PROC INTPOINT uses various schemes that page information between auxiliary memory (often your machine's disk) and RAM.

For small problems, specify BYTES=100000. For large problems (those with hundreds of thousands or millions of variables), BYTES=1000000 might do. For solving problems of that size, if you are running on a machine with an inadequate amount of RAM, PROC INTPOINT's performance will suffer since it will be forced to page or to rely on virtual memory.

If you specify the [MEMREP](#) option, PROC INTPOINT will issue messages on the SAS log informing you of its memory usage; that is, how much memory is required to prevent paging, and details about the amount of paging that must be performed, if applicable.

**CON\_SINGLE\_OBS**

improves how the [CONDATA=](#) data set is read. How it works depends on whether the CONDATA has a dense or sparse format.

If the [CONDATA=](#) data set has the [dense](#) format, specifying CON\_SINGLE\_OBS indicates that, for each constraint, data for each can be found in only one observation of the [CONDATA=](#) data set.

If the [CONDATA=](#) data set has a [sparse](#) format, and data for each arc, nonarc variable, or LP variable can be found in only one observation of the [CONDATA](#), then specify the CON\_SINGLE\_OBS option. If there are *n* SAS variables in the [ROW](#) and [COEF](#) list, then each arc or nonarc can have at most *n* constraint coefficients in the model. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

**DEFCAPACITY=*c*****DC=*c***

requests that the default arc capacity and the default nonarc variable value upper bound (or for LP problems, the default LP variable value upper bound) be *c*. If this option is not specified, then DEFCAPACITY= [INFINITY](#).

**DEFCTYPE=*c*****DEFTYPE=*c*****DCT=*c***

specifies the default constraint type. This default constraint type is either *less than or equal to* or is the type indicated by DEFCTYPE=*c*. Valid values for this option are

|               |                                     |
|---------------|-------------------------------------|
| LE, le, or <= | for <i>less than or equal to</i>    |
| EQ, eq, or =  | for <i>equal to</i>                 |
| GE, ge, or >= | for <i>greater than or equal to</i> |

The values do not need to be enclosed in quotes.

**DEFCOST=*c***

requests that the default arc cost and the default nonarc variable objective function coefficient (or for an LP, the default LP variable objective function coefficient) be *c*. If this option is not specified, then DEFCOST=0.0.

**DEFMINFLOW=*m*****DMF=*m***

requests that the default lower flow bound through arcs and the default lower value bound of nonarc variables (or for an LP, the default lower value bound of LP variables) be *m*. If a value is not specified, then DEFMINFLOW=0.0.

**DEMAND=*d***

specifies the demand at the **SINK** node specified by the **SINK=** option. The DEMAND= option should be used only if the **SINK=** option is given in the PROC INTPOINT statement and neither the **SHORTPATH** option nor the **MAXFLOW** option is specified. If you are solving a minimum cost network problem and the **SINK=** option is used to identify the sink node, and the DEMAND= option is not specified, then the demand at the sink node is made equal to the network's total supply.

**GROUPED=*grouped***

PROC INTPOINT can take a much shorter time to read data if the data have been grouped prior to the PROC INTPOINT call. This enables PROC INTPOINT to conclude that, for instance, a new NAME list variable value seen in the **ARCDATA=** data set grouped by the values of the NAME list variable before PROC INTPOINT was called is new. PROC INTPOINT does not need to check that the NAME has been read in a previous observation. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

- GROUPED=ARCDATA indicates that the **ARCDATA=** data set has been grouped by values of the **NAME** list variable. If **\_NAME\_** is the name of the **NAME** list variable, you could use

```
proc sort data=arcddata; by _name_;
```

prior to calling PROC INTPOINT. Technically, you do not have to sort the data, only to ensure that all similar values of the **NAME** list variable are grouped together. If you specify the **ARCS\_ONLY\_ARCDATA** option, PROC INTPOINT automatically works as if GROUPED=ARCDATA is also specified.

- GROUPED=CONDATA indicates that the **CONDATA=** data set has been grouped.

If the **CONDATA=** data set has a **dense** format, GROUPED=CONDATA indicates that the **CONDATA=** data set has been grouped by values of the **ROW** list variable. If **\_ROW\_** is the name of the **ROW** list variable, you could use

```
proc sort data=condata; by _row_;
```

prior to calling PROC INTPOINT. Technically, you do not have to sort the data, only to ensure that all similar values of the **ROW** list variable are grouped together. If you specify the **CON\_SINGLE\_OBS** option, or if there is no **ROW** list variable, PROC INTPOINT automatically works as if GROUPED=CONDATA has been specified.

If the **CONDATA=** data set has the **sparse** format, GROUPED=CONDATA indicates that **CONDATA** has been grouped by values of the **COLUMN** list variable. If **\_COL\_** is the name of the **COLUMN** list variable, you could use

```
proc sort data=condata; by _col_;
```

prior to calling PROC INTPOINT. Technically, you do not have to sort the data, only to ensure that all similar values of the **COLUMN** list variable are grouped together.

- **GROUPED=BOTH** indicates that both **GROUPED=ARCDATA** and **GROUPED=CONDATA** are TRUE.
- **GROUPED=NONE** indicates that the data sets have not been grouped, that is, neither **GROUPED=ARCDATA** nor **GROUPED=CONDATA** is TRUE. This is the default, but it is much better if **GROUPED=ARCDATA**, or **GROUPED=CONDATA**, or **GROUPED=BOTH**.

A data set like

```
... _XXXXX_ ....
    bbb
    bbb
    aaa
    ccc
    ccc
```

is a candidate for the **GROUPED=** option. Similar values are grouped together. When PROC INTPOINT is reading the  $i$ th observation, either the value of the **\_XXXXX\_** variable is the same as the  $(i - 1)$ st (that is, the previous observation's) **\_XXXXX\_** value, or it is a new **\_XXXXX\_** value not seen in any previous observation. This also means that if the  $i$ th **\_XXXXX\_** value is different from the  $(i - 1)$ st **\_XXXXX\_** value, the value of the  $(i - 1)$ st **\_XXXXX\_** variable will not be seen in any observations  $i, i + 1, \dots$

**INFINITY= $i$**

**INF= $i$**

is the largest number used by PROC INTPOINT in computations. A number too small can adversely affect the solution process. You should avoid specifying an enormous value for the **INFINITY=** option because numerical roundoff errors can result. If a value is not specified, then **INFINITY=99999999**. The **INFINITY=** option cannot be assigned a value less than 9999.

**MAXFLOW**

**MF**

specifies that PROC INTPOINT solve a maximum flow problem. In this case, the PROC INTPOINT procedure finds the maximum flow from the node specified by the **SOURCE=** option to the node specified by the **SINK=** option. PROC INTPOINT automatically assigns an **INFINITY=** option supply to the **SOURCE=** option node and the **SINK=** option is assigned the **INFINITY=** option demand. In this way, the **MAXFLOW** option sets up a maximum flow problem as an equivalent minimum cost problem.

You can use the **MAXFLOW** option when solving any flow problem (not necessarily a maximum flow problem) when the network has one supply node (with infinite supply) and one demand node (with infinite demand). The **MAXFLOW** option can be used in conjunction with all other options (except **SHORTPATH**, **SUPPLY=**, and **DEMAND=**) and capabilities of PROC INTPOINT.



**MAXIMIZE****MAX**

specifies that PROC INTPOINT find the maximum cost flow through the network. If both the MAXIMIZE and the [SHORTPATH](#) options are specified, the solution obtained is the longest path between the [SOURCE=](#) and [SINK=](#) nodes. Similarly, MAXIMIZE and [MAXFLOW](#) together cause PROC INTPOINT to find the minimum flow between these two nodes; this is zero if there are no nonzero lower flow bounds. If solving an LP, specifying the MAXIMIZE option is necessary if you want the maximal optimal solution found instead of the minimal optimum.

**MEMREP**

indicates that information on the memory usage and paging schemes (if necessary) is reported by PROC INTPOINT on the SAS log.

**NAMECTRL=*i***

is used to interpret arc and nonarc variable names in the [CONDATA=](#) data set. In the [ARCDATA=](#) data set, an arc is identified by its tail and head node. In the [CONDATA=](#) data set, arcs are identified by names. You can give a name to an arc by having a [NAME](#) list specification that indicates a SAS variable in the [ARCDATA=](#) data set that has names of arcs as values.

PROC INTPOINT requires that arcs that have information about them in the [CONDATA=](#) data set have names, but arcs that do not have information about them in the [CONDATA=](#) data set can also have names. Unlike a nonarc variable whose name uniquely identifies it, an arc can have several different names. An arc has a default name in the form *tail\_head*, that is, the name of the arc's tail node followed by an underscore and the name of the arc's head node.

In the [CONDATA=](#) data set, if the [dense](#) data format is used (described in the section “[CONDATA= Data Set](#)” on page 107), a name of an arc or a nonarc variable is the *name* of a SAS variable listed in the [VAR](#) list specification. If the [sparse](#) data format of the [CONDATA=](#) data set is used, a name of an arc or a nonarc variable is a *value* of the SAS variable listed in the [COLUMN](#) list specification.

The NAMECTRL= option is used when a name of an arc or a nonarc variable in the [CONDATA=](#) data set (either a [VAR](#) list variable name or a value of the [COLUMN](#) list variable) is in the form *tail\_head* and there exists an arc with these end nodes. If *tail\_head* has not already been tagged as belonging to an arc or nonarc variable in the [ARCDATA=](#) data set, PROC INTPOINT needs to know whether *tail\_head* is the name of the arc or the name of a nonarc variable.

If you specify NAMECTRL=1, a name that is not defined in the [ARCDATA=](#) data set is assumed to be the name of a nonarc variable. NAMECTRL=2 treats *tail\_head* as the name of the arc with these endnodes, provided no other name is used to associate data in the [CONDATA=](#) data set with this arc. If the arc does have other names that appear in the [CONDATA=](#) data set, *tail\_head* is assumed to be the name of a nonarc variable. If you specify NAMECTRL=3, *tail\_head* is assumed to be a name of the arc with these end nodes, whether the arc has other names or not. The default value of NAMECTRL is 3.

If the [dense](#) format is used for the [CONDATA=](#) data set, there are two circumstances that affect how this data set is read:

1. if you are running SAS Version 6, or a previous version to that, or if you are running SAS Version 7 onward and you specify

```
options validvarname=v6;
```

in your SAS session. Let's refer to this as *case 1*.

2. if you are running SAS Version 7 onward and you do not specify

```
options validvarname=v6;
```

in your SAS session. Let's refer to this as *case 2*.

For *case 1*, the SAS System converts SAS variable names in a SAS program to uppercase. The **VAR** list variable names are uppercased. Because of this, PROC INTPOINT automatically uppercases names of arcs and nonarc variables or LP variables (the values of the **NAME** list variable) in the **ARCDATA=** data set. The names of arcs and nonarc variables or LP variables (the values of the **NAME** list variable) appear uppercased in the **CONOUT=** data set.

Also, if the **dense** format is used for the **CONDATA=** data set, be careful with default arc names (names in the form **tailnode\_headnode**). Node names (values in the **TAILNODE** and **HEADNODE** list variables) in the **ARCDATA=** data set are not automatically uppercased by PROC INTPOINT. Consider the following statements:

```
data arcddata;
    input _from_ $ _to_ $ _name $ ;
    datalines;
from to1 .
from to2 arc2
TAIL TO3 .
;
data densecon;
    input from_to1 from_to2 arc2 tail_to3;
    datalines;
2 3 3 5
;
proc intpoint
    arcddata=arcddata condata=densecon;
run;
```

The SAS System does not uppercase character string values within SAS data sets. PROC INTPOINT never uppercases node names, so the arcs in observations 1, 2, and 3 in the preceding **ARCDATA=** data set have the default names **from\_to1**, **from\_to2**, and **TAIL\_TO3**, respectively. When the **dense** format of the **CONDATA=** data set is used, PROC INTPOINT does uppercase values of the **NAME** list variable, so the name of the arc in the second observation of the **ARCDATA=** data set is **ARC2**. Thus, the second arc has two names: its default **from\_to2** and the other that was specified **ARC2**.

As the SAS System uppercases program code, you must think of the input statement

```
input from_to1 from_to2 arc2 tail_to3;
```

as really being

```
INPUT FROM_TO1 FROM_TO2 ARC2 TAIL_TO3;
```



The SAS variables named FROM\_TO1 and FROM\_TO2 are *not* associated with any of the arcs in the preceding **ARCDATA=** data set. The values FROM\_TO1 and FROM\_TO2 are different from all of the arc names from\_to1, from\_to2, TAIL\_TO3, and ARC2. FROM\_TO1 and FROM\_TO2 could end up being the names of two nonarc variables.

The SAS variable named ARC2 is the name of the second arc in the **ARCDATA=** data set, even though the name specified in the **ARCDATA=** data set looks like arc2. The SAS variable named TAIL\_TO3 is the default name of the third arc in the **ARCDATA=** data set.

For *case 2*, the SAS System does not convert SAS variable names in a SAS program to uppercase. The **VAR** list variable names are not uppercased. PROC INTPOINT does not automatically uppercase names of arcs and nonarc variables or LP variables (the values of the **NAME** list variable) in the **ARCDATA=** data set. PROC INTPOINT does not uppercase any SAS variable names, data set values, or indeed anything. Therefore, PROC INTPOINT respects case, and characters in the data if compared must have the right case if you mean them to be the same. Note how the input statement in the DATA step that initialized the data set densecon below is specified in the following code:

```
data arcdata;
    input _from_ $ _to_ $ _name $ ;
    datalines;
from to1 .
from to2 arc2
TAIL TO3 .
;
data densecon;
    input from_to1 from_to2 arc2 TAIL_TO3;
    datalines;
2 3 3 5
;
proc intpoint
    arcdata=arcdata condata=densecon;
run;
```

#### **NARCS=*n***

specifies the approximate number of arcs. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

#### **NCOEFS=*n***

specifies the approximate number of constraint coefficients. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

#### **NCONS=*n***

specifies the approximate number of constraints. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

#### **NNAS=*n***

specifies the approximate number of nonarc variables. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

**NNODES=*n***

specifies the approximate number of nodes. See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

**NON\_REPLIC=*non\_replic***

prevents PROC INTPOINT from doing unnecessary checks of data previously read.

- NON\_REPLIC=COEFS indicates that each constraint coefficient is specified *once* in the **CONDATA=** data set.
- NON\_REPLIC=NONE indicates that constraint coefficients can be specified more than once in the **CONDATA=** data set. NON\_REPLIC=NONE is the default.

See the section “[How to Make the Data Read of PROC INTPOINT More Efficient](#)” on page 125.

**OPTIM\_TIMER**

indicates that the procedure is to issue a message to the SAS log giving the CPU time spent doing optimization. This includes the time spent preprocessing, performing optimization, and postprocessing. Not counted in that time is the rest of the procedure execution, which includes reading the data and creating output SAS data sets.

The time spent optimizing can be small compared to the total CPU time used by the procedure. This is especially true when the problem is quite small (e.g., fewer than 10,000 variables).

**RHSOBS=*charstr***

specifies the keyword that identifies a right-hand-side observation when using the **sparse** format for data in the **CONDATA=** data set. The keyword is expected as a value of the SAS variable in the **CONDATA=** data set named in the **COLUMN** list specification. The default value of the RHSOBS= option is **\_RHS\_** or **\_rhs\_**. If *charstr* is not a valid SAS variable name, enclose it in quotes.

**SCALE=*scale***

indicates that the NPSC side constraints or the LP constraints are to be scaled. Scaling is useful when some coefficients are either much larger or much smaller than other coefficients. Scaling might make all coefficients have values that have a smaller range, and this can make computations more stable numerically. Try the SCALE= option if PROC INTPOINT is unable to solve a problem because of numerical instability. Specify

- SCALE=ROW, SCALE=CON, or SCALE=CONSTRAINT if you want the largest absolute value of coefficients in each constraint to be about 1.0
- SCALE=COL, SCALE=COLUMN, or SCALE=NONARC if you want NPSC nonarc variable columns or LP variable columns to be scaled so that the absolute value of the largest constraint coefficient of that variable is near to 1
- SCALE=BOTH if you want the largest absolute value of coefficients in each constraint, and the absolute value of the largest constraint coefficient of an NPSC nonarc variable or LP variable to be near to 1. This is the default.
- SCALE=NONE if no scaling should be done

**SHORTPATH****SP**

specifies that PROC INTPOINT solve a shortest path problem. The INTPOINT procedure finds the shortest path between the nodes specified in the **SOURCE=** option and the **SINK=** option. The costs of arcs are their *lengths*. PROC INTPOINT automatically assigns a supply of one flow unit to the **SOURCE=** node, and the **SINK=** node is assigned to have a one flow unit demand. In this way, the **SHORTPATH** option sets up a shortest path problem as an equivalent minimum cost problem.

If a network has one supply node (with supply of one unit) and one demand node (with demand of one unit), you could specify the **SHORTPATH** option, with the **SOURCE=** and **SINK=** nodes, even if the problem is not a shortest path problem. You then should not provide any supply or demand data in the **NODEDATA=** data set or the **ARCDATA=** data set.

**SINK=sinkname**

**SINKNODE=sinkname**

identifies the demand node. The **SINK=** option is useful when you specify the **MAXFLOW** option or the **SHORTPATH** option and you need to specify toward which node the shortest path or maximum flow is directed. The **SINK=** option also can be used when a minimum cost problem has only one demand node. Rather than having this information in the **ARCDATA=** data set or the **NODEDATA=** data set, use the **SINK=** option with an accompanying **DEMAND=** specification for this node. The **SINK=** option must be the name of a head node of at least one arc; thus, it must have a character value. If the value of the **SINK=** option is not a valid SAS character variable name (if, for example, it contains embedded blanks), it must be enclosed in quotes.

**SOURCE=sourcename**

**SOURCENODE=sourcename**

identifies a supply node. The **SOURCE=** option is useful when you specify the **MAXFLOW** or the **SHORTPATH** option and need to specify from which node the shortest path or maximum flow originates. The **SOURCE=** option also can be used when a minimum cost problem has only one supply node. Rather than having this information in the **ARCDATA=** data set or the **NODEDATA=** data set, use the **SOURCE=** option with an accompanying **SUPPLY=** amount of supply at this node. The **SOURCE=** option must be the name of a tail node of at least one arc; thus, it must have a character value. If the value of the **SOURCE=** option is not a valid SAS character variable name (if, for example, it contains embedded blanks), it must be enclosed in quotes.

**SPARSECONDATA****SCDATA**

indicates that the **CONDATA=** data set has data in the *sparse* data format. Otherwise, it is assumed that the data are in the *dense* format.

**NOTE:** If the **SPARSECONDATA** option is not specified, and you are running SAS software Version 6 or you have specified

```
options validvarname=v6;
```

all **NAME** list variable values in the **ARCDATA=** data set are uppercased. See the section “Case Sensitivity” on page 116.

**SUPPLY=*s***

specifies the supply at the source node specified by the **SOURCE=** option. The **SUPPLY=** option should be used only if the **SOURCE=** option is given in the PROC INTPOINT statement and neither the **SHORTPATH** option nor the **MAXFLOW** option is specified. If you are solving a minimum cost network problem and the **SOURCE=** option is used to identify the source node and the **SUPPLY=** option is not specified, then by default the supply at the source node is made equal to the network's total demand.

**THRUNET**

tells PROC INTPOINT to force through the network any excess supply (the amount by which total supply exceeds total demand) or any excess demand (the amount by which total demand exceeds total supply) as is required. If a network problem has unequal total supply and total demand and the **THRUNET** option is not specified, PROC INTPOINT drains away the excess supply or excess demand in an optimal manner. The consequences of specifying or not specifying **THRUNET** are discussed in the section “Balancing Total Supply and Total Demand” on page 124.

**TYPEOBS=*charstr***

specifies the keyword that identifies a type observation when using the **sparse** format for data in the **CONDATA=** data set. The keyword is expected as a value of the SAS variable in the **CONDATA=** data set named in the **COLUMN** list specification. The default value of the **TYPEOBS=** option is **\_TYPE\_** or **\_type\_**. If *charstr* is not a valid SAS variable name, enclose it in quotes.

**VERBOSE=*v***

limits the number of similar messages that are displayed on the SAS log.

For example, when reading the **ARCDATA=** data set, PROC INTPOINT might have cause to issue the following message many times:

```
ERROR: The HEAD list variable value in obs i in ARCDATA is
       missing and the TAIL list variable value of this obs
       is nonmissing. This is an incomplete arc specification.
```

If there are many observations that have this fault, messages that are similar are issued for only the first **VERBOSE=** such observations. After the **ARCDATA=** data set has been read, PROC INTPOINT will issue the message

```
NOTE: More messages similar to the ones immediately above
      could have been issued but were suppressed as
      VERBOSE=v.
```

If observations in the **ARCDATA=** data set have this error, PROC INTPOINT stops and you have to fix the data. Imagine that this error is only a warning and PROC INTPOINT proceeded to other operations such as reading the **CONDATA=** data set. If PROC INTPOINT finds there are numerous errors when reading that data set, the number of messages issued to the SAS log are also limited by the **VERBOSE=** option.

When PROC INTPOINT finishes and messages have been suppressed, the message

```
NOTE: To see all messages, specify VERBOSE=vmin.
```

is issued. The value of *vmin* is the smallest value that should be specified for the `VERBOSE=` option so that *all* messages are displayed if PROC INTPOINT is run again with the same data and everything else (except `VERBOSE=vmin`) unchanged.

The default value for the `VERBOSE=` option is 12.

### **ZERO2=z**

#### **Z2=z**

specifies the zero tolerance level used when determining whether the final solution has been reached. `ZERO2=` is also used when outputting the solution to the `CONOUT=` data set. Values within *z* of zero are set to 0.0, where *z* is the value of the `ZERO2=` option. Flows close to the lower flow bound or capacity of arcs are reassigned those exact values. If there are nonarc variables, values close to the lower or upper value bound of nonarc variables are reassigned those exact values. When solving an LP problem, values close to the lower or upper value bound of LP variables are reassigned those exact values.

The `ZERO2=` option works when determining whether optimality has been reached or whether an element in the vector  $(\Delta x^k, \Delta y^k, \Delta s^k)$  is less than or greater than zero. It is crucial to know that when determining the maximal value for the step length  $\alpha$  in the formula

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

See the description of the `PDSTEPMULT=` option for more details on this computation.

Two values are deemed to be close if one is within *z* of the other. The default value for the `ZERO2=` option is 0.000001. Any value specified for the `ZERO2=` option that is  $< 0.0$  or  $> 0.0001$  is not valid.

### **ZEROTOL=z**

specifies the zero tolerance used when PROC INTPOINT must compare any real number with another real number, or zero. For example, if *x* and *y* are real numbers, then for *x* to be considered greater than *y*, *x* must be at least *y* + *z*. The `ZEROTOL=` option is used throughout any PROC INTPOINT run.

`ZEROTOL=z` controls the way PROC INTPOINT performs all double precision comparisons; that is, whether a double precision number is equal to, not equal to, greater than (or equal to), or less than (or equal to) zero or some other double precision number. A double precision number is deemed to be the same as another such value if the absolute difference between them is less than or equal to the value of the `ZEROTOL=` option.

The default value for the `ZEROTOL=` option is  $1.0\text{E}-14$ . You can specify the `ZEROTOL=` option in the INTPOINT statement. Valid values for the `ZEROTOL=` option must be  $> 0.0$  and  $< 0.0001$ . Do not specify a value too close to zero as this defeats the purpose of the `ZEROTOL=` option. Neither should the value be too large, as comparisons might be incorrectly performed.

## **Interior Point Algorithm Options**

### **FACT\_METHOD=f**

enables you to choose the type of algorithm used to factorize and solve the main linear systems at each iteration of the interior point algorithm.

`FACT_METHOD=LEFT_LOOKING` is new for SAS 9.1.2. It uses algorithms described in George, Liu, and Ng (2001). Left looking is one of the main methods used to perform Cholesky optimization

and, along with some recently developed implementation approaches, can be faster and require less memory than other algorithms.

Specify FACT\_METHOD=USE\_OLD if you want the procedure to use the only factorization available prior to SAS 9.1.2.

**TOLDINF=*t***

**RTOLDINF=*t***

specifies the allowed amount of dual infeasibility. In the section “[Interior Point Algorithmic Details](#)” on page 47, the vector *infeas<sub>d</sub>* is defined. If all elements of this vector are  $\leq t$ , the solution is considered dual feasible. *infeas<sub>d</sub>* is replaced by a zero vector, making computations faster. This option is the dual equivalent to the TOLPINF= option. Increasing the value of the TOLDINF= option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

**TOLPINF=*t***

**RTOLPINF=*t***

specifies the allowed amount of primal infeasibility. This option is the primal equivalent to the TOLDINF= option. In the section “[Interior Point: Upper Bounds](#)” on page 51, the vector *infeas<sub>b</sub>* is defined. In the section “[Interior Point Algorithmic Details](#)” on page 47, the vector *infeas<sub>c</sub>* is defined. If all elements in these vectors are  $\leq t$ , the solution is considered primal feasible. *infeas<sub>b</sub>* and *infeas<sub>c</sub>* are replaced by zero vectors, making computations faster. Increasing the value of the TOLPINF= option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

**TOLTOTDINF=*t***

**RTOLTOTDINF=*t***

specifies the allowed total amount of dual infeasibility. In the section “[Interior Point Algorithmic Details](#)” on page 47, the vector *infeas<sub>d</sub>* is defined. If  $\sum_{i=1}^n \text{infeas}_{di} \leq t$ , the solution is considered dual feasible. *infeas<sub>d</sub>* is replaced by a zero vector, making computations faster. This option is the dual equivalent to the TOLTOTPINF= option. Increasing the value of the TOLTOTDINF= option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

**TOLTOTPINF=*t***

**RTOLTOTPINF=*t***

specifies the allowed total amount of primal infeasibility. This option is the primal equivalent to the TOLTOTDINF= option. In the section “[Interior Point: Upper Bounds](#)” on page 51, the vector *infeas<sub>b</sub>* is defined. In the section “[Interior Point Algorithmic Details](#)” on page 47, the vector *infeas<sub>c</sub>* is defined. If  $\sum_{i=1}^n \text{infeas}_{bi} \leq t$  and  $\sum_{i=1}^m \text{infeas}_{ci} \leq t$ , the solution is considered primal feasible. *infeas<sub>b</sub>* and *infeas<sub>c</sub>* are replaced by zero vectors, making computations faster. Increasing the value of the TOLTOTPINF= option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

**CHOLTINYTOL=*c***

**RCHOLTINYTOL=*c***

specifies the cut-off tolerance for Cholesky factorization of the  $A \Theta A^{-1}$ . If a diagonal value drops below *c*, the row is essentially treated as dependent and is ignored in the factorization. Valid values for *c* are between 1.0E–30 and 1.0E–6. The default value is 1.0E–8.

**DENSETHR=*d*****RDENSETHR=*d***

specifies the density threshold for Cholesky factorization. When the [symbolic factorization](#) encounters a column of  $L$  (where  $L$  is the remaining unfactorized submatrix) that has DENSETHR= proportion of nonzeros and the remaining part of  $L$  is at least  $12 \times 12$ , the remainder of  $L$  is treated as dense. In practice, the lower right part of the Cholesky triangular factor  $L$  is quite dense and it can be computationally more efficient to treat it as 100% dense. The default value for  $d$  is 0.7. A specification of  $d \leq 0.0$  causes all dense processing;  $d \geq 1.0$  causes all sparse processing.

**PDSTEPMULT=*p*****RPDSTEPMULT=*p***

specifies the step-length multiplier. The maximum feasible step-length chosen by the interior point algorithm is multiplied by the value of the PDSTEPMULT= option. This number must be less than 1 to avoid moving beyond the barrier. An actual step-length greater than 1 indicates numerical difficulties. Valid values for  $p$  are between 0.01 and 0.999999. The default value is 0.99995.

In the section “[Interior Point Algorithmic Details](#)” on page 47, the solution of the next iteration is obtained by moving along a [direction](#) from the current iteration’s solution:

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

where  $\alpha$  is the maximum feasible step-length chosen by the interior point algorithm. If  $\alpha \leq 1$ , then  $\alpha$  is reduced slightly by multiplying it by  $p$ .  $\alpha$  is a value as large as possible but  $\leq 1.0$  and not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  of some variable  $i$  is “too close” to zero.

**PRSLTYPE=*p*****IPRSLTYPE=*p***

Preprocessing the linear programming problem often succeeds in allowing some variables and constraints to be temporarily eliminated from the resulting LP that must be solved. This reduces the solution time and possibly also the chance that the optimizer will run into numerical difficulties. The task of preprocessing is inexpensive to do.

You control how much preprocessing to do by specifying PRSLTYPE= $p$ , where  $p$  can be  $-1$ ,  $0$ ,  $1$ ,  $2$ , or  $3$ :

- $-1$  Do not perform preprocessing. For most problems, specifying PRSLTYPE= $-1$  is *not* recommended.
- $0$  Given upper and lower bounds on each variable, the greatest and least contribution to the row activity of each variable is computed. If these are within the limits set by the upper and lower bounds on the row activity, then the row is redundant and can be discarded. Otherwise, whenever possible, the bounds on any of the variables are tightened. For example, if all coefficients in a constraint are positive and all variables have zero lower bounds, then the row’s smallest contribution is zero. If the rhs value of this constraint is zero, then if the constraint type is  $=$  or  $\leq$ , all the variables in that constraint are fixed to zero. These variables and the constraint are removed. If the constraint type is  $\geq$ , the constraint is redundant. If the rhs is negative and the constraint is  $\leq$ , the problem is infeasible. If just one variable in a row is not fixed, the row is used to impose an implicit upper or lower bound on the variable and then this row is eliminated. The preprocessor also tries to tighten the bounds on constraint right-hand sides.



- 1 When there are exactly two unfixed variables with coefficients in an equality constraint, one variable is solved in terms of the other. The problem will have one less variable. The new matrix will have at least two fewer coefficients and one less constraint. In other constraints where both variables appear, two coefficients are combined into one. PRSLTYPE=0 reductions are also done.
- 2 It may be possible to determine that an equality constraint is not constraining a variable. That is, if all variables are nonnegative, then  $x - \sum_i y_i = 0$  does not constrain  $x$ , since it must be nonnegative if all the  $y_i$ 's are nonnegative. In this case,  $x$  is eliminated by subtracting this equation from all others containing  $x$ . This is useful when the only other entry for  $x$  is in the objective function. This reduction is performed if there is at most one other nonobjective coefficient. PRSLTYPE=0 reductions are also done.
- 3 All possible reductions are performed. PRSLTYPE=3 is the default.

Preprocessing is iterative. As variables are fixed and eliminated, and constraints are found to be redundant and they too are eliminated, and as variable bounds and constraint right-hand sides are tightened, the LP to be optimized is modified to reflect these changes. Another iteration of preprocessing of the modified LP may reveal more variables and constraints that are eliminated, or tightened.

#### PRINTLEVEL2=*p*

is used when you want to see PROC INTPOINT's progress to the optimum. PROC INTPOINT will produce a table on the SAS log. A row of the table is generated during each iteration and may consist of values of

- the [affine step](#) complementarity
- the [complementarity](#) of the solution for the next iteration
- the total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the [infeas<sub>b</sub>](#) array in the section “[Interior Point: Upper Bounds](#)” on page 51)
- the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the [infeas<sub>c</sub>](#) array in the section “[Interior Point Algorithmic Details](#)” on page 47)
- the total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the [infeas<sub>d</sub>](#) array in the section “[Interior Point Algorithmic Details](#)” on page 47)

As optimization progresses, the values in all columns should converge to zero. If you specify PRINTLEVEL2=2, all columns will appear in the table. If PRINTLEVEL2=1 is specified, only the [affine step](#) complementarity and the [complementarity](#) of the solution for the next iteration will appear. Some time is saved by not calculating the infeasibility values.

PRINTLEVEL2=2 is specified in all PROC INTPOINT runs in the section “[Examples: INTPOINT Procedure](#)” on page 132.

#### RTTOL=*r*

specifies the zero tolerance used during the ratio test of the interior point algorithm. The ratio test determines  $\alpha$ , the maximum feasible step length.

Valid values for  $r$  are greater than 1.0E–14. The default value is 1.0E–10.



In the section “[Interior Point Algorithmic Details](#)” on page 47, the solution of the next iteration is obtained by moving along a [direction](#) from the current iteration’s solution:

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

where  $\alpha$  is the maximum feasible step-length chosen by the interior point algorithm. If  $\alpha \leq 1$ , then  $\alpha$  is reduced slightly by multiplying it by the value of the [PDSTEPMULT=](#) option.  $\alpha$  is a value as large as possible but  $\leq 1.0$  and not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  of some variable  $i$  is negative. When determining  $\alpha$ , only negative elements of  $\Delta x$  and  $\Delta s$  are important.

RTTOL= $r$  indicates a number close to zero so that another number  $n$  is considered truly negative if  $n \leq -r$ . Even though  $n < 0$ , if  $n > -r$ ,  $n$  may be too close to zero and may have the wrong sign due to rounding error.

## Interior Point Algorithm Options: Stopping Criteria

**MAXITERB= $m$**

**IMAXITERB= $m$**

specifies the maximum number of iterations that the interior point algorithm can perform. The default value for  $m$  is 100. One of the most remarkable aspects of the interior point algorithm is that for most problems, it usually needs to do a small number of iterations, *no matter the size of the problem*.

**PDGAPTOL= $p$**

**RPDGAPTOL= $p$**

specifies the primal-dual gap or [duality gap](#) tolerance. [Duality gap](#) is defined in the section “[Interior Point Algorithmic Details](#)” on page 47. If the relative gap ( $duality\ gap / (c^T x)$ ) between the primal and dual objectives is smaller than the value of the PDGAPTOL= option and both the primal and dual problems are feasible, then PROC INTPOINT stops optimization with a solution that is deemed optimal. Valid values for  $p$  are between 1.0E–12 and 1.0E–1. The default is 1.0E–7.

**STOP\_C= $s$**

is used to determine whether optimization should stop. At the beginning of each iteration, if [complementarity](#) (the value of the Complement-ity column in the table produced when you specify [PRINTLEVEL2=1](#) or [PRINTLEVEL2=2](#)) is  $\leq s$ , optimization will stop. This option is discussed in the section “[Stopping Criteria](#)” on page 130.

**STOP\_DG= $s$**

is used to determine whether optimization should stop. At the beginning of each iteration, if the [duality gap](#) (the value of the Duality\_gap column in the table produced when you specify [PRINTLEVEL2=1](#) or [PRINTLEVEL2=2](#)) is  $\leq s$ , optimization will stop. This option is discussed in the section “[Stopping Criteria](#)” on page 130.

**STOP\_IB= $s$**

is used to determine whether optimization should stop. At the beginning of each iteration, if total bound infeasibility  $\sum_{i=1}^n infeas_{bi}$  (see the [infeas<sub>b</sub>](#) array in the section “[Interior Point: Upper Bounds](#)” on page 51; this value appears in the Tot\_infeasb column in the table produced when you specify [PRINTLEVEL2=1](#) or [PRINTLEVEL2=2](#)) is  $\leq s$ , optimization will stop. This option is discussed in the section “[Stopping Criteria](#)” on page 130.

**STOP\_IC=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeas<sub>c</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**STOP\_ID=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeas<sub>d</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_STOP\_C=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if *complementarity* (the value of the Complem-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the other conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_STOP\_DG=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if the *duality gap* (the value of the Duality\_gap column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the other conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_STOP\_IB=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 51; this value appears in the Tot\_infeas<sub>b</sub> column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the other conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_STOP\_IC=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeas<sub>c</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , and the other conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_STOP\_ID=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeas<sub>d</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , and the other conditions related to other AND\_STOP parameters are

also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 130.

#### KEEPGOING\_C=s

is used to determine whether optimization should stop. When a stopping condition is met, if **complementarity** (the value of the Complement-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### KEEPGOING\_DG=s

is used to determine whether optimization should stop. When a stopping condition is met, if the **duality gap** (the value of the Duality\_gap column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### KEEPGOING\_IB=s

is used to determine whether optimization should stop. When a stopping condition is met, if total bound infeasibility  $\sum_{i=1}^n infeas_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 51; this value appears in the Tot\_infeasb column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### KEEPGOING\_IC=s

is used to determine whether optimization should stop. When a stopping condition is met, if total constraint infeasibility  $\sum_{i=1}^m infeas_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeasc column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### KEEPGOING\_ID=s

is used to determine whether optimization should stop. When a stopping condition is met, if total dual infeasibility  $\sum_{i=1}^n infeas_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeasd column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### AND\_KEEPPGOING\_C=s

is used to determine whether optimization should stop. When a stopping condition is met, if **complementarity** (the value of the Complement-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , *and* the other conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

#### AND\_KEEPPGOING\_DG=s

is used to determine whether optimization should stop. When a stopping condition is met, if the **duality gap** (the value of the Duality\_gap column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , *and* the other conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_KEEPPGOING\_IB=s**

is used to determine whether optimization should stop. When a stopping condition is met, if total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 51; this value appears in the Tot\_infeasb column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , and the other conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_KEEPPGOING\_IC=s**

is used to determine whether optimization should stop. When a stopping condition is met, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeasc column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , and the other conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

**AND\_KEEPPGOING\_ID=s**

is used to determine whether optimization should stop. When a stopping condition is met, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 47; this value appears in the Tot\_infeasd column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , and the other conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 130.

---

## CAPACITY Statement

**CAPACITY** *variable* ;

**CAPAC** *variable* ;

**UPPERBD** *variable* ;

The CAPACITY statement identifies the SAS variable in the ARCDATA= data set that contains the maximum feasible flow or capacity of the network arcs. If an observation contains nonarc variable information, the CAPACITY list variable is the upper value bound for the nonarc variable named in the NAME list variable in that observation.

When solving an LP, the CAPACITY statement identifies the SAS variable in the ARCDATA= data set that contains the maximum feasible value of the LP variables.

The CAPACITY list variable must have numeric values. It is not necessary to have a CAPACITY statement if the name of the SAS variable is \_CAPAC\_, \_UPPER\_, \_UPPERBD, or \_HI\_.

---

## COEF Statement

**COEF** *variables* ;

The COEF list is used with the sparse input format of the CONDATA= data set. The COEF list can contain more than one SAS variable, each of which must have numeric values. If the COEF statement is not specified,

the **CONDATA=** data set is searched and SAS variables with names beginning with **\_COE** are used. The number of SAS variables in the **COEF** list must be no greater than the number of SAS variables in the **ROW** list.

The values of the **COEF** list variables in an observation can be interpreted differently than these variables' values in other observations. The values can be coefficients in the side constraints, costs and objective function coefficients, bound data, constraint type data, or rhs data. If the **COLUMN** list variable has a value that is a name of an arc or a nonarc variable, the  $i$ th **COEF** list variable is associated with the constraint or special row name named in the  $i$ th **ROW** list variable. Otherwise, the **COEF** list variables indicate type values, rhs values, or missing values.

When solving an LP, the values of the **COEF** list variables in an observation can be interpreted differently than these variables' values in other observations. The values can be coefficients in the constraints, objective function coefficients, bound data, constraint type data, or rhs data. If the **COLUMN** list variable has a value that is a name of an LP variable, the  $i$ th **COEF** list variable is associated with the constraint or special row name named in the  $i$ th **ROW** list variable. Otherwise, the **COEF** list variables indicate type values, rhs values, or missing values.

---

## COLUMN Statement

**COLUMN** *variable* ;

The **COLUMN** list is used with the **sparse** input format of the **CONDATA=** data set.

This list consists of one SAS variable in the **CONDATA=** data set that has as values the names of arc variables, nonarc variables, or missing values. When solving an LP, this list consists of one SAS variable in the **CONDATA=** data set that has as values the names of LP variables, or missing values. Some, if not all, of these values also can be values of the **NAME** list variables of the **ARCDATA=** data set. The **COLUMN** list variable can have other special values (Refer to the **TYPEOBS=** and **RHSOBS=** options). If the **COLUMN** list is not specified after the **PROC INTPOINT** statement, the **CONDATA=** data set is searched and a SAS variable named **\_COLUMN\_** is used. The **COLUMN** list variable must have character values.

---

## COST Statement

**COST** *variable* ;

**OBJFN** *variable* ;

The **COST** statement identifies the SAS variable in the **ARCDATA=** data set that contains the per unit flow cost through an arc. If an observation contains nonarc variable information, the value of the **COST** list variable is the objective function coefficient of the nonarc variable named in the **NAME** list variable in that observation.

If solving an LP, the **COST** statement identifies the SAS variable in the **ARCDATA=** data set that contains the per unit objective function coefficient of an LP variable named in the **NAME** list variable in that observation.

The **COST** list variable must have numeric values. It is not necessary to specify a **COST** statement if the name of the SAS variable is **\_COST\_** or **\_LENGTH\_**.

---

## DEMAND Statement

**DEMAND** *variable* ;

The DEMAND statement identifies the SAS variable in the **ARCDATA=** data set that contains the demand at the node named in the corresponding **HEADNODE** list variable. The DEMAND list variable must have numeric values. It is not necessary to have a DEMAND statement if the name of this SAS variable is **\_DEMAND\_**. See the section “Missing S Supply and Missing D Demand Values” on page 119 for cases when the SUPDEM list variable values can have other values. There should be no DEMAND statement if you are solving an LP.

---

## HEADNODE Statement

**HEADNODE** *variable* ;

**HEAD** *variable* ;

**TONODE** *variable* ;

**TO** *variable* ;

The HEADNODE statement specifies the SAS variable that must be present in the **ARCDATA=** data set that contains the names of nodes toward which arcs are directed. It is not necessary to have a HEADNODE statement if the name of the SAS variable is **\_HEAD\_** or **\_TO\_**. The HEADNODE variable must have character values.

There should be no HEAD statement if you are solving an LP.

---

## ID Statement

**ID** *variables* ;

The ID statement specifies SAS variables containing values for pre- and post-optimal processing and analysis. These variables are not processed by PROC INTPOINT but are read by the procedure and written in the **CONOUT=** data set. For example, imagine a network used to model a distribution system. The SAS variables listed on the ID statement can contain information on the type of vehicle, the transportation mode, the condition of the road, the time to complete the journey, the name of the driver, or other ancillary information useful for report writing or describing facets of the operation that do not have bearing on the optimization. The ID variables can be character, numeric, or both.

If no ID list is specified, the procedure forms an ID list of all SAS variables not included in any other implicit or explicit list specification. If the ID list is specified, any SAS variables in the **ARCDATA=** data set not in any list are dropped and do not appear in the **CONOUT=** data set.

---

## LO Statement

**LO** *variable* ;

**LOWERBD** *variable* ;

**MINFLOW** *variable* ;

The LO statement identifies the SAS variable in the **ARCDATA=** data set that contains the minimum feasible flow or lower flow bound for arcs in the network. If an observation contains nonarc variable information, the LO list variable has the value of the lower bound for the nonarc variable named in the **NAME** list variable. If solving an LP, the LO statement identifies the SAS variable in the **ARCDATA=** data set that contains the lower value bound for LP variables. The LO list variables must have numeric values. It is not necessary to have a LO statement if the name of this SAS variable is **\_LOWER\_**, **\_LO\_**, **\_LOWERBD**, or **\_MINFLOW**.

---

## NAME Statement

**NAME** *variable* ;

**ARCNAME** *variable* ;

**VARNAME** *variable* ;

Each arc and nonarc variable in an NPSC, or each variable in an LP, that has data in the **CONDATA=** data set must have a unique name. This variable is identified in the **ARCDATA=** data set. The NAME list variable must have character values (see the **NAMECTRL=** option in the **PROC INTPOINT** statement for more information). It is not necessary to have a NAME statement if the name of this SAS variable is **\_NAME\_**.

---

## NODE Statement

**NODE** *variable* ;

The NODE list variable, which must be present in the **NODEDATA=** data set, has names of nodes as values. These values must also be values of the **TAILNODE** list variable, the **HEADNODE** list variable, or both. If this list is not explicitly specified, the **NODEDATA=** data set is searched for a SAS variable with the name **\_NODE\_**. The NODE list variable must have character values.

---

## QUIT Statement

**QUIT** ;

The QUIT statement indicates that PROC INTPOINT is to stop immediately. The solution is not saved in the **CONOUT=** data set. The QUIT statement has no options.



---

## RHS Statement

**RHS** *variable* ;

The RHS variable list is used when the **dense** format of the **CONDATA=** data set is used. The values of the SAS variable specified in the RHS list are constraint right-hand-side values. If the RHS list is not specified, the **CONDATA=** data set is searched and a SAS variable with the name **\_RHS\_** is used. The RHS list variable must have numeric values. If there is no RHS list and no SAS variable named **\_RHS\_**, all constraints are assumed to have zero right-hand-side values.

---

## ROW Statement

**ROW** *variables* ;

The ROW list is used when either the **sparse** or the **dense** format of the **CONDATA=** data set is being used. SAS variables in the ROW list have values that are constraint or special row names. The SAS variables in the ROW list must have character values.

If the **dense** data format is used, there must be only one SAS variable in this list. In this case, if a ROW list is not specified, the **CONDATA=** data set is searched and the SAS variable with the name **\_ROW\_** or **\_CON\_** is used. If that search fails to find a suitable SAS variable, data for each constraint must reside in only one observation.

If the **sparse** data format is used and the ROW statement is not specified, the **CONDATA=** data set is searched and SAS variables with names beginning with **\_ROW** or **\_CON** are used. The number of SAS variables in the ROW list must not be less than the number of SAS variables in the **COEF** list. The *i*th ROW list variable is paired with the *i*th **COEF** list variable. If the number of ROW list variables is greater than the number of **COEF** list variables, the last ROW list variables have no **COEF** partner. These ROW list variables that have no corresponding **COEF** list variable are used in observations that have a **TYPE** list variable value. All ROW list variable values are tagged as having the type indicated. If there is no **TYPE** list variable, all ROW list variable values are constraint names.

---

## RUN Statement

**RUN** ;

The RUN statement causes optimization to be started. The RUN statement has no options. If PROC INTPOINT is called and is not terminated because of an error or a **QUIT** statement, and you have not used a RUN statement, a RUN statement is assumed implicitly as the last statement of PROC INTPOINT. Therefore, PROC INTPOINT reads that data, performs optimization, and saves the optimal solution in the **CONOUT=** data set.



---

## SUPDEM Statement

**SUPDEM** *variable* ;

The SAS variable in this list, which must be present in the **NODEDATA=** data set, contains supply and demand information for the nodes in the **NODE** list. A positive SUPDEM list variable value  $s$  ( $s > 0$ ) denotes that the node named in the **NODE** list variable can supply  $s$  units of flow. A negative SUPDEM list variable value  $-d$  ( $d > 0$ ) means that this node demands  $d$  units of flow. If a SAS variable is not explicitly specified, a SAS variable with the name **\_SUPDEM\_** or **\_SD\_** in the **NODEDATA=** data set is used as the SUPDEM variable. If a node is a transshipment node (neither a supply nor a demand node), an observation associated with this node need not be present in the **NODEDATA=** data set. If present, the SUPDEM list variable value must be zero or a missing value. See the section “[Missing S Supply and Missing D Demand Values](#)” on page 119 for cases when the SUPDEM list variable values can have other values.

---

## SUPPLY Statement

**SUPPLY** *variable* ;

The SUPPLY statement identifies the SAS variable in the **ARCDATA=** data set that contains the supply at the node named in that observation’s **TAILNODE** list variable. If a tail node does not supply flow, use zero or a missing value for the observation’s SUPPLY list variable value. If a tail node has supply capability, a missing value indicates that the supply quantity is given in another observation. It is not necessary to have a SUPPLY statement if the name of this SAS variable is **\_SUPPLY\_**. See the section “[Missing S Supply and Missing D Demand Values](#)” on page 119 for cases when the SUPDEM list variable values can have other values. There should be no SUPPLY statement if you are solving an LP.

---

## TAILNODE Statement

**TAILNODE** *variable* ;

**TAIL** *variable* ;

**FROMNODE** *variable* ;

**FROM** *variable* ;

The TAILNODE statement specifies the SAS variable that must (when solving an NPSC problem) be present in the **ARCDATA=** data set that has as values the names of tail nodes of arcs. The TAILNODE variable must have character values. It is not necessary to have a TAILNODE statement if the name of the SAS variable is **\_TAIL\_** or **\_FROM\_**. If the TAILNODE list variable value is missing, it is assumed that the observation of the **ARCDATA=** data set contains information concerning a nonarc variable. There should be no TAILNODE statement if you are solving an LP.

## TYPE Statement

**TYPE** *variable* ;

**CONTYPE** *variable* ;

The TYPE list, which is optional, names the SAS variable that has as values keywords that indicate either the constraint type for each constraint or the type of special rows in the **CONDATA=** data set. The values of the TYPE list variable also indicate, in each observation of the **CONDATA=** data set, how values of the **VAR** or **COEF** list variables are to be interpreted and how the type of each constraint or special row name is determined. If the TYPE list is not specified, the **CONDATA=** data set is searched and a SAS variable with the name **\_TYPE\_** is used. Valid keywords for the TYPE variable are given below. If there is no TYPE statement and no other method is used to furnish type information (see the **DEFCONTYPE=** option), all constraints are assumed to be of the type “less than or equal to” and no special rows are used. The TYPE list variable must have character values and can be used when the data in the **CONDATA=** data set is in either the **sparse** or the **dense** format. If the TYPE list variable value has a \* as its first character, the observation is ignored because it is a comment observation.

## TYPE List Variable Values

The following are valid TYPE list variable values. The letters in boldface denote the characters that PROC INTPOINT uses to determine what type the value suggests. You need to have at least these characters. In the following list, the minimal TYPE list variable values have additional characters to aid you in remembering these values.

|                  |  |
|------------------|--|
| <b>&lt;</b>      | less than or equal to ( $\leq$ )   |
| <b>=</b>         | equal to ( $=$ )   |
| <b>&gt;</b>      | greater than or equal to ( $\geq$ )  |
| <b>CAPAC</b>     | capacity   |
| <b>COST</b>      | cost   |
| <b>EQ</b>        | equal to   |
| <b>FREE</b>      | free row (used only for linear programs solved by interior point)              |
| <b>GE</b>        | greater than or equal to   |
| <b>LE</b>        | less than or equal to  |
| <b>LOWERBD</b>   | lower flow or value bound  |
| <b>LOWblank</b>  | lower flow or value bound  |
| <b>MAXIMIZE</b>  | maximize (opposite of cost)  |
| <b>MINIMIZE</b>  | minimize (same as cost)  |
| <b>OBJECTIVE</b> | objective function (same as cost)  |
| <b>RHS</b>       | rhs of constraint  |
| <b>TYPE</b>      | type of constraint   |
| <b>UPPCOST</b>   | reserved for future use  |
| <b>UNREST</b>    | unrestricted variable (used only for linear programs solved by interior point) |
| <b>UPPER</b>     | upper value bound or capacity; second letter must not be N                     |

The valid TYPE list variable values in function order are

- **LE** less than or equal to ( $\leq$ )
- **EQ** equal to ( $=$ )
- **GE** greater than or equal to ( $\geq$ )
- **COST**  
MINIMIZE  
MAXIMIZE  
OBJECTIVE  
cost or objective function coefficient
- **CAPAC**  
UPPER  
capacity or upper value bound
- **LOWERBD**  
**LOWblank**  
lower flow or value bound
- **RHS** rhs of constraint
- **TYPE** type of constraint

A TYPE list variable value that has the first character \* causes the observation to be treated as a comment. If the first character is a negative sign, then  $\leq$  is the type. If the first character is a zero, then  $=$  is the type. If the first character is a positive number, then  $\geq$  is the type.

---

## VAR Statement

**VAR** *variables* ;

The VAR variable list is used when the **dense** data format is used for the **CONDATA=** data set. The names of these SAS variables are also names of the arc and nonarc variables that have data in the **CONDATA=** data set. If solving an LP, the names of these SAS variables are also names of the LP variables. If no explicit VAR list is specified, all numeric SAS variables in the **CONDATA=** data set that are not in other SAS variable lists are put onto the VAR list. The VAR list variables must have numeric values. The values of the VAR list variables in some observations can be interpreted differently than in other observations. The values can be coefficients in the side constraints, costs and objective function coefficients, or bound data. When solving an LP, the values of the SAS variables in the VAR list can be constraint coefficients, objective function coefficients, or bound data. How these numeric values are interpreted depends on the value of each observation's **TYPE** or **ROW** list variable value. If there are no **TYPE** list variables, the VAR list variable values are all assumed to be side constraint coefficients.

## Details: INTPOINT Procedure

### Input Data Sets

PROC INTPOINT is designed so that there are as few rules as possible that you must obey when inputting a problem's data. Raw data are acceptable. This should cut the amount of processing required to groom the data before it is input to PROC INTPOINT. Data formats are so flexible that, due to space restrictions, all possible forms for a problem's data are not shown here. Try any reasonable form for your problem's data; it should be acceptable. PROC INTPOINT will outline its objections.

You can supply the same piece of data several ways. You do not have to restrict yourself to using any particular one. If you use several ways, PROC INTPOINT checks that the data are consistent each time that the data are encountered. After all input data sets have been read, data are merged so that the problem is described completely. The observations can be in any order.

### ARC DATA= Data Set

See the section “[Getting Started: NPSC Problems](#)” on page 61 and the section “[Introductory NPSC Example](#)” on page 62 for a description of this input data set.

**NOTE:** Information for an arc or nonarc variable can be specified in more than one observation. For example, consider an arc directed from node A toward node B that has a cost of 50, capacity of 100, and lower flow bound of 10 flow units. Some possible observations in the `ARC DATA=` data set are as follows:

| <code>_tail_</code> | <code>_head_</code> | <code>_cost_</code> | <code>_capac_</code> | <code>_lo_</code> |
|---------------------|---------------------|---------------------|----------------------|-------------------|
| A                   | B                   | 50                  | .                    | .                 |
| A                   | B                   | .                   | 100                  | .                 |
| A                   | B                   | .                   | .                    | 10                |
| A                   | B                   | 50                  | 100                  | .                 |
| A                   | B                   | .                   | 100                  | 10                |
| A                   | B                   | 50                  | .                    | 10                |
| A                   | B                   | 50                  | 100                  | 10                |

Similarly, for a nonarc variable that has an upper bound of 100, a lower bound of 10, and an objective function coefficient of 50, the `_TAIL_` and `_HEAD_` values are missing.

When solving an LP that has an LP variable named `my_var` with an upper bound of 100, a lower bound of 10, and an objective function coefficient of 50, some possible observations in the `ARC DATA=` data set are

| <code>_name_</code> | <code>_cost_</code> | <code>_capac_</code> | <code>_lo_</code> |
|---------------------|---------------------|----------------------|-------------------|
| <code>my_var</code> | 50                  | .                    | .                 |
| <code>my_var</code> | .                   | 100                  | .                 |
| <code>my_var</code> | .                   | .                    | 10                |
| <code>my_var</code> | 50                  | 100                  | .                 |
| <code>my_var</code> | .                   | 100                  | 10                |
| <code>my_var</code> | 50                  | .                    | 10                |
| <code>my_var</code> | 50                  | 100                  | 10                |

## CONDATA= Data Set

Regardless of whether the data in the **CONDATA=** data set is in the [sparse](#) or [dense](#) format, you will receive a warning if PROC INTPOINT finds a constraint row that has no coefficients. You will also be warned if any nonarc or LP variable has no constraint coefficients.

### Dense Input Format

If the dense format is used, most SAS variables in the **CONDATA=** data set belong to the **VAR** list. The names of the SAS variables belonging to this list have names of arc and nonarc variables or, if solving an LP, names of the LP variables. These names can be values of the SAS variables in the **ARCDATA=** data set that belong to the **NAME** list, or names of nonarc variables, or names in the form *tail\_head*, or any combination of these three forms. Names in the form *tail\_head* are default arc names, and if you use them, you must specify node names in the **ARCDATA=** data set (values of the **TAILNODE** and **HEADNODE** list variables).

The **CONDATA=** data set can have three other SAS variables belonging, respectively, to the **ROW**, the **TYPE**, and the **RHS** lists. The **CONDATA=** data set of the oil industry example in the section “[Introductory NPSC Example](#)” on page 62 uses the dense data format.

Consider the SAS code that creates a dense format **CONDATA=** data set that has data for three constraints. This data set was used in the section “[Introductory NPSC Example](#)” on page 62.

```
data cond1;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
-2   .   1   .   .   .   >=  -15
.  -2   .   .   1   .   GE   -15
.   .  -3   4   .   .   EQ    0
.   .   .   .  -3   4   =     0
;
```

You can use nonconstraint type values to furnish data on costs, capacities, lower flow bounds (and, if there are nonarc or LP variables, objective function coefficients and upper and lower bounds). You need not have such (or as much) data in the **ARCDATA=** data set. The first three observations in the following data set are examples of observations that provide cost, capacity, and lower bound data.

```
data cond1b;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
63 81 200   . 220   . cost   .
95 80 175 140 100 100 capac   .
20 10  50   .  35   . lo     .
-2   .   1   .   .   .   >=  -15
.  -2   .   .   1   .   GE   -15
.   .  -3   4   .   .   EQ    0
.   .   .   .  -3   4   =     0
;
```

If a **ROW** list variable is used, the data for a constraint can be spread over more than one observation. To illustrate, the data for the first constraint (which is called *con1*) and the cost and capacity data (in special rows called *costrow* and *caprow*, respectively) are spread over more than one observation in the following data set.

```

data cond1c;
  input _row_ $
        m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
costrow 63 . . . . . .
costrow . 81 200 . . . cost .
. . . . . 220 . cost .
caprow . . . . . . capac .
caprow 95 . 175 . 100 100 . .
caprow . 80 175 140 . . . .
lorow 20 10 50 . 35 . lo .
con1 -2 . 1 . . . . .
con1 . . . . . . >= -15
con2 . -2 . . 1 . GE -15
con3 . . -3 4 . . EQ 0
con4 . . . . -3 4 = 0
;

```

Using both **ROW** and **TYPE** lists, you can use special row names. Examples of these are `costrow` and `caprow` in the last data set. It should be restated that in any of the input data sets of PROC INTPOINT, the order of the observations does not matter. However, the **CONDATA=** data set can be read more quickly if PROC INTPOINT knows what type of constraint or special row a **ROW** list variable value is. For example, when the first observation is read, PROC INTPOINT does not know whether `costrow` is a constraint or special row and how to interpret the value 63 for the arc with the name `m_e_ref1`. When PROC INTPOINT reads the second observation, it learns that `costrow` has `cost` type and that the values 81 and 200 are costs. When the entire **CONDATA=** data set has been read, PROC INTPOINT knows the type of all special rows and constraints. Data that PROC INTPOINT had to set aside (such as the first observation 63 value and the `costrow` **ROW** list variable value, which at the time had unknown type, but is subsequently known to be a cost special row) is reprocessed. During this second pass, if a **ROW** list variable value has unassigned constraint or special row type, it is treated as a constraint with **DEFCONTYPE=** (or **DEFCONTYPE=** default) type. Associated **VAR** list variable values are coefficients of that constraint.

### Sparse Input Format

The side constraints usually become sparse as the problem size increases. When the sparse data format of the **CONDATA=** data set is used, only nonzero constraint coefficients must be specified. Remember to specify the **SPARSECONDATA** option in the PROC INTPOINT statement. With the sparse method of specifying constraint information, the names of arc and nonarc variables or, if solving an LP, the names of LP variables do not have to be valid SAS variable names.

A sparse format **CONDATA=** data set for the oil industry example in the section “[Introductory NPSC Example](#)” on page 62 is displayed below.

```

title 'Setting Up Condata = Cond2 for PROC INTPOINT';
data cond2;
  input _column_ $ _row1 $ _coef1 _row2 $ _coef2 ;
  datalines;
m_e_ref1 con1 -2 . .
m_e_ref2 con2 -2 . .
thruput1 con1 1 con3 -3
r1_gas . . con3 4

```

```

thruput2  con2    1  con4  -3
r2_gas    .      .  con4    4
_type_    con1    1  con2    1
_type_    con3    0  con4    0
_rhs_     con1 -15  con2 -15
;

```

Recall that the **COLUMN** list variable values `_type_` and `_rhs_` are the default values of the **TYPEOBS=** and **RHSOBS=** options. Also, the default rhs value of constraints (con3 and con4) is zero. The third to last observation has the value `_type_` for the **COLUMN** list variable. The `_ROW1` variable value is con1, and the `_COEF1_` variable has the value 1. This indicates that the constraint con1 is *greater than* or equal to type (because the value 1 is *greater than* zero). Similarly, the data in the second to last observation's `_ROW2` and `_COEF2` variables indicate that con2 is an *equality* constraint (0 *equals* zero).

An alternative, using a **TYPE** list variable, is

```

title 'Setting Up Condata = Cond3 for PROC INTPOINT';
data cond3;
  input _column_ $ _row1 $ _coef1 _row2 $ _coef2 _type_ $ ;
  datalines;
m_e_ref1  con1  -2      .      .  >=
m_e_ref2  con2  -2      .      .  .
thruput1  con1   1  con3  -3  .
r1_gas    .      .  con3   4  .
thruput2  con2   1  con4  -3  .
r2_gas    .      .  con4   4  .
.          con3   .  con4   .  eq
.          con1 -15  con2 -15  ge
;

```

If the **COLUMN** list variable is missing in a particular observation (the last 2 observations in the data set cond3, for instance), the constraints named in the **ROW** list variables all have the constraint type indicated by the value in the **TYPE** list variable. It is for this type of observation that you are allowed more **ROW** list variables than **COEF** list variables. If corresponding **COEF** list variables are not missing (for example, the last observation in the data set cond3), these values are the rhs values of those constraints. Therefore, you can specify both constraint type and rhs in the same observation.

As in the previous **CONDATA=** data set, if the **COLUMN** list variable is an arc or nonarc variable, the **COEF** list variable values are coefficient values for that arc or nonarc variable in the constraints indicated in the corresponding **ROW** list variables. If in this same observation the **TYPE** list variable contains a constraint type, all constraints named in the **ROW** list variables in that observation have this constraint type (for example, the first observation in the data set cond3). Therefore, you can specify both constraint type and coefficient information in the same observation.

Also note that **DEFCONTYPE=EQ** could have been specified, saving you from having to include in the data that con3 and con4 are of this type.

In the oil industry example, arc costs, capacities, and lower flow bounds are presented in the **ARCDATA=** data set. Alternatively, you could have used the following input data sets. The **arcd2** data set has only two SAS variables. For each arc, there is an observation in which the arc's tail and head node are specified.

```

title3 'Setting Up Arcdata = Arcd2 for PROC INTPOINT';
data arcd2;
    input _from_&$11. _to_&$15. ;
    datalines;
middle east refinery 1
middle east refinery 2
u.s.a. refinery 1
u.s.a. refinery 2
refinery 1 r1
refinery 2 r2
r1 ref1 gas
r1 ref1 diesel
r2 ref2 gas
r2 ref2 diesel
ref1 gas servstn1 gas
ref1 gas servstn2 gas
ref1 diesel servstn1 diesel
ref1 diesel servstn2 diesel
ref2 gas servstn1 gas
ref2 gas servstn2 gas
ref2 diesel servstn1 diesel
ref2 diesel servstn2 diesel
;

title 'Setting Up Condata = Cond4 for PROC INTPOINT';
data cond4;
    input _column_&$27. _row1_ $ _coef1 _row2_ $ _coef2 _type_ $ ;
    datalines;
. con1 -15 con2 -15 ge
. costrow . . cost
. . . caprow . capac
middle east_refinery 1 con1 -2 . .
middle east_refinery 2 con2 -2 . .
refinery 1_r1 con1 1 con3 -3
r1_ref1 gas . . con3 4 =
refinery 2_r2 con2 1 con4 -3
r2_ref2 gas . . con4 4 eq
middle east_refinery 1 costrow 63 caprow 95
middle east_refinery 2 costrow 81 caprow 80
u.s.a._refinery 1 costrow 55 . .
u.s.a._refinery 2 costrow 49 . .
refinery 1_r1 costrow 200 caprow 175
refinery 2_r2 costrow 220 caprow 100
r1_ref1 gas . . caprow 140
r1_ref1 diesel . . caprow 75
r2_ref2 gas . . caprow 100
r2_ref2 diesel . . caprow 75
ref1 gas_servstn1 gas costrow 15 caprow 70
ref1 gas_servstn2 gas costrow 22 caprow 60
ref1 diesel_servstn1 diesel costrow 18 . .
ref1 diesel_servstn2 diesel costrow 17 . .
ref2 gas_servstn1 gas costrow 17 caprow 35
ref2 gas_servstn2 gas costrow 31 . .

```



```

ref2 diesel_servstn1 diesel costrow 36      .      .      .
ref2 diesel_servstn2 diesel costrow 23      .      .      .
middle east_refinery 1      . 20      .      .      lo
middle east_refinery 2      . 10      .      .      lo
refinery 1_r1                . 50      .      .      lo
refinery 2_r2                . 35      .      .      lo
ref2 gas_servstn1 gas        . 5       .      .      lo
;

```

The first observation in the cond4 data set defines con1 and con2 as *greater than or equal to* ( $\geq$ ) constraints that both (by coincidence) have rhs values of -15. The second observation defines the special row costrow as a cost row. When costrow is a **ROW** list variable value, the associated **COEF** list variable value is interpreted as a cost or objective function coefficient. PROC INTPOINT has to do less work if constraint names and special rows are defined in observations near the top of a data set, but this is not a strict requirement. The fourth to ninth observations contain constraint coefficient data. Observations seven and nine have **TYPE** list variable values that indicate that constraints con3 and con4 are equality constraints. The last five observations contain lower flow bound data. Observations that have an arc or nonarc variable name in the **COLUMN** list variable, a nonconstraint type **TYPE** list variable value, and a value in (one of) the **COEF** list variables are valid.

The following data set is equivalent to the cond4 data set.

```

title 'Setting Up Condata = Cond5 for PROC INTPOINT';
data cond5;
  input _column_&$27. _row1 $ _coef1 _row2 $ _coef2 _type_ $ ;
  datalines;
middle east_refinery 1      con1 -2 costrow 63      .
middle east_refinery 2      con2 -2 lorow 10      .
refinery 1_r1                .      .      con3 -3      =
r1_ref1 gas                  caprow 140      con3 4      .
refinery 2_r2                con2 1      con4 -3      .
r2_ref2 gas                  .      .      con4 4      eq
.                             CON1 -15      CON2 -15      GE
ref2 diesel_servstn1 diesel  . 36 costrow . cost
.                             .      .      caprow . capac
.                             lorow .      .      .      lo
middle east_refinery 1      caprow 95      lorow 20      .
middle east_refinery 2      caprow 80 costrow 81      .
u.s.a._refinery 1          .      .      .      55      cost
u.s.a._refinery 2          costrow 49      .      .      .
refinery 1_r1                con1 1      caprow 175      .
refinery 1_r1                lorow 50 costrow 200      .
refinery 2_r2                costrow 220      caprow 100      .
refinery 2_r2                . 35      .      .      lo
r1_ref1 diesel              caprow2 75      .      .      capac
r2_ref2 gas                  .      .      caprow 100      .
r2_ref2 diesel              caprow2 75      .      .      .
ref1 gas_servstn1 gas        costrow 15      caprow 70      .
ref1 gas_servstn2 gas        caprow2 60 costrow 22      .
ref1 diesel_servstn1 diesel  .      .      costrow 18      .
ref1 diesel_servstn2 diesel  costrow 17      .      .      .
ref2 gas_servstn1 gas        costrow 17      lorow 5      .
ref2 gas_servstn1 gas        .      .      caprow2 35      .

```

```

ref2 gas_servstn2 gas          . 31          . . cost
ref2 diesel_servstn2 diesel    . . costrow 23      .
;

```

### Converting from an NPSC to an LP Problem

If you have data for a linear programming program that has an embedded network, the steps required to change that data into a form that is acceptable by PROC INTPOINT are

1. Identify the nodal flow conservation constraints. The coefficient matrix of these constraints (a submatrix of the LP's constraint coefficient matrix) has only two nonzero elements in each column, -1 and 1.
2. Assign a node to each nodal flow conservation constraint.
3. The rhs values of conservation constraints are the corresponding node's supplies and demands. Use this information to create the **NODEDATA=** data set.
4. Assign an arc to each column of the flow conservation constraint coefficient matrix. The arc is directed from the node associated with the row that has the 1 element in it and directed toward to the node associated with the row that has the -1 element in it. Set up the **ARCDATA=** data set that has two SAS variables. This data set could resemble **ARCDATA=arcd2**. These will eventually be the **TAILNODE** and **HEADNODE** list variables when PROC INTPOINT is used. Each observation consists of the tail and head node of each arc.
5. Remove from the data of the linear program all data concerning the nodal flow conservation constraints.
6. Put the remaining data into a **CONDATA=** data set. This data set will probably resemble **CONDATA=cond4** or **CONDATA=cond5**.

### The Sparse Format Summary

The following list illustrates possible **CONDATA=** data set observation sparse formats. a1, b1, b2, b3 and c1 have as a **\_COLUMN\_** variable value either the name of an arc (possibly in the form *tail\_head*) or the name of a nonarc variable (if you are solving an NPSC), or the name of the LP variable (if you are solving an LP). These are collectively referred to as variable in the tables that follow.

- If there is no **TYPE** list variable in the **CONDATA=** data set, the problem must be constrained and there is no nonconstraint data in the **CONDATA=** data set:

|    | <b>_COLUMN_</b>                                 | <b>_ROWx_</b> | <b>_COEFx_</b> | <b>_ROWy_</b><br>(no <b>_COEFy_</b> )<br>(may not be<br>in CONDATA) |
|----|---|---------------|----------------|---|
| a1 | variable  | constraint    | lhs coef       | +-----+   |
| a2 | <b>_TYPE_</b> or<br><b>TYPEOBS=</b>             | constraint    | -1 0 1         |   |
| a3 | <b>_RHS_</b> or<br><b>RHSOBS=</b> or<br>missing | constraint    | rhs value      | constraint  <br>  or  <br>  missing                                 |
| a4 | <b>_TYPE_</b> or<br><b>TYPEOBS=</b>             | constraint    | missing        |   |
| a5 | <b>_RHS_</b> or<br><b>RHSOBS=</b> or<br>missing | constraint    | missing        | <br>+-----+   |

Observations of the form a4 and a5 serve no useful purpose but are still allowed to make problem generation easier.

- If there are no **ROW** list variables in the data set, the problem has no constraints and the information is nonconstraint data. There must be a **TYPE** list variable and only one **COEF** list variable in this case. The **COLUMN** list variable has as values the names of arcs or nonarc variables and must not have missing values or special row names as values:

|    | <b>_COLUMN_</b> | <b>_TYPE_</b> | <b>_COEFx_</b> |
|----|-----------------|---------------|----------------|
| b1 | variable        | UPPERBD       | capacity       |
| b2 | variable        | LOWERBD       | lower flow     |
| b3 | variable        | COST          | cost           |

- Using a **TYPE** list variable for constraint data implies the following:

|    | <b>_COLUMN_</b>                          | <b>_TYPE_</b> | <b>_ROWx_</b> | <b>_COEFx_</b> | <b>_ROWy_</b><br>(no <b>_COEFy_</b> )<br>(may not be<br>in CONDATA) |
|----|--|---------------|---------------|----------------|---|
| c1 | variable                                 | missing       | +-----+       | lhs coef       | +-----+   |
| c2 | <b>_TYPE_</b> or<br>TYPEOBS=             | missing       | c             | -1 0 1         |   |
|    |  |               | o             |                |   |
| c3 | <b>_RHS_</b> or<br>missing<br>or RHSOBS= | missing       | n             | rhs value      | constraint  |
|    |  |               | s             |                | or  |
|    |  |               | t             |                | missing   |
| c4 | variable                                 | con type      | r             | lhs coef       |   |
| c5 | <b>_RHS_</b> or<br>missing<br>or RHSOBS= | con type      | a             | rhs value      |   |
|    |  |               | i             |                |   |
|    |  |               | n             |                |   |
| c6 | missing                                  | TYPE          | t             | -1 0 1         |   |
| c7 | missing                                  | RHS           | +-----+       | rhs value      | +-----+   |

If the observation is in form c4 or c5, and the **\_COEFx\_** values are missing, the constraint is assigned the type data specified in the **\_TYPE\_** variable.

- Using a **TYPE** list variable for arc and nonarc variable data implies the following:

|    | <b>_COLUMN_</b> | <b>_TYPE_</b> | <b>_ROWx_</b> | <b>_COEFx_</b> | <b>_ROWy_</b><br>(no <b>_COEFy_</b> )<br>(may not be<br>in CONDATA) |
|----|-----------------|---------------|---------------|----------------|---|
| d1 | variable        | UPPERBD       | missing       | capacity       | missing   |
| d2 | variable        | LOWERBD       | or            | lowerflow      | or  |
| d3 | variable        | COST          | special       | cost           | special   |
|    |                 |               | row           |                | row   |
|    |                 |               | name          |                | name  |
|    |                 |               | +-----+       |                |   |
| d4 | missing         |               | special       |                |   |
|    |                 |               | row           |                |   |
|    |                 |               | name          |                |   |
|    |                 |               | +-----+       |                | +-----+   |
| d5 | variable        | missing       |               | value that     | missing   |

```

|           |is interpreted
|           |according to
+-----+  _ROWx_

```

The observations of the form d1 to d5 can have **ROW** list variable values. Observation d4 must have **ROW** list variable values. The **ROW** value is put into the ROW name tree so that when dealing with observation d4 or d5, the **COEF** list variable value is interpreted according to the type of **ROW** list variable value. For example, the following three observations define the **\_ROWx\_** variable values **up\_row**, **lo\_row**, and **co\_row** as being an upper value bound row, lower value bound row, and cost row, respectively:

| <b>_COLUMN_</b> | <b>_TYPE_</b> | <b>_ROWx_</b> | <b>_COEFx_</b> |
|-----------------|---------------|---------------|----------------|
| .               | UPPERBD       | up_row        | .              |
| variable_a      | LOWERBD       | lo_row        | lower flow     |
| variable_b      | COST          | co_row        | cost           |

PROC INTPOINT is now able to correctly interpret the following observation:

| <b>_COLUMN_</b> | <b>_TYPE_</b> | <b>_ROW1_</b> | <b>_COEF1_</b> | <b>_ROW2_</b> | <b>_COEF2_</b> | <b>_ROW3_</b> | <b>_COEF3_</b> |
|-----------------|---------------|---------------|----------------|---------------|----------------|---------------|----------------|
| var_c           | .             | up_row        | upval          | lo_row        | loval          | co_row        | cost           |

If the **TYPE** list variable value is a constraint type and the value of the **COLUMN** list variable equals the value of the **TYPEOBS=** option or the default value **\_TYPE\_**, the **TYPE** list variable value is ignored.

## NODEDATA= Data Set

See the section “Getting Started: NPSC Problems” on page 61 and the section “Introductory NPSC Example” on page 62 for a description of this input data set.

---

## Output Data Sets

For NPSC problems, the procedure determines the flow that should pass through each arc as well as the value that should be assigned to each nonarc variable. The goal is that the minimum flow bounds, capacities, lower and upper value bounds, and side constraints are not violated. This goal is reached when total cost incurred by such a flow pattern and value assignment is feasible and optimal. The solution found must also conserve flow at each node.

For LP problems, the procedure determines the value that should be assigned to each variable. The goal is that the lower and upper value bounds and the constraints are not violated. This goal is reached when the total cost incurred by such a value assignment is feasible and optimal.

The **CONOUT=** data set can be produced and contains a solution obtained after performing optimization.

## CONOUT= Data Set

The variables in the **CONOUT=** data set depend on whether or not the problem has a network component. If the problem has a network component, the variables and their possible values in an observation are as follows:

|                 |   |
|-----------------|---|
| <b>_FROM_</b>   | a tail node of an arc. This is a missing value if an observation has information about a nonarc variable.                                     |
| <b>_TO_</b>     | a head node of an arc. This is a missing value if an observation has information about a nonarc variable.                                     |
| <b>_COST_</b>   | the cost of an arc or the objective function coefficient of a nonarc variable   |
| <b>_CAPAC_</b>  | the capacity of an arc or upper value bound of a nonarc variable  |
| <b>_LO_</b>     | the lower flow bound of an arc or lower value bound of a nonarc variable  |
| <b>_NAME_</b>   | a name of an arc or nonarc variable   |
| <b>_SUPPLY_</b> | the supply of the tail node of the arc in the observation. This is a missing value if an observation has information about a nonarc variable. |
| <b>_DEMAND_</b> | the demand of the head node of the arc in the observation. This is a missing value if an observation has information about a nonarc variable. |
| <b>_FLOW_</b>   | the flow through the arc or value of the nonarc variable  |
| <b>_FCOST_</b>  | flow cost, the product of <b>_COST_</b> and <b>_FLOW_</b>   |
| <b>_RCOST_</b>  | the reduced cost of the arc or nonarc variable  |
| <b>_ANUMB_</b>  | the number of the arc (positive) or nonarc variable (nonpositive); used for warm starting PROC NETFLOW  |
| <b>_TNUMB_</b>  | the number of the tail node in the network basis spanning tree; used for warm starting PROC NETFLOW   |
| <b>_STATUS_</b> | the status of the arc or nonarc variable  |

If the problem does not have a network component, the variables and their possible values in an observation are as follows:

|                 |  |
|-----------------|--|
| <b>_OBJFN_</b>  | the objective function coefficient of a variable   |
| <b>_UPPERBD</b> | the upper value bound of a variable  |
| <b>_LOWERBD</b> | the lower value bound of a variable  |
| <b>_NAME_</b>   | the name of a variable   |
| <b>_VALUE_</b>  | the value of the variable  |
| <b>_FCOST_</b>  | objective function value for that variable; the product of <b>_OBJFN_</b> and <b>_VALUE_</b> |

The variables present in the **ARCDATA=** data set are present in a **CONOUT=** data set. For example, if there is a variable called **tail** in the **ARCDATA=** data set and you specified the SAS variable list

```
from tail;
```

then tail is a variable in the **CONOUT=** data sets instead of **\_FROM\_**. Any **ID** list variables also appear in the **CONOUT=** data sets.

## MPSOUT= Data Set

The **MPSOUT=** data set contains problem data converted from a PROC INTPOINT format into an MPS-format SAS data set. The six fields, FIELD1 to FIELD6, in the **MPSOUT=** data set correspond to the six columns in MPS standard. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*).

---

## Converting Any PROC INTPOINT Format to an MPS-Format SAS Data Set

The **MPSOUT=** option enables you to convert an input data set for the INTPOINT procedure into an MPS-format SAS data set. The converted data set is readable by the OPTLP procedure.

The conversion can handle linear programs and network flow formulations. If you specify a network flow formulation, it will be converted into an equivalent linear program. When multiple objective row names are present, rows with the name encountered first are combined into the objective row. The remaining rows are marked as free rows.

For information about how the contents of the MPS-format SAS data set are interpreted, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*). For examples that demonstrate the use of the **MPSOUT=** option and migration to the OPTMODEL procedure, see the section “Examples: INTPOINT Procedure” on page 132.

---

## Case Sensitivity

Whenever the INTPOINT procedure has to compare character strings, whether they are node names, arc names, nonarc names, LP variable names, or constraint names, if the two strings have different lengths, or on a character by character basis the character is different *or has different cases*, PROC INTPOINT judges the character strings to be different.

Not only is this rule enforced when one or both character strings are obtained as values of SAS variables in PROC INTPOINT’s input data sets, it also should be obeyed if one or both character strings were originally SAS variable names, or were obtained as the values of options or statements parsed to PROC INTPOINT. For example, if the network has only one node that has supply capability, or if you are solving a **MAXFLOW** or **SHORTPATH** problem, you can indicate that node using the **SOURCE=** option. If you specify

```
proc intpoint source=NotableNode
```

then PROC INTPOINT looks for a value of the **TAILNODE** list variable that is NotableNode.

Version 6 of the SAS System converts text that makes up statements into uppercase. The name of the node searched for would be NOTABLENODE, even if this was your SAS code:

```
proc intpoint source=NotableNode
```

If you want PROC INTPOINT to behave as it did in Version 6, specify

```
options validvarname=v6;
```

If the [SPARSECONDATA](#) option is not specified, and you are running SAS software Version 6, or you are running SAS software Version 7 onward and have specified

```
options validvarname=v6;
```

all values of the SAS variables that belong to the [NAME](#) list are uppercased. This is because the SAS System has uppercased all SAS variable names, particularly those in the [VAR](#) list of the [CONDATA=](#) data set.

Entities that contain blanks must be enclosed in quotes.

---

## Loop Arcs

Loop arcs (which are arcs directed toward nodes from which they originate) are prohibited. Rather, introduce a dummy intermediate node in loop arcs. For example, replace arc (A,A) with (A,B) and (B,A); B is the name of a new node, and it must be distinct for each loop arc.

---

## Multiple Arcs

Multiple arcs with the same tail and head nodes are prohibited. PROC INTPOINT checks to ensure there are no such arcs before proceeding with the optimization. Introduce a new dummy intermediate node in multiple arcs. This node must be distinct for each multiple arc. For example, if some network has three arcs directed from node A toward node B, then replace one of these three with arcs (A,C) and (C,B) and replace another one with (A,D) and (D,B). C and D are new nodes added to the network.

---

## Flow and Value Bounds

The capacity and lower flow bound of an arc can be equal. Negative arc capacities and lower flow bounds are permitted. If both arc capacities and lower flow bounds are negative, the lower flow bound must be at least as negative as the capacity. An arc (A,B) that has a negative flow of  $-f$  units can be interpreted as an arc that conveys  $f$  units of flow from node B to node A.

The upper and lower value bound of a nonarc variable can be equal. Negative upper and lower bounds are permitted. If both are negative, the lower bound must be at least as negative as the upper bound.

When solving an LP, the upper and lower value bounds of an LP variable can be equal. Negative upper and lower bounds are permitted. If both are negative, the lower bound must be at least as negative as the upper bound.

In short, for any problem to be feasible, a lower bound must be  $\leq$  the associated upper bound.

---

## Tightening Bounds and Side Constraints

If any piece of data is furnished to PROC INTPOINT more than once, PROC INTPOINT checks for consistency so that no conflict exists concerning the data values. For example, if the cost of some arc is seen to be one value and as more data are read, the cost of the same arc is seen to be another value, PROC INTPOINT issues an error message on the SAS log and stops. There are two exceptions to this:

- The bounds of arcs and nonarc variables, or the bounds of LP variables, are made as tight as possible. If several different values are given for the lower flow bound of an arc, the greatest value is used. If several different values are given for the lower bound of a nonarc or LP variable, the greatest value is used. If several different values are given for the capacity of an arc, the smallest value is used. If several different values are given for the upper bound of a nonarc or LP variable, the smallest value is used.
- Several values can be given for inequality constraint right-hand sides. For a particular constraint, the lowest rhs value is used for the rhs if the constraint is of *less than or equal to* type. For a particular constraint, the greatest rhs value is used for the rhs if the constraint is of *greater than or equal to* type.

---

## Reasons for Infeasibility

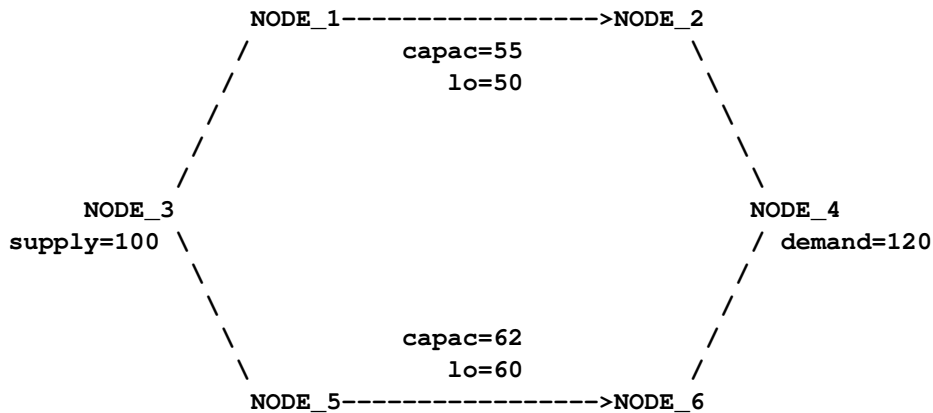
Before optimization commences, PROC INTPOINT tests to ensure that the problem is not infeasible by ensuring that, with respect to supplies, demands, and arc flow bounds, flow conservation can be obeyed at each node:

- Let  $IN$  be the sum of lower flow bounds of arcs directed toward a node plus the node's supply. Let  $OUT$  be the sum of capacities of arcs directed from that node plus the node's demand. If  $IN$  exceeds  $OUT$ , not enough flow can leave the node.
- Let  $OUT$  be the sum of lower flow bounds of arcs directed from a node plus the node's demand. Let  $IN$  be the total capacity of arcs directed toward the node plus the node's supply. If  $OUT$  exceeds  $IN$ , not enough flow can arrive at the node.

Reasons why a network problem can be infeasible are similar to those previously mentioned but apply to a set of nodes rather than for an individual node.

Consider the network illustrated in [Figure 5.10](#).



**Figure 5.10** An Infeasible Network

The demand of NODE\_4 is 120. That can never be satisfied because the maximal flow through arcs (NODE\_1, NODE\_2) and (NODE\_5, NODE\_6) is 117. More specifically, the implicit supply of NODE\_2 and NODE\_6 is only 117, which is insufficient to satisfy the demand of other nodes (real or implicit) in the network.

Furthermore, the lower flow bounds of arcs (NODE\_1, NODE\_2) and (NODE\_5, NODE\_6) are greater than the flow that can reach the tail nodes of these arcs, that, by coincidence, is the total supply of the network. The implicit demand of nodes NODE\_1 and NODE\_5 is 110, which is greater than the amount of flow that can reach these nodes.

## Missing S Supply and Missing D Demand Values

In some models, you may want a node to be either a supply or demand node but you want the node to supply or demand the optimal number of flow units. To indicate that a node is such a supply node, use a missing S value in the **SUPPLY** list variable in the **ARCDATA=** data set or the **SUPDEM** list variable in the **NODEDATA=** data set. To indicate that a node is such a demand node, use a missing D value in the **DEMAND** list variable in the **ARCDATA=** data set or the **SUPDEM** list variable in the **NODEDATA=** data set.

Suppose the oil example in the section “Introductory NPSC Example” on page 62 is changed so that crude oil can be obtained from either the Middle East or U.S.A. in any amounts. You should specify that the node middle east is a supply node, but you do not want to stipulate that it supplies 100 units, as before. The node u.s.a. should also remain a supply node, but you do not want to stipulate that it supplies 80 units. You must specify that these nodes have missing S supply capabilities:

```

title 'Oil Industry Example';
title3 'Crude Oil can come from anywhere';
data miss_s;
  missing S;
  input _node_&$15. _sd_;
  datalines;
middle east          S
u.s.a.               S
servstn1 gas         -95
servstn1 diesel      -30
servstn2 gas         -40
  
```

```
servstn2 diesel    -15
;
```

The following PROC INTPOINT run uses the same ARCDATA= and CONDATA= data sets used in the section “[Introductory NPSC Example](#)” on page 62:

```
proc intpoint
  bytes=100000
  nodedata=miss_s      /* the supply (missing S) and */
                      /* demand data          */
  arcdata=arcd1        /* the arc descriptions      */
  condata=cond1        /* the side constraints      */
  conout=solution;     /* the solution data set    */
run;

proc print;
  var _from_ _to_ _cost_ _capac_ _lo_ _flow_ _fcost_;
  sum _fcost_;
run;
```

The following messages appear on the SAS log:

```
NOTE: Number of nodes= 14 .
NOTE: All supply nodes have unspecified (.S) supply capability. Number of these
      nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 0 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of side constraint coefficients= 8 .
NOTE: The following messages relate to the equivalent Linear Programming
      problem solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 17 .
NOTE: Number of >= constraints= 2 .
NOTE: Number of constraint coefficients= 48 .
NOTE: Number of variables= 20 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 5.
NOTE: After preprocessing, number of >= constraints= 2.
NOTE: The preprocessor eliminated 12 constraints from the problem.
NOTE: The preprocessor eliminated 33 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 6.
NOTE: The preprocessor eliminated 14 variables from the problem.
NOTE: 6 columns, 0 rows and 6 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 19 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 7 factor nodes make up 2 supernodes
NOTE: There are 4 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
NOTE: Bound feasibility attained by iteration 1.
NOTE: Dual feasibility attained by iteration 1.
NOTE: Constraint feasibility attained by iteration 1.
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 6
      iterations.
NOTE: Optimum reached.
NOTE: Objective= 50075.
NOTE: The data set WORK.SOLUTION has 18 observations and 10 variables.
NOTE: There were 18 observations read from the data set WORK.ARC1.
NOTE: There were 6 observations read from the data set WORK.MISS_S.
NOTE: There were 4 observations read from the data set WORK.COND1.
```

The CONOUT= data set is shown in Figure 5.11.

**Figure 5.11** Missing S SUPDEM Values in NODEDATA

| Oil Industry Example             |             |                 |        |          |      |         |          |
|----------------------------------|-------------|-----------------|--------|----------|------|---------|----------|
| Crude Oil can come from anywhere |             |                 |        |          |      |         |          |
| Obs                              | _from_      | _to_            | _cost_ | _capac_  | _lo_ | _FLOW_  | _FCOST_  |
| 1                                | refinery 1  | r1              | 200    | 175      | 50   | 145.000 | 29000.00 |
| 2                                | refinery 2  | r2              | 220    | 100      | 35   | 35.000  | 7700.00  |
| 3                                | r1          | ref1 diesel     | 0      | 75       | 0    | 36.250  | 0.00     |
| 4                                | r1          | ref1 gas        | 0      | 140      | 0    | 108.750 | 0.00     |
| 5                                | r2          | ref2 diesel     | 0      | 75       | 0    | 8.750   | 0.00     |
| 6                                | r2          | ref2 gas        | 0      | 100      | 0    | 26.250  | 0.00     |
| 7                                | middle east | refinery 1      | 63     | 95       | 20   | 20.000  | 1260.00  |
| 8                                | u.s.a.      | refinery 1      | 55     | 99999999 | 0    | 125.000 | 6875.00  |
| 9                                | middle east | refinery 2      | 81     | 80       | 10   | 10.000  | 810.00   |
| 10                               | u.s.a.      | refinery 2      | 49     | 99999999 | 0    | 25.000  | 1225.00  |
| 11                               | ref1 diesel | servstn1 diesel | 18     | 99999999 | 0    | 30.000  | 540.00   |
| 12                               | ref2 diesel | servstn1 diesel | 36     | 99999999 | 0    | 0.000   | 0.00     |
| 13                               | ref1 gas    | servstn1 gas    | 15     | 70       | 0    | 68.750  | 1031.25  |
| 14                               | ref2 gas    | servstn1 gas    | 17     | 35       | 5    | 26.250  | 446.25   |
| 15                               | ref1 diesel | servstn2 diesel | 17     | 99999999 | 0    | 6.250   | 106.25   |
| 16                               | ref2 diesel | servstn2 diesel | 23     | 99999999 | 0    | 8.750   | 201.25   |
| 17                               | ref1 gas    | servstn2 gas    | 22     | 60       | 0    | 40.000  | 880.00   |
| 18                               | ref2 gas    | servstn2 gas    | 31     | 99999999 | 0    | 0.000   | 0.00     |
|                                  |             |                 |        |          |      |         | =====    |
|                                  |             |                 |        |          |      |         | 50075.00 |

The optimal supplies of nodes middle east and u.s.a. are 30 and 150 units, respectively. For this example, the same optimal solution is obtained if these nodes had supplies less than these values (each supplies 1 unit, for example) and the **THRUNET** option was specified in the **PROC INTPOINT** statement. With the **THRUNET** option active, when total supply exceeds total demand, the specified nonmissing demand values are the lowest number of flow units that must be absorbed by the corresponding node. This is demonstrated in the following PROC INTPOINT run. The missing S is most useful when nodes are to supply optimal numbers of flow units and it turns out that for some nodes, the optimal supply is 0.

```
data miss_s_x;
  missing S;
  input  _node_&$15. _sd_;
  datalines;
middle east      1
u.s.a.           1
servstn1 gas     -95
servstn1 diesel -30
servstn2 gas     -40
servstn2 diesel -15
;

proc intpoint
  bytes=100000
```

```

thrunet
nodedata=miss_s_x      /* No supply (missing S)      */
arcdata=arcd1          /* the arc descriptions      */
condata=cond1          /* the side constraints      */
conout=solution;       /* the solution data set    */
run;

proc print;
var _from _to _cost _capac _lo _flow _fcost_;
sum _fcost_;
run;

```

The following messages appear on the SAS log. Note that the Total supply= 2, not 0 as in the last run:

```

NOTE: Number of nodes= 14 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 2 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of side constraint coefficients= 8 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 17 .
NOTE: Number of >= constraints= 2 .
NOTE: Number of constraint coefficients= 48 .
NOTE: Number of variables= 20 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 5.
NOTE: After preprocessing, number of >= constraints= 2.
NOTE: The preprocessor eliminated 12 constraints from the problem.
NOTE: The preprocessor eliminated 33 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 6.
NOTE: The preprocessor eliminated 14 variables from the problem.
NOTE: 6 columns, 0 rows and 6 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 19 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 7 factor nodes make up 2 supernodes
NOTE: There are 4 nonzero sub-rows or sub-columns outside the supernodal triangular
      regions along the factors leading diagonal.
NOTE: Bound feasibility attained by iteration 1.
NOTE: Dual feasibility attained by iteration 1.
NOTE: Constraint feasibility attained by iteration 1.
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 6
      iterations.
NOTE: Optimum reached.
NOTE: Objective= 50075.
NOTE: The data set WORK.SOLUTION has 18 observations and 10 variables.
NOTE: There were 18 observations read from the data set WORK.ARC1.
NOTE: There were 6 observations read from the data set WORK.MISS_S_X.
NOTE: There were 4 observations read from the data set WORK.COND1.

```

If total supply exceeds total demand, any missing S values are ignored. If total demand exceeds total supply, any missing D values are ignored.

## Balancing Total Supply and Total Demand

### When Total Supply Exceeds Total Demand

When total supply of a network problem exceeds total demand, PROC INTPOINT adds an extra node (called the *excess node*) to the problem and sets the demand at that node equal to the difference between total supply and total demand. There are three ways that this excess node can be joined to the network. All three ways entail PROC INTPOINT generating a set of arcs (henceforth referred to as the *generated arcs*) that are directed toward the excess node. The total amount of flow in generated arcs equals the demand of the excess node. The generated arcs originate from one of three sets of nodes.

When you specify the **THRUNET** option, the set of nodes that generated arcs originate from are all demand nodes, even those demand nodes with unspecified demand capability. You indicate that a node has unspecified demand capability by using a missing D value instead of an actual value for demand data (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 119). The value specified as the demand of a demand node is in effect a lower bound of the number of flow units that node can actually demand. For missing D demand nodes, this lower bound is zero.

If you do not specify the **THRUNET** option, the way in which the excess node is joined to the network depends on whether there are demand nodes with unspecified demand capability (nodes with missing D demand) or not.

If there are missing D demand nodes, these nodes are the set of nodes that generated arcs originate from. The value specified as the demand of a demand node, if not missing D, is the number of flow units that node can actually demand. For a missing D demand node, the actual demand of that node may be zero or greater.

If there are no missing D demand nodes, the set of nodes that generated arcs originate from are the set of supply nodes. The value specified as the supply of a supply node is in effect an upper bound of the number of flow units that node can actually supply. For missing S supply nodes (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 119), this upper bound is zero, so missing S nodes when total supply exceeds total demand are transshipment nodes, that is, nodes that neither supply nor demand flow.

### When Total Supply Is Less Than Total Demand

When total supply of a network problem is less than total demand, PROC INTPOINT adds an extra node (called the *excess node*) to the problem and sets the supply at that node equal to the difference between total demand and total supply. There are three ways that this excess node can be joined to the network. All three ways entail PROC INTPOINT generating a set of arcs (henceforth referred to as the *generated arcs*) that originate from the excess node. The total amount of flow in generated arcs equals the supply of the excess node. The generated arcs are directed toward one of three sets of nodes.

When you specify the **THRUNET** option, the set of nodes that generated arcs are directed toward are all supply nodes, even those supply nodes with unspecified supply capability. You indicate that a node has unspecified supply capability by using a missing S value instead of an actual value for supply data (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 119). The value specified as the

supply of a supply node is in effect a lower bound of the number of flow units that the node can actually supply. For missing S supply nodes, this lower bound is zero.

If you do not specify the **THRUNET** option, the way in which the excess node is joined to the network depends on whether there are supply nodes with unspecified supply capability (nodes with missing S supply) or not.

If there are missing S supply nodes, these nodes are the set of nodes that generated arcs are directed toward. The value specified as the supply of a supply node, if not missing S, is the number of flow units that the node can actually supply. For a missing S supply node, the actual supply of that node may be zero or greater.

If there are no missing S supply nodes, the set of nodes that generated arcs are directed toward are the set of demand nodes. The value specified as the demand of a demand node is in effect an upper bound of the number of flow units that node can actually demand. For missing D demand nodes (discussed in the section “Missing S Supply and Missing D Demand Values” on page 119), this upper bound is zero, so missing D nodes when total supply is less than total demand are transshipment nodes, that is, nodes that neither supply nor demand flow.

---

## How to Make the Data Read of PROC INTPOINT More Efficient

This section contains information that is useful when you want to solve large constrained network problems. However, much of this information is also useful if you have a large linear programming problem. All of the options described in this section that are not directly applicable to networks (options such as **ARCS\_ONLY\_ARCDATA**, **ARC\_SINGLE\_OBS**, **NNODES=**, and **NARCS=**) can be specified to improve the speed at which LP data are read.

### Large Constrained Network Problems

Many of the models presented to PROC INTPOINT are enormous. They can be considered large by linear programming standards; problems with thousands, even millions, of variables and constraints. When dealing with side constrained network programming problems, models can have not only a linear programming component of that magnitude, but also a larger, possibly *much* larger, network component.

The majority of network problem’s decision variables are arcs. Like an LP decision variable, an arc has an objective function coefficient, upper and lower value bounds, and a name. Arcs can have coefficients in constraints. Therefore, an arc is quite similar to an LP variable and places the same memory demands on optimization software as an LP variable. But a typical network model has many more arcs and nonarc variables than the typical LP model has variables. And arcs have tail and head nodes. Storing and processing node names require huge amounts of memory. To make matters worse, node names occupy memory at times when a large amount of other data should also reside in memory.

While memory requirements are lower for a model with embedded network component compared with the equivalent LP *once optimization starts*, the same is usually not true *during the data read*. Even though nodal flow conservation constraints in the LP should not be specified in the constrained network formulation, the memory requirements to read the latter are greater because each arc (unlike an LP variable) originates at one node and is directed toward another.

## Paging

PROC INTPOINT has facilities to read data when the available memory is insufficient to store all the data at once. PROC INTPOINT does this by allocating memory for different purposes; for example, to store an array or receive data read from an input SAS data set. After that memory has filled, the information is written to disk and PROC INTPOINT can resume filling that memory with new information. Often, information must be retrieved from disk so that data previously read can be examined or checked for consistency. Sometimes, to prevent any data from being lost, or to retain any changes made to the information in memory, the contents of the memory must be sent to disk before other information can take its place. This process of swapping information to and from disk is called paging. Paging can be very time-consuming, so it is crucial to minimize the amount of paging performed.

There are several steps you can take to make PROC INTPOINT read the data of network and linear programming models more efficiently, particularly when memory is scarce and the amount of paging must be reduced. PROC INTPOINT will then be able to tackle large problems in what can be considered reasonable amounts of time.

## The Order of Observations

PROC INTPOINT is quite flexible in the ways data can be supplied to it. Data can be given by any reasonable means. PROC INTPOINT has convenient defaults that can save you work when generating the data. There can be several ways to supply the same piece of data, and some pieces of data can be given more than once. PROC INTPOINT reads everything, then merges it all together. However, this flexibility and convenience come at a price; PROC INTPOINT may not assume the data has a characteristic that, if possessed by the data, could save time and memory during the data read. Several options can indicate that the data has some exploitable characteristic.

For example, an arc cost can be specified once or several times in the `ARC DATA=` data set or the `CON DATA=` data set, or both. Every time it is given in the `ARC DATA=` data set, a check is made to ensure that the new value is the same as any corresponding value read in a previous observation of the `ARC DATA=` data set. Every time it is given in the `CON DATA=` data set, a check is made to ensure that the new value is the same as the value read in a previous observation of the `CON DATA=` data set, or previously in the `ARC DATA=` data set. PROC INTPOINT would save time if it knew that arc cost data would be encountered only once while reading the `ARC DATA=` data set, so performing the time-consuming check for consistency would not be necessary. Also, if you indicate that the `CON DATA=` data set contains data for constraints only, PROC INTPOINT will not expect any arc information, so memory will not be allocated to receive such data while reading the `CON DATA=` data set. This memory is used for other purposes and this might lead to a reduction in paging. If applicable, use the `ARC_SINGLE_OBS` or the `CON_SINGLE_OBS` option, or both, and the `NON_REPLIC=COEFS` specification to improve how the `ARC DATA=` data set and the `CON DATA=` data set are read.

PROC INTPOINT allows the observations in input data sets to be in any order. However, major time savings can result if you are prepared to order observations in particular ways. Time spent by the SORT procedure to sort the input data sets, particularly the `CON DATA=` data set, may be more than made up for when PROC INTPOINT reads them, because PROC INTPOINT has in memory information possibly used when the previous observation was read. PROC INTPOINT can assume a piece of data is either similar to that of the last observation read or is new. In the first case, valuable information such as an arc or a nonarc variable number or a constraint number is retained from the previous observation. In the last case, checking the data with what has been read previously is not necessary.



Even if you do not sort the `CONDATA=` data set, grouping observations that contain data for the same arc or nonarc variable or the same row pays off. PROC INTPOINT establishes whether an observation being read is similar to the observation just read.

In practice, many input data sets for PROC INTPOINT have this characteristic, because it is natural for data for each constraint to be grouped together (when using the `dense` format of the `CONDATA=` data set) or data for each column to be grouped together (when using the `sparse` format of the `CONDATA=` data set). If data for each arc or nonarc is spread over more than one observation of the `ARCDATA=` data set, it is natural to group these observations together.

Use the `GROUPED=` option to indicate whether observations of the `ARCDATA=` data set, the `CONDATA=` data set, or both, are grouped in a way that can be exploited during data read.

You can save time if the type data for each row appears near the top of the `CONDATA=` data set, especially if it has the `sparse` format. Otherwise, when reading an observation, if PROC INTPOINT does not know if a row is a constraint or special row, the data are set aside. Once the data set has been completely read, PROC INTPOINT must reprocess the data it set aside. By then, it knows the type of each constraint or row or, if its type was not provided, it is assumed to have a default type.

## Better Memory Utilization

In order for PROC INTPOINT to make better utilization of available memory, you can specify options that indicate the approximate size of the model. PROC INTPOINT then knows what to expect. For example, if you indicate that the problem has no nonarc variables, PROC INTPOINT will not allocate memory to store nonarc data. That memory is better utilized for other purposes. Memory is often allocated to receive or store data of some type. If you indicate that the model does not have much data of a particular type, the memory that would otherwise have been allocated to receive or store that data can be used to receive or store data of another type.

The problem size options are as follows:

- `NNODES=` approximate number of nodes
- `NARCS=` approximate number of arcs
- `NNAS=` approximate number of nonarc variables or LP variables
- `NCONS=` approximate number of NPSC side constraints or LP constraints
- `NCOEFS=` approximate number of NPSC side constraint coefficients or LP constraint coefficients

These options will sometimes be referred to as `Nxxxx=` options.

You do not need to specify all these options for the model, but the more you do, the better. If you do not specify some or all of these options, PROC INTPOINT guesses the size of the problem by using what it already knows about the model. Sometimes PROC INTPOINT guesses the size of the model by looking at the number of observations in the `ARCDATA=` and the `CONDATA=` data sets. However, PROC INTPOINT uses rough rules of thumb, that typical models are proportioned in certain ways (for example, if there are constraints, then arcs, nonarc variables, or LP variables usually have about five constraint coefficients). If your model has an unusual shape or structure, you are encouraged to use these options.

If you do use the options and you do not know the exact values to specify, *overestimate* the values. For example, if you specify `NARCS=10000` but the model has 10100 arcs, when dealing with the last 100 arcs,

PROC INTPOINT might have to page out data for 10000 arcs each time one of the last arcs must be dealt with. Memory could have been allocated for all 10100 arcs without affecting (much) the rest of the data read, so NARCS=10000 could be more of a hindrance than a help.

The point of these Nxxxx= options is to indicate the model size when PROC INTPOINT does not know it. When PROC INTPOINT knows the “real” value, that value is used instead of Nxxxx=.

ARCS\_ONLY\_ARCDATA indicates that data for only arcs are in the ARCDATA= data set. Memory would not be wasted to receive data for nonarc variables.

Use the memory usage options:

- The BYTES= option specifies the size of PROC INTPOINT main working memory in number of bytes.
- The MEMREP option indicates that memory usage report is to be displayed on the SAS log.

Specifying an appropriate value for the BYTES= parameter is particularly important. Specify as large a number as possible, but not so large a number that will cause PROC INTPOINT (that is, the SAS System running underneath PROC INTPOINT) to run out of memory.

PROC INTPOINT reports its memory requirements on the SAS log if you specify the MEMREP option.

### Use Defaults to Reduce the Amount of Data

Use the parameters that specify default values as much as possible. For example, if there are many arcs with the same cost value *c*, use DEFCOST=*c* for arcs that have that cost. Use missing values in the COST variable in the ARCDATA= data set instead of *c*. PROC INTPOINT ignores missing values, but must read, store, and process nonmissing values, even if they are equal to a default option or could have been equal to a default parameter had it been specified. Sometimes, using default parameters makes the need for some SAS variables in the ARCDATA= and the CONDATA= data sets no longer necessary, or reduces the quantity of data that must be read. The default options are

- DEFCOST= default cost of arcs, objective function of nonarc variables or LP variables
- DEFMINFLOW= default lower flow bound of arcs, lower bound of nonarc variables or LP variables
- DEFCAPACITY= default capacity of arcs, upper bound of nonarc variables or LP variables
- DEFCTYPE= LE or DEFCTYPE= <=  
DEFCTYPE= EQ or DEFCTYPE= =  
DEFCTYPE= GE or DEFCTYPE= >=

DEFCTYPE=LE is the default.

The default options themselves have defaults. For example, you do not need to specify DEFCOST=0 in the PROC INTPOINT statement. You should still have missing values in the COST variable in the ARCDATA= data set for arcs that have zero costs.

If the network has only one supply node, one demand node, or both, use

- SOURCE= name of single node that has supply capability

- **SUPPLY=** the amount of supply at **SOURCE**
- **SINK=** name of single node that demands flow
- **DEMAND=** the amount of flow **SINK** demands

Do not specify that a constraint has zero right-hand-side values. That is the default. The only time it might be practical to specify a zero rhs is in observations of the **CONDATA=** data set read early so that PROC INTPOINT can infer that a row is a constraint. This could prevent coefficient data from being put aside because PROC INTPOINT did not know the row was a constraint.

## Names of Things

To cut data read time and memory requirements, reduce the number of bytes in the longest node name, the longest arc name, the longest nonarc variable name, the longest LP variable name, and the longest constraint name to 8 bytes or less. The longer a name, the more bytes must be stored and compared with other names.

If an arc has no constraint coefficients, do not give it a name in the **NAME** list variable in the **ARCDATA=** data set. Names for such arcs serve no purpose.

PROC INTPOINT can have a default name for each arc. If an arc is directed from node *tailname* toward node *headname*, the default name for that arc is *tailname\_headname*. If you do not want PROC INTPOINT to use these default arc names, specify **NAMECTRL=1**. Otherwise, PROC INTPOINT must use memory for storing node names and these node names must be searched often.

If you want to use the default *tailname\_headname* name, that is, **NAMECTRL=2** or **NAMECTRL=3**, do not use underscores in node names. If the **CONDATA** has a **dense** format and has a variable in the **VAR** list **A\_B\_C\_D**, or if the value **A\_B\_C\_D** is encountered as a value of the **COLUMN** list variable when reading the **CONDATA=** data set that has the **sparse** format, PROC INTPOINT first looks for a node named A. If it finds it, it looks for a node called B\_C\_D. It then looks for a node with the name A\_B and possibly a node with name C\_D. A search is then conducted for a node named A\_B\_C and possibly a node named D is done. Underscores could have caused PROC INTPOINT to look unnecessarily for nonexistent nodes. Searching for node names can be expensive, and the amount of memory to store node names is often large. It might be better to assign the arc name **A\_B\_C\_D** directly to an arc by having that value as a **NAME** list variable value for that arc in the **ARCDATA=** data set and specify **NAMECTRL=1**.

## Other Ways to Speed Up Data Reads

Arcs and nonarc variables, or LP variables, can have associated with them values or quantities that have no bearing on the optimization. This information is given in the **ARCDATA=** data set in the **ID** list variables. For example, in a distribution problem, information such as truck number and driver's name can be associated with each arc. This is useful when the optimal solution saved in the **CONOUT=** data set is analyzed. However, PROC INTPOINT needs to reserve memory to process this information when data are being read. For large problems when memory is scarce, it might be better to remove ancillary data from the **ARCDATA**. After PROC INTPOINT runs, use SAS software to merge this information into the **CONOUT=** data set that contains the optimal solution.

## Stopping Criteria

There are several reasons why PROC INTPOINT stops interior point optimization. Optimization stops when

- the number of iteration equals `MAXITERB=m`
- the relative gap ( $duality\ gap/(c^T x)$ ) between the primal and dual objectives is smaller than the value of the `PDGAPTOL=` option, and both the primal and dual problems are feasible. **Duality gap** is defined in the section “[Interior Point Algorithmic Details](#)” on page 47.

PROC INTPOINT may stop optimization when it detects that the rate at which the **complementarity** or **duality gap** is being reduced is too slow; that is, that there are consecutive iterations when the **complementarity** or **duality gap** has stopped getting smaller and the infeasibilities, if nonzero, have also stalled. Sometimes this indicates that the problem is infeasible.

The reasons to stop optimization outlined in the previous paragraph will be termed the *usual* stopping conditions in the following explanation.

However, when solving some problems, especially if the problems are large, the usual stopping criteria are inappropriate. PROC INTPOINT might stop optimizing prematurely. If it were allowed to perform additional optimization, a better solution would be found. On other occasions, PROC INTPOINT might do too much work. A sufficiently good solution might be reached several iterations before PROC INTPOINT eventually stops.

You can see PROC INTPOINT’s progress to the optimum by specifying `PRINTLEVEL2=2`. PROC INTPOINT will produce a table on the SAS log. A row of the table is generated during each iteration and consists of values of the **affine step** complementarity, the **complementarity** of the solution for the next iteration, the total bound infeasibility  $\sum_{i=1}^n infeas_{bi}$  (see the  $infeas_b$  array in the section “[Interior Point: Upper Bounds](#)” on page 51), the total constraint infeasibility  $\sum_{i=1}^m infeas_{ci}$  (see the  $infeas_c$  array in the section “[Interior Point Algorithmic Details](#)” on page 47), and the total dual infeasibility  $\sum_{i=1}^n infeas_{di}$  (see the  $infeas_d$  array in the section “[Interior Point Algorithmic Details](#)” on page 47). As optimization progresses, the values in all columns should converge to zero.

To tailor stopping criteria to your problem, you can use two sets of parameters: the `STOP_x` and the `KEEPGOING_x` parameters. The `STOP_x` parameters ( `STOP_C`, `STOP_DG`, `STOP_IB`, `STOP_IC`, and `STOP_ID` ) are used to test for some condition at the beginning of each iteration and if met, to stop optimizing immediately. The `KEEPGOING_x` parameters ( `KEEPGOING_C`, `KEEPGOING_DG`, `KEEPGOING_IB`, `KEEPGOING_IC`, and `KEEPGOING_ID` ) are used when PROC INTPOINT would ordinarily stop optimizing but does not if some conditions are not met.

For the sake of conciseness, a set of options might be referred to as the part of the option name they have in common followed by the suffix x. For example, `STOP_C`, `STOP_DG`, `STOP_IB`, `STOP_IC`, and `STOP_ID` will collectively be referred to as `STOP_x`.

At the beginning of each iteration, PROC INTPOINT will test whether **complementarity** is  $\leq$  `STOP_C` (provided you have specified a `STOP_C` parameter) and if it is, PROC INTPOINT will stop optimizing. If the **duality gap** is  $\leq$  `STOP_DG` (provided you have specified a `STOP_DG` parameter), PROC INTPOINT will stop optimizing immediately. This is also true for the other `STOP_x` parameters that are related to infeasibilities, `STOP_IB`, `STOP_IC`, and `STOP_ID`.

For example, if you want PROC INTPOINT to stop optimizing for the usual stopping conditions, plus the additional condition,  $\text{complementarity} \leq 100$  or  $\text{duality gap} \leq 0.001$ , then use

```
proc intpoint stop_c=100 stop_dg=0.001
```

If you want PROC INTPOINT to stop optimizing for the usual stopping conditions, plus the additional condition,  $\text{complementarity} \leq 1000$  and  $\text{duality gap} \leq 0.001$  and constraint infeasibility  $\leq 0.0001$ , then use

```
proc intpoint
  and_stop_c=1000 and_stop_dg=0.01 and_stop_ic=0.0001
```

Unlike the STOP\_x parameters that cause PROC INTPOINT to stop optimizing when any one of them is satisfied, the corresponding AND\_STOP\_x parameters ( AND\_STOP\_C, AND\_STOP\_DG, AND\_STOP\_IB, AND\_STOP\_IC, and AND\_STOP\_ID) cause PROC INTPOINT to stop only if all (more precisely, all that are specified) options are satisfied. For example, if PROC INTPOINT should stop optimizing when

- $\text{complementarity} \leq 100$  or  $\text{duality gap} \leq 0.001$  or
- $\text{complementarity} \leq 1000$  and  $\text{duality gap} \leq 0.001$  and constraint infeasibility  $\leq 0.000$

then use

```
proc intpoint
  stop_c=100 stop_dg=0.001
  and_stop_c=1000 and_stop_dg=0.01 and_stop_ic=0.0001
```

Just as the STOP\_x parameters have AND\_STOP\_x partners, the KEEPGOING\_x parameters have AND\_KEEPGOING\_x partners. The role of the KEEPGOING\_x and AND\_KEEPGOING\_x parameters is to prevent optimization from stopping too early, even though a usual stopping criteria is met.

When PROC INTPOINT detects that it should stop optimizing for a usual stopping condition, it will perform the following tests:

- It will test whether  $\text{complementarity}$  is  $> \text{KEEPGOING\_C}$  (provided you have specified a KEEPGOING\_C parameter), and if it is, PROC INTPOINT will perform more optimization.
- Otherwise, PROC INTPOINT will then test whether the primal-dual gap is  $> \text{KEEPGOING\_DG}$  (provided you have specified a KEEPGOING\_DG parameter), and if it is, PROC INTPOINT will perform more optimization.
- Otherwise, PROC INTPOINT will then test whether the total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi} > \text{KEEPGOING\_IB}$  (provided you have specified a KEEPGOING\_IB parameter), and if it is, PROC INTPOINT will perform more optimization.
- Otherwise, PROC INTPOINT will then test whether the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci} > \text{KEEPGOING\_IC}$  (provided you have specified a KEEPGOING\_IC parameter), and if it is, PROC INTPOINT will perform more optimization.

- Otherwise, PROC INTPOINT will then test whether the total dual infeasibility  $\sum_{i=1}^n infeas_{di} > \text{KEEPGOING\_ID}$  (provided you have specified a `KEEPGOING_ID` parameter), and if it is, PROC INTPOINT will perform more optimization.
- Otherwise it will test whether `complementarity` is  $> \text{AND\_KEEPGOING\_C}$  (provided you have specified an `AND\_KEEPGOING\_C` parameter), *and* the primal-dual gap is  $> \text{AND\_KEEPGOING\_DG}$  (provided you have specified an `AND\_KEEPGOING\_DG` parameter), *and* the total bound infeasibility  $\sum_{i=1}^n infeas_{bi} > \text{AND\_KEEPGOING\_IB}$  (provided you have specified an `AND\_KEEPGOING\_IB` parameter), *and* the total constraint infeasibility  $\sum_{i=1}^m infeas_{ci} > \text{AND\_KEEPGOING\_IC}$  (provided you have specified an `AND\_KEEPGOING\_IC` parameter), *and* the total dual infeasibility  $\sum_{i=1}^n infeas_{di} > \text{AND\_KEEPGOING\_ID}$  (provided you have specified an `AND\_KEEPGOING\_ID` parameter), and if it is, PROC INTPOINT will perform more optimization.

If all these tests to decide whether more optimization should be performed are false, optimization is stopped.

The following PROC INTPOINT example is used to illustrate how several stopping criteria options can be used together:

```
proc intpoint
  stop_c=1000
  and_stop_c=2000 and_stop_dg=0.01
  and_stop_ib=1 and_stop_ic=1 and_stop_id=1
  keepgoing_c=1500
  and_keepgoing_c=2500 and_keepgoing_dg=0.05
  and_keepgoing_ib=1 and_keepgoing_ic=1 and_keepgoing_id=1
```

At the beginning of each iteration, PROC INTPOINT will stop optimizing if

- `complementarity`  $\leq 1000$  or
- `complementarity`  $\leq 2000$  and `duality gap`  $\leq 0.01$  and the total bound, constraint, and dual infeasibilities are each  $\leq 1$

When PROC INTPOINT determines it should stop optimizing because a usual stopping condition is met, it will stop optimizing only if

- `complementarity`  $\leq 1500$  or
- `complementarity`  $\leq 2500$  and `duality gap`  $\leq 0.05$  and the total bound, constraint, and dual infeasibilities are each  $\leq 1$

---

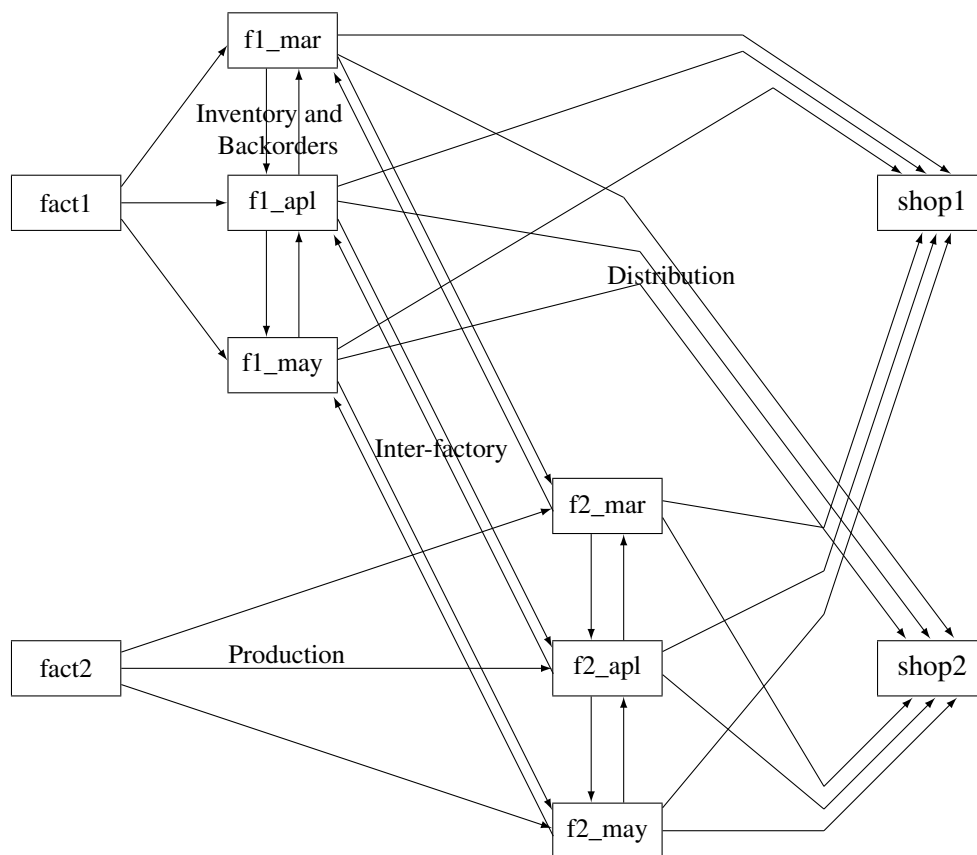
## Examples: INTPOINT Procedure

The following examples illustrate some of the capabilities of PROC INTPOINT. These examples, together with the other SAS/OR examples, can be found in the SAS sample library.

In order to illustrate variations in the use of the INTPOINT procedure, [Example 5.1](#) through [Example 5.5](#) use data from a company that produces two sizes of televisions. The company makes televisions with a diagonal screen measurement of either 19 inches or 25 inches. These televisions are made between March and May at both of the company's two factories. Each factory has a limit on the total number of televisions of each screen dimension that can be made during those months.

The televisions are distributed to one of two shops, stored at the factory where they were made, and sold later or shipped to the other factory. Some sets can be used to fill backorders from the previous months. Each shop demands a number of each type of TV for the months of March through May. The following network in [Figure 5.12](#) illustrates the model. Arc costs can be interpreted as production costs, storage costs, backorder penalty costs, inter-factory transportation costs, and sales profits. The arcs can have capacities and lower flow bounds.

**Figure 5.12** TV Problem



There are two similarly structured networks, one for the 19-inch televisions and the other for the 25-inch screen TVs. The minimum cost production, inventory, and distribution plan for both TV types can be determined in the same run of PROC INTPOINT. To ensure that node names are unambiguous, the names of nodes in the 19-inch network have suffix `_1`, and the node names in the 25-inch network have suffix `_2`.

## Example 5.1: Production, Inventory, Distribution Problem

The following code shows how to save a specific problem's data in data sets and solve the model with PROC INTPOINT.



```

title 'Production Planning/Inventory/Distribution';
title2 'Minimum Cost Flow problem';
title3;

data node0;
    input _node_ $ _supdem_ ;
    datalines;
fact1_1    1000
fact2_1     850
fact1_2    1000
fact2_2    1500
shop1_1    -900
shop2_1    -900
shop1_2    -900
shop2_2   -1450
;

data arc0;
    input _tail_ $ _head_ $ _cost_ _capac_ _lo_ diagonal factory
          key_id $10. mth_made $ _name_&$17. ;
    datalines;
fact1_1 f1_mar_1  127.9  500 50 19 1 production March prod f1 19 mar
fact1_1 f1_apr_1   78.6  600 50 19 1 production April prod f1 19 apl
fact1_1 f1_may_1   95.1  400 50 19 1 production May   .
f1_mar_1 f1_apr_1   15     50 . 19 1 storage   March .
f1_apr_1 f1_may_1   12     50 . 19 1 storage   April .
f1_apr_1 f1_mar_1   28     20 . 19 1 backorder April back f1 19 apl
f1_may_1 f1_apr_1   28     20 . 19 1 backorder May   back f1 19 may
f1_mar_1 f2_mar_1   11     . . 19 . f1_to_2   March .
f1_apr_1 f2_apr_1   11     . . 19 . f1_to_2   April .
f1_may_1 f2_may_1   16     . . 19 . f1_to_2   May   .
f1_mar_1 shop1_1  -327.65 250 . 19 1 sales     March .
f1_apr_1 shop1_1  -300    250 . 19 1 sales     April .
f1_may_1 shop1_1  -285    250 . 19 1 sales     May   .
f1_mar_1 shop2_1  -362.74 250 . 19 1 sales     March .
f1_apr_1 shop2_1  -300    250 . 19 1 sales     April .
f1_may_1 shop2_1  -245    250 . 19 1 sales     May   .
fact2_1 f2_mar_1   88.0  450 35 19 2 production March prod f2 19 mar
fact2_1 f2_apr_1   62.4  480 35 19 2 production April prod f2 19 apl
fact2_1 f2_may_1  133.8  250 35 19 2 production May   .
f2_mar_1 f2_apr_1   18     30 . 19 2 storage   March .
f2_apr_1 f2_may_1   20     30 . 19 2 storage   April .
f2_apr_1 f2_mar_1   17     15 . 19 2 backorder April back f2 19 apl
f2_may_1 f2_apr_1   25     15 . 19 2 backorder May   back f2 19 may
f2_mar_1 f1_mar_1   10     40 . 19 . f2_to_1   March .
f2_apr_1 f1_apr_1   11     40 . 19 . f2_to_1   April .
f2_may_1 f1_may_1   13     40 . 19 . f2_to_1   May   .
f2_mar_1 shop1_1  -297.4  250 . 19 2 sales     March .
f2_apr_1 shop1_1  -290    250 . 19 2 sales     April .
f2_may_1 shop1_1  -292    250 . 19 2 sales     May   .
f2_mar_1 shop2_1  -272.7  250 . 19 2 sales     March .
f2_apr_1 shop2_1  -312    250 . 19 2 sales     April .
f2_may_1 shop2_1  -299    250 . 19 2 sales     May   .

```



```

fact1_2  f1_mar_2  217.9  400 40 25 1 production March prod f1 25 mar
fact1_2  f1_apr_2  174.5  550 50 25 1 production April prod f1 25 apl
fact1_2  f1_may_2  133.3  350 40 25 1 production May .
f1_mar_2  f1_apr_2   20    40 . 25 1 storage March .
f1_apr_2  f1_may_2   18    40 . 25 1 storage April .
f1_apr_2  f1_mar_2   32    30 . 25 1 backorder April back f1 25 apl
f1_may_2  f1_apr_2   41    15 . 25 1 backorder May back f1 25 may
f1_mar_2  f2_mar_2   23    . . 25 . f1_to_2 March .
f1_apr_2  f2_apr_2   23    . . 25 . f1_to_2 April .
f1_may_2  f2_may_2   26    . . 25 . f1_to_2 May .
f1_mar_2  shop1_2  -559.76 . . 25 1 sales March .
f1_apr_2  shop1_2  -524.28 . . 25 1 sales April .
f1_may_2  shop1_2  -475.02 . . 25 1 sales May .
f1_mar_2  shop2_2  -623.89 . . 25 1 sales March .
f1_apr_2  shop2_2  -549.68 . . 25 1 sales April .
f1_may_2  shop2_2  -460.00 . . 25 1 sales May .
fact2_2  f2_mar_2  182.0  650 35 25 2 production March prod f2 25 mar
fact2_2  f2_apr_2  196.7  680 35 25 2 production April prod f2 25 apl
fact2_2  f2_may_2  201.4  550 35 25 2 production May .
f2_mar_2  f2_apr_2   28    50 . 25 2 storage March .
f2_apr_2  f2_may_2   38    50 . 25 2 storage April .
f2_apr_2  f2_mar_2   31    15 . 25 2 backorder April back f2 25 apl
f2_may_2  f2_apr_2   54    15 . 25 2 backorder May back f2 25 may
f2_mar_2  f1_mar_2   20    25 . 25 . f2_to_1 March .
f2_apr_2  f1_apr_2   21    25 . 25 . f2_to_1 April .
f2_may_2  f1_may_2   43    25 . 25 . f2_to_1 May .
f2_mar_2  shop1_2  -567.83 500 . 25 2 sales March .
f2_apr_2  shop1_2  -542.19 500 . 25 2 sales April .
f2_may_2  shop1_2  -461.56 500 . 25 2 sales May .
f2_mar_2  shop2_2  -542.83 500 . 25 2 sales March .
f2_apr_2  shop2_2  -559.19 500 . 25 2 sales April .
f2_may_2  shop2_2  -489.06 500 . 25 2 sales May .

```

```
;
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```

proc intpoint
  bytes=1000000
  printlevel2=2
  nodedata=node0
  arcdata=arc0
  conout=arcl;
  run;

proc print data=arcl width=min;
  var _tail_ _head_ _cost_ _capac_ _lo_ _flow_ _fcost_
      diagonal factory key_id mth_made;
  sum _fcost_;
  run;

```

The following notes appear on the SAS log:

```
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 21 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 136 .
NOTE: Number of variables= 68 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 20.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 1 constraints from the problem.
NOTE: The preprocessor eliminated 9 constraint coefficients from the problem.
NOTE: 0 columns, 0 rows and 0 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 48 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 20 factor nodes make up 8 supernodes
NOTE: There are 27 nonzero sub-rows or sub-columns outside the supernodal triangular
      regions along the factors leading diagonal.
```

| Iter | Complem_aff | Complem-ity | Duality_gap  | Tot_infeasb | Tot_infeasc | Tot_infeasd |
|------|-------------|-------------|--------------|-------------|-------------|-------------|
| 0    | -1.000000   | 192857968   | 0.895105     | 66024       | 25664       | 0           |
| 1    | 37620673    | 24479828    | 0.919312     | 4575.155540 | 1778.391068 | 0           |
| 2    | 4392127     | 1833947     | 0.594993     | 0           | 0           | 0           |
| 3    | 654204      | 426961      | 0.249790     | 0           | 0           | 0           |
| 4    | 161214      | 108340      | 0.075186     | 0           | 0           | 0           |
| 5    | 50985       | 43146       | 0.030894     | 0           | 0           | 0           |
| 6    | 37774       | 34993       | 0.025167     | 0           | 0           | 0           |
| 7    | 17695       | 9774.172272 | 0.007114     | 0           | 0           | 0           |
| 8    | 2421.777663 | 1427.435257 | 0.001042     | 0           | 0           | 0           |
| 9    | 522.394743  | 240.454270  | 0.000176     | 0           | 0           | 0           |
| 10   | 57.447587   | 7.581156    | 0.000005540  | 0           | 0           | 0           |
| 11   | 0.831035    | 0.007569    | 5.5317231E-9 | 0           | 0           | 0           |

```
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 11
      iterations.
NOTE: Optimum reached.
NOTE: Objective= -1281110.338.
NOTE: The data set WORK.ARC1 has 64 observations and 14 variables.
NOTE: There were 64 observations read from the data set WORK.ARC0.
NOTE: There were 8 observations read from the data set WORK.NODE0.
```

The solution is given in the `CONOUT=arc1` data sets. In the `CONOUT=` data set, shown in [Output 5.1.1](#), the variables `diagonal`, `factory`, `key_id`, and `month_made` form an implicit **ID** list. The `diagonal` variable has one of two values, 19 or 25. `factory` also has one of two values, 1 or 2, to denote the factory where either production or storage occurs, from where TVs are either sold to shops or used to satisfy backorders. `production`, `storage`, `sales`, and `backorder` are values of the `key_id` variable.

Other values of this variable, `f1_to_2` and `f2_to_1`, are used when flow through arcs represents the transportation of TVs between factories. The `month_made` variable has values `March`, `April`, and `May`, the months when TVs that are modeled as flow through an arc were made (assuming that no televisions are stored for more than one month and none manufactured in May are used to fill March backorders).

These **ID** variables can be used after the `PROC INTPOINT` run to produce reports and perform analysis on particular parts of the company's operation. For example, reports can be generated for production numbers for each factory; optimal sales figures for each shop; and how many TVs should be stored, used to fill backorders, sent to the other factory, or any combination of these, for TVs with a particular screen, those produced in a particular month, or both.

## Output 5.1.1 CONOUT=ARC1

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem |  |  |   |  |  |   |  |  |     |  |  |
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**Output 5.1.1** *continued*

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem |          |         |         |          |   |         |             |    |   |       |       |
|---|----------|---------|---------|----------|---|---------|-------------|----|---|-------|-------|
|   |          |         |         |          |   |         | d           |    |   | m     |       |
|   |          |         |         |          |   |         | i           | f  |   | t     |       |
|   |          |         |         |          |   |         | a           | a  | k | h     |       |
|   |          |         |         |          |   |         | g           | c  | e | _     |       |
|   |          |         |         |          |   |         | o           | t  | y | m     |       |
| O   | i        | a       | s       | a        | l | O       | S           | n  | o | _     | a     |
| b   | l        | d       | t       | c        | o | W       | T           | a  | r | i     | d     |
| s   | _        | _       | _       | _        | _ | _       | _           | l  | y | d     | e     |
| 44  | f2_mar_1 | shop1_1 | -297.40 | 250      | 0 | 250.000 | -74349.99   | 19 | 2 | sales | March |
| 45  | f2_apr_1 | shop1_1 | -290.00 | 250      | 0 | 245.001 | -71050.17   | 19 | 2 | sales | April |
| 46  | f2_may_1 | shop1_1 | -292.00 | 250      | 0 | 0.000   | 0.00        | 19 | 2 | sales | May   |
| 47  | f1_mar_2 | shop1_2 | -559.76 | 99999999 | 0 | 0.000   | 0.00        | 25 | 1 | sales | March |
| 48  | f1_apr_2 | shop1_2 | -524.28 | 99999999 | 0 | 0.000   | -0.01       | 25 | 1 | sales | April |
| 49  | f1_may_2 | shop1_2 | -475.02 | 99999999 | 0 | 25.000  | -11875.64   | 25 | 1 | sales | May   |
| 50  | f2_mar_2 | shop1_2 | -567.83 | 500      | 0 | 500.000 | -283915.00  | 25 | 2 | sales | March |
| 51  | f2_apr_2 | shop1_2 | -542.19 | 500      | 0 | 375.000 | -203321.08  | 25 | 2 | sales | April |
| 52  | f2_may_2 | shop1_2 | -461.56 | 500      | 0 | 0.000   | 0.00        | 25 | 2 | sales | May   |
| 53  | f1_mar_1 | shop2_1 | -362.74 | 250      | 0 | 250.000 | -90685.00   | 19 | 1 | sales | March |
| 54  | f1_apr_1 | shop2_1 | -300.00 | 250      | 0 | 250.000 | -75000.00   | 19 | 1 | sales | April |
| 55  | f1_may_1 | shop2_1 | -245.00 | 250      | 0 | 0.000   | 0.00        | 19 | 1 | sales | May   |
| 56  | f2_mar_1 | shop2_1 | -272.70 | 250      | 0 | 0.000   | 0.00        | 19 | 2 | sales | March |
| 57  | f2_apr_1 | shop2_1 | -312.00 | 250      | 0 | 250.000 | -78000.00   | 19 | 2 | sales | April |
| 58  | f2_may_1 | shop2_1 | -299.00 | 250      | 0 | 150.000 | -44850.00   | 19 | 2 | sales | May   |
| 59  | f1_mar_2 | shop2_2 | -623.89 | 99999999 | 0 | 455.000 | -283869.94  | 25 | 1 | sales | March |
| 60  | f1_apr_2 | shop2_2 | -549.68 | 99999999 | 0 | 535.000 | -294078.78  | 25 | 1 | sales | April |
| 61  | f1_may_2 | shop2_2 | -460.00 | 99999999 | 0 | 0.000   | 0.00        | 25 | 1 | sales | May   |
| 62  | f2_mar_2 | shop2_2 | -542.83 | 500      | 0 | 120.000 | -65139.47   | 25 | 2 | sales | March |
| 63  | f2_apr_2 | shop2_2 | -559.19 | 500      | 0 | 320.000 | -178940.96  | 25 | 2 | sales | April |
| 64  | f2_may_2 | shop2_2 | -489.06 | 500      | 0 | 20.000  | -9781.20    | 25 | 2 | sales | May   |
|   |          |         |         |          |   |         | =====       |    |   |       |       |
|   |          |         |         |          |   |         | -1281110.34 |    |   |       |       |

## Example 5.2: Altering Arc Data

This example examines the effect of changing some of the arc costs. The backorder penalty costs are increased by 20 percent. The sales profit of 25-inch TVs sent to the shops in May is increased by 30 units. The backorder penalty costs of 25-inch TVs manufactured in May for April consumption is decreased by 30 units. The production cost of 19-inch and 25-inch TVs made in May are decreased by 5 units and 20 units, respectively. How does the optimal solution of the network after these arc cost alterations compare with the optimum of the original network?

These SAS statements produce the new **NODEDATA=** and **ARCDATA=** data sets:

```

title2 'Minimum Cost Flow problem- Altered Arc Data';
data arc2;
  set arc1;
  oldcost=_cost_;
  oldfc=_fcost_;
  oldflow=_flow_;
  if key_id='backorder'
    then _cost_=_cost_*1.2;
  else if _tail_='f2_may_2' then _cost_=_cost_-30;
  if key_id='production' & mth_made='May' then
    if diagonal=19 then _cost_=_cost_-5;
    else _cost_=_cost_-20;

run;

proc intpoint
  bytes=100000
  printlevel2=2
  nodedata=node0
  arcdata=arc2
  conout=arc3;
run;

proc print data=arc3;
var _tail_ _head_ _capac_ _lo_ _supply_ _demand_ _name_
  _cost_ _flow_ _fcost_ oldcost oldflow oldfc
  diagonal factory key_id mth_made;
/* to get this variable order */
  sum oldfc _fcost_;
run;

```

The following notes appear on the SAS log:

```
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 21 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 136 .
NOTE: Number of variables= 68 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 20.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 1 constraints from the problem.
NOTE: The preprocessor eliminated 9 constraint coefficients from the problem.
NOTE: 0 columns, 0 rows and 0 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 48 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 20 factor nodes make up 8 supernodes
NOTE: There are 27 nonzero sub-rows or sub-columns outside the supernodal triangular
      regions along the factors leading diagonal.
```

| Iter | Complem_aff | Complem-ity | Duality_gap  | Tot_infeasb | Tot_infeasc | Tot_infeasd |
|------|-------------|-------------|--------------|-------------|-------------|-------------|
| 0    | -1.000000   | 193775969   | 0.894415     | 66024       | 25664       | 0           |
| 1    | 37797544    | 24594220    | 0.918149     | 4566.893212 | 1775.179450 | 0           |
| 2    | 4408681     | 1844606     | 0.590964     | 0           | 0           | 0           |
| 3    | 347168      | 312126      | 0.194113     | 0           | 0           | 0           |
| 4    | 145523      | 86002       | 0.060330     | 0           | 0           | 0           |
| 5    | 43008       | 38240       | 0.027353     | 0           | 0           | 0           |
| 6    | 31097       | 21145       | 0.015282     | 0           | 0           | 0           |
| 7    | 9308.807034 | 4158.399675 | 0.003029     | 0           | 0           | 0           |
| 8    | 1710.832075 | 752.174595  | 0.000549     | 0           | 0           | 0           |
| 9    | 254.197112  | 47.755299   | 0.000034846  | 0           | 0           | 0           |
| 10   | 5.252560    | 0.010692    | 7.8017573E-9 | 0           | 0           | 0           |

```
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 10
      iterations.
NOTE: Optimum reached.
NOTE: Objective= -1285086.442.
NOTE: The data set WORK.ARC3 has 64 observations and 17 variables.
NOTE: There were 64 observations read from the data set WORK.ARC2.
NOTE: There were 8 observations read from the data set WORK.NODE0.
```

The solution is displayed in [Output 5.2.1](#).

**Output 5.2.1** CONOUT=ARC3

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem- Altered arc data |          |          |      |          |          |                |         |         |
|---|----------|----------|------|----------|----------|----------------|---------|---------|
| _tail_  | _head_   | _capac_  | _lo_ | _SUPPLY_ | _DEMAND_ | _name_         | _cost_  | _FLOW_  |
| fact1_1   | f1_apr_1 | 600      | 50   | 1000     | .        | prod f1 19 apl | 78.60   | 540.000 |
| f1_mar_1  | f1_apr_1 | 50       | 0    | .        | .        |                | 15.00   | 0.000   |
| f1_may_1  | f1_apr_1 | 20       | 0    | .        | .        | back f1 19 may | 33.60   | 0.000   |
| f2_apr_1  | f1_apr_1 | 40       | 0    | .        | .        |                | 11.00   | 0.000   |
| fact1_2   | f1_apr_2 | 550      | 50   | 1000     | .        | prod f1 25 apl | 174.50  | 250.000 |
| f1_mar_2  | f1_apr_2 | 40       | 0    | .        | .        |                | 20.00   | 0.000   |
| f1_may_2  | f1_apr_2 | 15       | 0    | .        | .        | back f1 25 may | 49.20   | 15.000  |
| f2_apr_2  | f1_apr_2 | 25       | 0    | .        | .        |                | 21.00   | 0.000   |
| fact1_1   | f1_mar_1 | 500      | 50   | 1000     | .        | prod f1 19 mar | 127.90  | 340.000 |
| f1_apr_1  | f1_mar_1 | 20       | 0    | .        | .        | back f1 19 apl | 33.60   | 20.000  |
| f2_mar_1  | f1_mar_1 | 40       | 0    | .        | .        |                | 10.00   | 40.000  |
| fact1_2   | f1_mar_2 | 400      | 40   | 1000     | .        | prod f1 25 mar | 217.90  | 400.000 |
| f1_apr_2  | f1_mar_2 | 30       | 0    | .        | .        | back f1 25 apl | 38.40   | 30.000  |
| f2_mar_2  | f1_mar_2 | 25       | 0    | .        | .        |                | 20.00   | 25.000  |
| fact1_1   | f1_may_1 | 400      | 50   | 1000     | .        |                | 90.10   | 115.000 |
| f1_apr_1  | f1_may_1 | 50       | 0    | .        | .        |                | 12.00   | 0.000   |
| f2_may_1  | f1_may_1 | 40       | 0    | .        | .        |                | 13.00   | 0.000   |
| fact1_2   | f1_may_2 | 350      | 40   | 1000     | .        |                | 113.30  | 350.000 |
| f1_apr_2  | f1_may_2 | 40       | 0    | .        | .        |                | 18.00   | 0.000   |
| f2_may_2  | f1_may_2 | 25       | 0    | .        | .        |                | 13.00   | 0.000   |
| f1_apr_1  | f2_apr_1 | 99999999 | 0    | .        | .        |                | 11.00   | 20.000  |
| fact2_1   | f2_apr_1 | 480      | 35   | 850      | .        | prod f2 19 apl | 62.40   | 480.000 |
| f2_mar_1  | f2_apr_1 | 30       | 0    | .        | .        |                | 18.00   | 0.000   |
| f2_may_1  | f2_apr_1 | 15       | 0    | .        | .        | back f2 19 may | 30.00   | 0.000   |
| f1_apr_2  | f2_apr_2 | 99999999 | 0    | .        | .        |                | 23.00   | 0.000   |
| fact2_2   | f2_apr_2 | 680      | 35   | 1500     | .        | prod f2 25 apl | 196.70  | 680.000 |
| f2_mar_2  | f2_apr_2 | 50       | 0    | .        | .        |                | 28.00   | 0.000   |
| f2_may_2  | f2_apr_2 | 15       | 0    | .        | .        | back f2 25 may | 64.80   | 0.000   |
| f1_mar_1  | f2_mar_1 | 99999999 | 0    | .        | .        |                | 11.00   | 0.000   |
| fact2_1   | f2_mar_1 | 450      | 35   | 850      | .        | prod f2 19 mar | 88.00   | 290.000 |
| f2_apr_1  | f2_mar_1 | 15       | 0    | .        | .        | back f2 19 apl | 20.40   | 0.000   |
| f1_mar_2  | f2_mar_2 | 99999999 | 0    | .        | .        |                | 23.00   | 0.000   |
| fact2_2   | f2_mar_2 | 650      | 35   | 1500     | .        | prod f2 25 mar | 182.00  | 635.000 |
| f2_apr_2  | f2_mar_2 | 15       | 0    | .        | .        | back f2 25 apl | 37.20   | 0.000   |
| f1_may_1  | f2_may_1 | 99999999 | 0    | .        | .        |                | 16.00   | 115.000 |
| fact2_1   | f2_may_1 | 250      | 35   | 850      | .        |                | 128.80  | 35.000  |
| f2_apr_1  | f2_may_1 | 30       | 0    | .        | .        |                | 20.00   | 0.000   |
| f1_may_2  | f2_may_2 | 99999999 | 0    | .        | .        |                | 26.00   | 335.000 |
| fact2_2   | f2_may_2 | 550      | 35   | 1500     | .        |                | 181.40  | 35.000  |
| f2_apr_2  | f2_may_2 | 50       | 0    | .        | .        |                | 38.00   | 0.000   |
| f1_mar_1  | shop1_1  | 250      | 0    | .        | 900      |                | -327.65 | 150.000 |
| f1_apr_1  | shop1_1  | 250      | 0    | .        | 900      |                | -300.00 | 250.000 |
| f1_may_1  | shop1_1  | 250      | 0    | .        | 900      |                | -285.00 | 0.000   |
| f2_mar_1  | shop1_1  | 250      | 0    | .        | 900      |                | -297.40 | 250.000 |
| f2_apr_1  | shop1_1  | 250      | 0    | .        | 900      |                | -290.00 | 250.000 |



Output 5.2.1 *continued*

| Production Planning/Inventory/Distribution  |               |                |             |                 |                 |               |               |               |
|---|---------------|----------------|-------------|-----------------|-----------------|---------------|---------------|---------------|
| Minimum Cost Flow problem- Altered arc data |               |                |             |                 |                 |               |               |               |
| <u>_tail_</u>                               | <u>_head_</u> | <u>_capac_</u> | <u>_lo_</u> | <u>_SUPPLY_</u> | <u>_DEMAND_</u> | <u>_name_</u> | <u>_cost_</u> | <u>_FLOW_</u> |
| f2_may_1                                    | shop1_1       | 250            | 0           | .               | 900             |               | -292.00       | 0.000         |
| f1_mar_2                                    | shop1_2       | 99999999       | 0           | .               | 900             |               | -559.76       | 0.000         |
| f1_apr_2                                    | shop1_2       | 99999999       | 0           | .               | 900             |               | -524.28       | 0.000         |
| f1_may_2                                    | shop1_2       | 99999999       | 0           | .               | 900             |               | -475.02       | 0.000         |
| f2_mar_2                                    | shop1_2       | 500            | 0           | .               | 900             |               | -567.83       | 500.000       |
| f2_apr_2                                    | shop1_2       | 500            | 0           | .               | 900             |               | -542.19       | 400.000       |
| f2_may_2                                    | shop1_2       | 500            | 0           | .               | 900             |               | -491.56       | 0.000         |
| f1_mar_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -362.74       | 250.000       |
| f1_apr_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -300.00       | 250.000       |
| f1_may_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -245.00       | 0.000         |
| f2_mar_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -272.70       | 0.000         |
| f2_apr_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -312.00       | 250.000       |
| f2_may_1                                    | shop2_1       | 250            | 0           | .               | 900             |               | -299.00       | 150.000       |
| f1_mar_2                                    | shop2_2       | 99999999       | 0           | .               | 1450            |               | -623.89       | 455.000       |
| f1_apr_2                                    | shop2_2       | 99999999       | 0           | .               | 1450            |               | -549.68       | 235.000       |
| f1_may_2                                    | shop2_2       | 99999999       | 0           | .               | 1450            |               | -460.00       | 0.000         |
| f2_mar_2                                    | shop2_2       | 500            | 0           | .               | 1450            |               | -542.83       | 110.000       |
| f2_apr_2                                    | shop2_2       | 500            | 0           | .               | 1450            |               | -559.19       | 280.000       |
| f2_may_2                                    | shop2_2       | 500            | 0           | .               | 1450            |               | -519.06       | 370.000       |

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem- Altered arc data |           |         |         |           |          |         |            |          |
|---|-----------|---------|---------|-----------|----------|---------|------------|----------|
| Obs   | _FCOST_   | oldcost | oldflow | oldfc     | diagonal | factory | key_id     | mth_made |
| 1   | 42444.01  | 78.60   | 600.000 | 47160.00  | 19       | 1       | production | April    |
| 2   | 0.00      | 15.00   | 0.000   | 0.00      | 19       | 1       | storage    | March    |
| 3   | 0.00      | 28.00   | 0.000   | 0.00      | 19       | 1       | backorder  | May      |
| 4   | 0.00      | 11.00   | 0.000   | 0.00      | 19       | .       | f2_to_1    | April    |
| 5   | 43625.00  | 174.50  | 550.000 | 95975.00  | 25       | 1       | production | April    |
| 6   | 0.00      | 20.00   | 0.000   | 0.00      | 25       | 1       | storage    | March    |
| 7   | 738.00    | 41.00   | 15.000  | 615.00    | 25       | 1       | backorder  | May      |
| 8   | 0.00      | 21.00   | 0.000   | 0.00      | 25       | .       | f2_to_1    | April    |
| 9   | 43486.02  | 127.90  | 344.999 | 44125.43  | 19       | 1       | production | March    |
| 10  | 672.00    | 28.00   | 20.000  | 560.00    | 19       | 1       | backorder  | April    |
| 11  | 400.00    | 10.00   | 40.000  | 400.00    | 19       | .       | f2_to_1    | March    |
| 12  | 87160.00  | 217.90  | 400.000 | 87160.00  | 25       | 1       | production | March    |
| 13  | 1152.00   | 32.00   | 30.000  | 960.00    | 25       | 1       | backorder  | April    |
| 14  | 500.00    | 20.00   | 25.000  | 500.00    | 25       | .       | f2_to_1    | March    |
| 15  | 10361.47  | 95.10   | 50.001  | 4755.06   | 19       | 1       | production | May      |
| 16  | 0.00      | 12.00   | 50.000  | 600.00    | 19       | 1       | storage    | April    |
| 17  | 0.00      | 13.00   | 0.000   | 0.00      | 19       | .       | f2_to_1    | May      |
| 18  | 39655.00  | 133.30  | 40.000  | 5332.04   | 25       | 1       | production | May      |
| 19  | 0.00      | 18.00   | 0.000   | 0.00      | 25       | 1       | storage    | April    |
| 20  | 0.00      | 43.00   | 0.000   | 0.00      | 25       | .       | f2_to_1    | May      |
| 21  | 220.00    | 11.00   | 30.000  | 330.00    | 19       | .       | f1_to_2    | April    |
| 22  | 29952.00  | 62.40   | 480.000 | 29952.00  | 19       | 2       | production | April    |
| 23  | 0.00      | 18.00   | 0.000   | 0.00      | 19       | 2       | storage    | March    |
| 24  | 0.00      | 25.00   | 0.000   | 0.00      | 19       | 2       | backorder  | May      |
| 25  | 0.00      | 23.00   | 0.000   | 0.00      | 25       | .       | f1_to_2    | April    |
| 26  | 133755.99 | 196.70  | 680.000 | 133755.99 | 25       | 2       | production | April    |
| 27  | 0.00      | 28.00   | 0.000   | 0.00      | 25       | 2       | storage    | March    |
| 28  | 0.00      | 54.00   | 15.000  | 810.00    | 25       | 2       | backorder  | May      |
| 29  | 0.00      | 11.00   | 0.000   | 0.00      | 19       | .       | f1_to_2    | March    |
| 30  | 25520.00  | 88.00   | 290.000 | 25520.00  | 19       | 2       | production | March    |
| 31  | 0.00      | 17.00   | 0.000   | 0.00      | 19       | 2       | backorder  | April    |
| 32  | 0.00      | 23.00   | 0.000   | 0.00      | 25       | .       | f1_to_2    | March    |
| 33  | 115570.01 | 182.00  | 645.000 | 117389.96 | 25       | 2       | production | March    |
| 34  | 0.00      | 31.00   | 0.000   | 0.00      | 25       | 2       | backorder  | April    |
| 35  | 1840.00   | 16.00   | 100.000 | 1600.01   | 19       | .       | f1_to_2    | May      |
| 36  | 4508.00   | 133.80  | 35.000  | 4683.00   | 19       | 2       | production | May      |
| 37  | 0.00      | 20.00   | 15.000  | 299.99    | 19       | 2       | storage    | April    |
| 38  | 8710.00   | 26.00   | 0.000   | 0.00      | 25       | .       | f1_to_2    | May      |
| 39  | 6349.00   | 201.40  | 35.000  | 7049.00   | 25       | 2       | production | May      |
| 40  | 0.00      | 38.00   | 0.000   | 0.00      | 25       | 2       | storage    | April    |
| 41  | -49147.54 | -327.65 | 154.999 | -50785.56 | 19       | 1       | sales      | March    |
| 42  | -75000.00 | -300.00 | 250.000 | -75000.00 | 19       | 1       | sales      | April    |
| 43  | -0.01     | -285.00 | 0.000   | 0.00      | 19       | 1       | sales      | May      |
| 44  | -74350.00 | -297.40 | 250.000 | -74349.99 | 19       | 2       | sales      | March    |
| 45  | -72499.96 | -290.00 | 245.001 | -71050.17 | 19       | 2       | sales      | April    |

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem- Altered arc data |             |         |         |             |          |         |        |          |
|---|-------------|---------|---------|-------------|----------|---------|--------|----------|
| Obs   | _FCOST_     | oldcost | oldflow | oldfc       | diagonal | factory | key_id | nth_made |
| 46  | 0.00        | -292.00 | 0.000   | 0.00        | 19       | 2       | sales  | May      |
| 47  | 0.00        | -559.76 | 0.000   | 0.00        | 25       | 1       | sales  | March    |
| 48  | -0.01       | -524.28 | 0.000   | -0.01       | 25       | 1       | sales  | April    |
| 49  | -0.06       | -475.02 | 25.000  | -11875.64   | 25       | 1       | sales  | May      |
| 50  | -283915.00  | -567.83 | 500.000 | -283915.00  | 25       | 2       | sales  | March    |
| 51  | -216875.92  | -542.19 | 375.000 | -203321.08  | 25       | 2       | sales  | April    |
| 52  | 0.00        | -461.56 | 0.000   | 0.00        | 25       | 2       | sales  | May      |
| 53  | -90685.00   | -362.74 | 250.000 | -90685.00   | 19       | 1       | sales  | March    |
| 54  | -75000.00   | -300.00 | 250.000 | -75000.00   | 19       | 1       | sales  | April    |
| 55  | 0.00        | -245.00 | 0.000   | 0.00        | 19       | 1       | sales  | May      |
| 56  | -0.01       | -272.70 | 0.000   | 0.00        | 19       | 2       | sales  | March    |
| 57  | -78000.00   | -312.00 | 250.000 | -78000.00   | 19       | 2       | sales  | April    |
| 58  | -44849.99   | -299.00 | 150.000 | -44850.00   | 19       | 2       | sales  | May      |
| 59  | -283869.94  | -623.89 | 455.000 | -283869.94  | 25       | 1       | sales  | March    |
| 60  | -129174.80  | -549.68 | 535.000 | -294078.78  | 25       | 1       | sales  | April    |
| 61  | 0.00        | -460.00 | 0.000   | 0.00        | 25       | 1       | sales  | May      |
| 62  | -59711.32   | -542.83 | 120.000 | -65139.47   | 25       | 2       | sales  | March    |
| 63  | -156573.27  | -559.19 | 320.000 | -178940.96  | 25       | 2       | sales  | April    |
| 64  | -192052.13  | -489.06 | 20.000  | -9781.20    | 25       | 2       | sales  | May      |
| =====   |             |         |         |             |          |         |        |          |
|   | -1285086.44 |         |         | -1281110.34 |          |         |        |          |

### Example 5.3: Adding Side Constraints

The manufacturer of Gizmo chips, which are parts needed to make televisions, can supply only 2,600 chips to factory 1 and 3,750 chips to factory 2 in time for production in each of the months of March and April. However, Gizmo chips will not be in short supply in May. Three chips are required to make each 19-inch TV while the 25-inch TVs require four chips each. To limit the production of televisions produced at factory 1 in March so that the TVs have the correct number of chips, a side constraint called FACT1 MAR GIZMO is used. The form of this constraint is

```
3 * prod f1 19 mar    +    4 * prod f1 25 mar    <=    2600
```

prod f1 19 mar is the name of the arc directed from the node fact1\_1 toward node f1\_mar\_1 and, in the previous constraint, designates the flow assigned to this arc. The [ARCDATA=](#) and [CONOUT=](#) data sets have arc names in a variable called `_name_`.

The other side constraints (shown below) are called FACT2 MAR GIZMO, FACT1 APL GIZMO, and FACT2 APL GIZMO.

```
3 * prod f2 19 mar    +    4 * prod f2 25 mar    <=    3750
3 * prod f1 19 apl    +    4 * prod f1 25 apl    <=    2600
3 * prod f2 19 apl    +    4 * prod f2 25 apl    <=    3750
```

To maintain customer goodwill, the total number of backorders is not to exceed 50 sets. The side constraint TOTAL BACKORDER that models this restriction is

```
back f1 19 apl + back f1 25 apl +
back f2 19 apl + back f2 25 apl +
back f1 19 may + back f1 25 may +
back f2 19 may + back f2 25 may <= 50
```

The `sparse CONDATA=` data set format is used. All side constraints are of less than or equal type. Because this is the default type value for the `DEFCONTYPE=` option, type information is not necessary in the following `CONDATA=con3`. Also, `DEFCONTYPE= <=` does not have to be specified in the PROC INTPOINT statement that follows. Notice that the `_column_` variable value CHIP/BO LIMIT indicates that an observation of the con3 data set contains rhs information. Therefore, specify `RHSOBS='CHIP/BO LIMIT'`

```
title2 'Adding Side Constraints';
data con3;
  input _column_ &$14. _row_ &$15. _coef_ ;
  datalines;
prod f1 19 mar FACT1 MAR GIZMO 3
prod f1 25 mar FACT1 MAR GIZMO 4
CHIP/BO LIMIT FACT1 MAR GIZMO 2600
prod f2 19 mar FACT2 MAR GIZMO 3
prod f2 25 mar FACT2 MAR GIZMO 4
CHIP/BO LIMIT FACT2 MAR GIZMO 3750
prod f1 19 apl FACT1 APL GIZMO 3
prod f1 25 apl FACT1 APL GIZMO 4
CHIP/BO LIMIT FACT1 APL GIZMO 2600
prod f2 19 apl FACT2 APL GIZMO 3
prod f2 25 apl FACT2 APL GIZMO 4
CHIP/BO LIMIT FACT2 APL GIZMO 3750
back f1 19 apl TOTAL BACKORDER 1
back f1 25 apl TOTAL BACKORDER 1
back f2 19 apl TOTAL BACKORDER 1
back f2 25 apl TOTAL BACKORDER 1
back f1 19 may TOTAL BACKORDER 1
back f1 25 may TOTAL BACKORDER 1
back f2 19 may TOTAL BACKORDER 1
back f2 25 may TOTAL BACKORDER 1
CHIP/BO LIMIT TOTAL BACKORDER 50
;
```

The four pairs of data sets that follow can be used as **ARCDATA=** and **NODEDATA=** data sets in the following PROC INTPOINT run. The set used depends on which cost information the arcs are to have.

```
ARCDATA=arc0      NODEDATA=node0
ARCDATA=arc1      NODEDATA=node0
ARCDATA=arc2      NODEDATA=node0
ARCDATA=arc3      NODEDATA=node0
```

arc0, node0, and arc1 were created in [Example 5.1](#). The first two data sets are the original input data sets.

In the previous example, arc2 was created by modifying arc1 to reflect different arc costs. arc2 and node0 can also be used as the **ARCDATA=** and **NODEDATA=** data sets in a PROC INTPOINT run.

If you are going to continue optimization using the changed arc costs, it is probably best to use arc3 and node0 as the **ARCDATA=** and **NODEDATA=** data sets.

PROC INTPOINT is used to find the changed cost network solution that obeys the chip limit and backorder side constraints. An explicit **ID** list has also been specified so that the variables oldcost, oldfc, and oldflow do not appear in the subsequent output data sets:

```
proc intpoint
  bytes=1000000
  printlevel2=2
  nodedata=node0 arcdata=arc3
  condata=con3 sparsesecondata rhsobs='CHIP/BO LIMIT'
  conout=arc4;
  id diagonal factory key_id mth_made;
  run;

proc print data=arc4;
  var _tail_ _head_ _cost_ _capac_ _lo_ _flow_ _fcost_;
  /* to get this variable order */
  sum _fcost_;
  run;
```

The following messages appear on the SAS log:

```
NOTE: The following variables in ARCDATA do not belong to any SAS variable list.
      These will be ignored.
      _FLOW_
      _FCOST_
      oldcost
      oldfc
      oldflow
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: Number of <= side constraints= 5 .
NOTE: Number of == side constraints= 0 .
NOTE: Number of >= side constraints= 0 .
NOTE: Number of side constraint coefficients= 16 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 5 .
NOTE: Number of == constraints= 21 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 152 .
NOTE: Number of variables= 68 .
NOTE: After preprocessing, number of <= constraints= 5.
NOTE: After preprocessing, number of == constraints= 20.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 1 constraints from the problem.
NOTE: The preprocessor eliminated 9 constraint coefficients from the problem.
NOTE: 5 columns, 0 rows and 5 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 74 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 25 factor nodes make up 17 supernodes
NOTE: There are 88 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
  Iter  Complem_aff  Complem-ity  Duality_gap  Tot_infeasb  Tot_infeasc  Tot_infeasd
      0      -1.000000    199456613    0.894741      65408      35351      10906
      1      38664128    25735020    0.919726  4738.839318  2561.195456  248.292591
      2      5142982     1874540    0.595158           0           0      6.669426
      3      366112      338310    0.207256           0           0      1.207816
      4      172159      90907     0.063722           0           0      0.238703
      5      48403       38889     0.027839           0           0      0.115586
      6      28882       17979     0.013029           0           0      0.019825
      7  7800.003324  3605.779203    0.002631           0           0      0.004077
      8  1564.193112   422.251530    0.000309           0           0      0.000225
      9    94.768595   16.589795    0.000012126           0           0           0
     10    0.294833    0.001048   5.96521E-10           0           0           0
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 10
      iterations.
NOTE: Optimum reached.
NOTE: Objective= -1282708.622.
NOTE: The data set WORK.ARC4 has 64 observations and 14 variables.
NOTE: There were 64 observations read from the data set WORK.ARC3.
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 21 observations read from the data set WORK.CON3.
```

## Output 5.3.1 CONOUT=ARC4

| Production Planning/Inventory/Distribution<br>Adding Side Constraints |          |          |         |          |      |         |           |
|---|----------|----------|---------|----------|------|---------|-----------|
| Obs   | _tail_   | _head_   | _cost_  | _capac_  | _lo_ | _FLOW_  | _FCOST_   |
| 1   | fact1_1  | f1_apr_1 | 78.60   | 600      | 50   | 533.333 | 41920.00  |
| 2   | f1_mar_1 | f1_apr_1 | 15.00   | 50       | 0    | 0.000   | 0.00      |
| 3   | f1_may_1 | f1_apr_1 | 33.60   | 20       | 0    | 0.000   | 0.00      |
| 4   | f2_apr_1 | f1_apr_1 | 11.00   | 40       | 0    | 0.000   | 0.00      |
| 5   | fact1_2  | f1_apr_2 | 174.50  | 550      | 50   | 250.000 | 43625.00  |
| 6   | f1_mar_2 | f1_apr_2 | 20.00   | 40       | 0    | 0.000   | 0.00      |
| 7   | f1_may_2 | f1_apr_2 | 49.20   | 15       | 0    | 0.000   | 0.00      |
| 8   | f2_apr_2 | f1_apr_2 | 21.00   | 25       | 0    | 0.000   | 0.00      |
| 9   | fact1_1  | f1_mar_1 | 127.90  | 500      | 50   | 333.333 | 42633.33  |
| 10  | f1_apr_1 | f1_mar_1 | 33.60   | 20       | 0    | 20.000  | 672.00    |
| 11  | f2_mar_1 | f1_mar_1 | 10.00   | 40       | 0    | 40.000  | 400.00    |
| 12  | fact1_2  | f1_mar_2 | 217.90  | 400      | 40   | 400.000 | 87160.00  |
| 13  | f1_apr_2 | f1_mar_2 | 38.40   | 30       | 0    | 30.000  | 1152.00   |
| 14  | f2_mar_2 | f1_mar_2 | 20.00   | 25       | 0    | 25.000  | 500.00    |
| 15  | fact1_1  | f1_may_1 | 90.10   | 400      | 50   | 128.333 | 11562.83  |
| 16  | f1_apr_1 | f1_may_1 | 12.00   | 50       | 0    | 0.000   | 0.00      |
| 17  | f2_may_1 | f1_may_1 | 13.00   | 40       | 0    | 0.000   | 0.00      |
| 18  | fact1_2  | f1_may_2 | 113.30  | 350      | 40   | 350.000 | 39655.00  |
| 19  | f1_apr_2 | f1_may_2 | 18.00   | 40       | 0    | 0.000   | 0.00      |
| 20  | f2_may_2 | f1_may_2 | 13.00   | 25       | 0    | 0.000   | 0.00      |
| 21  | f1_apr_1 | f2_apr_1 | 11.00   | 99999999 | 0    | 13.333  | 146.67    |
| 22  | fact2_1  | f2_apr_1 | 62.40   | 480      | 35   | 480.000 | 29952.00  |
| 23  | f2_mar_1 | f2_apr_1 | 18.00   | 30       | 0    | 0.000   | 0.00      |
| 24  | f2_may_1 | f2_apr_1 | 30.00   | 15       | 0    | 0.000   | 0.00      |
| 25  | f1_apr_2 | f2_apr_2 | 23.00   | 99999999 | 0    | 0.000   | 0.00      |
| 26  | fact2_2  | f2_apr_2 | 196.70  | 680      | 35   | 577.500 | 113594.25 |
| 27  | f2_mar_2 | f2_apr_2 | 28.00   | 50       | 0    | 0.000   | 0.00      |
| 28  | f2_may_2 | f2_apr_2 | 64.80   | 15       | 0    | 0.000   | 0.00      |
| 29  | f1_mar_1 | f2_mar_1 | 11.00   | 99999999 | 0    | 0.000   | 0.00      |
| 30  | fact2_1  | f2_mar_1 | 88.00   | 450      | 35   | 290.000 | 25520.00  |
| 31  | f2_apr_1 | f2_mar_1 | 20.40   | 15       | 0    | 0.000   | 0.00      |
| 32  | f1_mar_2 | f2_mar_2 | 23.00   | 99999999 | 0    | 0.000   | 0.00      |
| 33  | fact2_2  | f2_mar_2 | 182.00  | 650      | 35   | 650.000 | 118300.00 |
| 34  | f2_apr_2 | f2_mar_2 | 37.20   | 15       | 0    | 0.000   | 0.00      |
| 35  | f1_may_1 | f2_may_1 | 16.00   | 99999999 | 0    | 115.000 | 1840.00   |
| 36  | fact2_1  | f2_may_1 | 128.80  | 250      | 35   | 35.000  | 4508.00   |
| 37  | f2_apr_1 | f2_may_1 | 20.00   | 30       | 0    | 0.000   | 0.00      |
| 38  | f1_may_2 | f2_may_2 | 26.00   | 99999999 | 0    | 350.000 | 9100.00   |
| 39  | fact2_2  | f2_may_2 | 181.40  | 550      | 35   | 122.500 | 22221.50  |
| 40  | f2_apr_2 | f2_may_2 | 38.00   | 50       | 0    | 0.000   | 0.00      |
| 41  | f1_mar_1 | shop1_1  | -327.65 | 250      | 0    | 143.333 | -46963.16 |
| 42  | f1_apr_1 | shop1_1  | -300.00 | 250      | 0    | 250.000 | -75000.00 |
| 43  | f1_may_1 | shop1_1  | -285.00 | 250      | 0    | 13.333  | -3800.00  |
| 44  | f2_mar_1 | shop1_1  | -297.40 | 250      | 0    | 250.000 | -74350.00 |
| 45  | f2_apr_1 | shop1_1  | -290.00 | 250      | 0    | 243.333 | -70566.67 |

**Output 5.3.1** *continued*

| Production Planning/Inventory/Distribution |               |               |               |                |             |               |                |
|--|---------------|---------------|---------------|----------------|-------------|---------------|----------------|
| Adding Side Constraints                    |               |               |               |                |             |               |                |
| Obs  | <u>_tail_</u> | <u>_head_</u> | <u>_cost_</u> | <u>_capac_</u> | <u>_lo_</u> | <u>_FLOW_</u> | <u>_FCOST_</u> |
| 46   | f2_may_1      | shop1_1       | -292.00       | 250            | 0           | 0.000         | 0.00           |
| 47   | f1_mar_2      | shop1_2       | -559.76       | 99999999       | 0           | 0.000         | 0.00           |
| 48   | f1_apr_2      | shop1_2       | -524.28       | 99999999       | 0           | 0.000         | 0.00           |
| 49   | f1_may_2      | shop1_2       | -475.02       | 99999999       | 0           | 0.000         | 0.00           |
| 50   | f2_mar_2      | shop1_2       | -567.83       | 500            | 0           | 500.000       | -283915.00     |
| 51   | f2_apr_2      | shop1_2       | -542.19       | 500            | 0           | 400.000       | -216876.00     |
| 52   | f2_may_2      | shop1_2       | -491.56       | 500            | 0           | 0.000         | 0.00           |
| 53   | f1_mar_1      | shop2_1       | -362.74       | 250            | 0           | 250.000       | -90685.00      |
| 54   | f1_apr_1      | shop2_1       | -300.00       | 250            | 0           | 250.000       | -75000.00      |
| 55   | f1_may_1      | shop2_1       | -245.00       | 250            | 0           | 0.000         | 0.00           |
| 56   | f2_mar_1      | shop2_1       | -272.70       | 250            | 0           | 0.000         | 0.00           |
| 57   | f2_apr_1      | shop2_1       | -312.00       | 250            | 0           | 250.000       | -78000.00      |
| 58   | f2_may_1      | shop2_1       | -299.00       | 250            | 0           | 150.000       | -44850.00      |
| 59   | f1_mar_2      | shop2_2       | -623.89       | 99999999       | 0           | 455.000       | -283869.95     |
| 60   | f1_apr_2      | shop2_2       | -549.68       | 99999999       | 0           | 220.000       | -120929.60     |
| 61   | f1_may_2      | shop2_2       | -460.00       | 99999999       | 0           | 0.000         | 0.00           |
| 62   | f2_mar_2      | shop2_2       | -542.83       | 500            | 0           | 125.000       | -67853.75      |
| 63   | f2_apr_2      | shop2_2       | -559.19       | 500            | 0           | 177.500       | -99256.23      |
| 64   | f2_may_2      | shop2_2       | -519.06       | 500            | 0           | 472.500       | -245255.85     |
|  |               |               |               |                |             |               | =====          |
|  |               |               |               |                |             |               | -1282708.62    |



## Example 5.4: Using Constraints and More Alteration to Arc Data

Suppose the 25-inch screen TVs produced at factory 1 in May can be sold at either shop with an increased profit of 40 dollars each. What is the new optimal solution?

```

title2 'Using Constraints and Altering arc data';
data new_arc4;
  set arc4;
  oldcost=_cost_;
  oldflow=_flow_;
  oldfc=_fcost_;
  if _tail_='f1_may_2' & (_head_='shop1_2' | _head_='shop2_2')
    then _cost_=_cost_-40;
run;

proc intpoint
bytes=1000000
printlevel2=2
arcdata=new_arc4 nodedata=node0
condata=con3 sparsecondata rhsobs='CHIP/BO LIMIT'
conout=arc5;
run;

title2 'Using Constraints and Altering arc data';
proc print data=arc5;
  var _tail_ _head_ _cost_ _capac_ _lo_
    _supply_ _demand_ _name_ _flow_ _fcost_ oldflow oldfc;
  /* to get this variable order */
  sum oldfc _fcost_;
run;

```

The following messages appear on the SAS log:

```
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: Number of <= side constraints= 5 .
NOTE: Number of == side constraints= 0 .
NOTE: Number of >= side constraints= 0 .
NOTE: Number of side constraint coefficients= 16 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 5 .
NOTE: Number of == constraints= 21 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 152 .
NOTE: Number of variables= 68 .
NOTE: After preprocessing, number of <= constraints= 5.
NOTE: After preprocessing, number of == constraints= 20.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 1 constraints from the problem.
NOTE: The preprocessor eliminated 9 constraint coefficients from the problem.
NOTE: 5 columns, 0 rows and 5 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 74 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 25 factor nodes make up 17 supernodes
NOTE: There are 88 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
  Iter  Complem_aff  Complem-ity  Duality_gap  Tot_infeasb  Tot_infeasc  Tot_infeasd
    0      -1.000000      201073760      0.894528      65408      35351      10995
    1      39022799      25967436      0.919693  4741.966761  2562.885742  256.192394
    2       5186078      1844990      0.589523          0          0      6.174556
    3       371920      320310      0.197224          0          0      1.074616
    4       151369      87643      0.060906          0          0      0.267952
    5        35115      25158      0.018017          0          0      0.072961
    6        14667  6194.354873      0.004475          0          0      0.005048
    7  2723.955063  2472.352937      0.001789          0          0      0.001714
    8  1028.390365   280.346187      0.000203          0          0      0.000235
    9   39.957867    5.611483  0.000004063          0          0          0
   10    0.014117    0.000291  9.492379E-11          0          0          0
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 10
      iterations.
NOTE: Optimum reached.
NOTE: Objective= -1295661.8.
NOTE: The data set WORK.ARC5 has 64 observations and 17 variables.
NOTE: There were 64 observations read from the data set WORK.NEW_ARC4.
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 21 observations read from the data set WORK.CON3.
```

## Output 5.4.1 CONOUT=ARC5

| Production Planning/Inventory/Distribution<br>Using Constraints and Altering arc data |          |          |         |          |      |          |          |
|---|----------|----------|---------|----------|------|----------|----------|
| Obs   | _tail_   | _head_   | _cost_  | _capac_  | _lo_ | _SUPPLY_ | _DEMAND_ |
| 1   | fact1_1  | f1_apr_1 | 78.60   | 600      | 50   | 1000     | .        |
| 2   | f1_mar_1 | f1_apr_1 | 15.00   | 50       | 0    | .        | .        |
| 3   | f1_may_1 | f1_apr_1 | 33.60   | 20       | 0    | .        | .        |
| 4   | f2_apr_1 | f1_apr_1 | 11.00   | 40       | 0    | .        | .        |
| 5   | fact1_2  | f1_apr_2 | 174.50  | 550      | 50   | 1000     | .        |
| 6   | f1_mar_2 | f1_apr_2 | 20.00   | 40       | 0    | .        | .        |
| 7   | f1_may_2 | f1_apr_2 | 49.20   | 15       | 0    | .        | .        |
| 8   | f2_apr_2 | f1_apr_2 | 21.00   | 25       | 0    | .        | .        |
| 9   | fact1_1  | f1_mar_1 | 127.90  | 500      | 50   | 1000     | .        |
| 10  | f1_apr_1 | f1_mar_1 | 33.60   | 20       | 0    | .        | .        |
| 11  | f2_mar_1 | f1_mar_1 | 10.00   | 40       | 0    | .        | .        |
| 12  | fact1_2  | f1_mar_2 | 217.90  | 400      | 40   | 1000     | .        |
| 13  | f1_apr_2 | f1_mar_2 | 38.40   | 30       | 0    | .        | .        |
| 14  | f2_mar_2 | f1_mar_2 | 20.00   | 25       | 0    | .        | .        |
| 15  | fact1_1  | f1_may_1 | 90.10   | 400      | 50   | 1000     | .        |
| 16  | f1_apr_1 | f1_may_1 | 12.00   | 50       | 0    | .        | .        |
| 17  | f2_may_1 | f1_may_1 | 13.00   | 40       | 0    | .        | .        |
| 18  | fact1_2  | f1_may_2 | 113.30  | 350      | 40   | 1000     | .        |
| 19  | f1_apr_2 | f1_may_2 | 18.00   | 40       | 0    | .        | .        |
| 20  | f2_may_2 | f1_may_2 | 13.00   | 25       | 0    | .        | .        |
| 21  | f1_apr_1 | f2_apr_1 | 11.00   | 99999999 | 0    | .        | .        |
| 22  | fact2_1  | f2_apr_1 | 62.40   | 480      | 35   | 850      | .        |
| 23  | f2_mar_1 | f2_apr_1 | 18.00   | 30       | 0    | .        | .        |
| 24  | f2_may_1 | f2_apr_1 | 30.00   | 15       | 0    | .        | .        |
| 25  | f1_apr_2 | f2_apr_2 | 23.00   | 99999999 | 0    | .        | .        |
| 26  | fact2_2  | f2_apr_2 | 196.70  | 680      | 35   | 1500     | .        |
| 27  | f2_mar_2 | f2_apr_2 | 28.00   | 50       | 0    | .        | .        |
| 28  | f2_may_2 | f2_apr_2 | 64.80   | 15       | 0    | .        | .        |
| 29  | f1_mar_1 | f2_mar_1 | 11.00   | 99999999 | 0    | .        | .        |
| 30  | fact2_1  | f2_mar_1 | 88.00   | 450      | 35   | 850      | .        |
| 31  | f2_apr_1 | f2_mar_1 | 20.40   | 15       | 0    | .        | .        |
| 32  | f1_mar_2 | f2_mar_2 | 23.00   | 99999999 | 0    | .        | .        |
| 33  | fact2_2  | f2_mar_2 | 182.00  | 650      | 35   | 1500     | .        |
| 34  | f2_apr_2 | f2_mar_2 | 37.20   | 15       | 0    | .        | .        |
| 35  | f1_may_1 | f2_may_1 | 16.00   | 99999999 | 0    | .        | .        |
| 36  | fact2_1  | f2_may_1 | 128.80  | 250      | 35   | 850      | .        |
| 37  | f2_apr_1 | f2_may_1 | 20.00   | 30       | 0    | .        | .        |
| 38  | f1_may_2 | f2_may_2 | 26.00   | 99999999 | 0    | .        | .        |
| 39  | fact2_2  | f2_may_2 | 181.40  | 550      | 35   | 1500     | .        |
| 40  | f2_apr_2 | f2_may_2 | 38.00   | 50       | 0    | .        | .        |
| 41  | f1_mar_1 | shop1_1  | -327.65 | 250      | 0    | .        | 900      |
| 42  | f1_apr_1 | shop1_1  | -300.00 | 250      | 0    | .        | 900      |
| 43  | f1_may_1 | shop1_1  | -285.00 | 250      | 0    | .        | 900      |
| 44  | f2_mar_1 | shop1_1  | -297.40 | 250      | 0    | .        | 900      |
| 45  | f2_apr_1 | shop1_1  | -290.00 | 250      | 0    | .        | 900      |

Output 5.4.1 continued

| Production Planning/Inventory/Distribution<br>Using Constraints and Altering arc data |          |         |         |          |      |          |          |
|---|----------|---------|---------|----------|------|----------|----------|
| Obs   | _tail_   | _head_  | _cost_  | _capac_  | _lo_ | _SUPPLY_ | _DEMAND_ |
| 46  | f2_may_1 | shop1_1 | -292.00 | 250      | 0    | .        | 900      |
| 47  | f1_mar_2 | shop1_2 | -559.76 | 99999999 | 0    | .        | 900      |
| 48  | f1_apr_2 | shop1_2 | -524.28 | 99999999 | 0    | .        | 900      |
| 49  | f1_may_2 | shop1_2 | -515.02 | 99999999 | 0    | .        | 900      |
| 50  | f2_mar_2 | shop1_2 | -567.83 | 500      | 0    | .        | 900      |
| 51  | f2_apr_2 | shop1_2 | -542.19 | 500      | 0    | .        | 900      |
| 52  | f2_may_2 | shop1_2 | -491.56 | 500      | 0    | .        | 900      |
| 53  | f1_mar_1 | shop2_1 | -362.74 | 250      | 0    | .        | 900      |
| 54  | f1_apr_1 | shop2_1 | -300.00 | 250      | 0    | .        | 900      |
| 55  | f1_may_1 | shop2_1 | -245.00 | 250      | 0    | .        | 900      |
| 56  | f2_mar_1 | shop2_1 | -272.70 | 250      | 0    | .        | 900      |
| 57  | f2_apr_1 | shop2_1 | -312.00 | 250      | 0    | .        | 900      |
| 58  | f2_may_1 | shop2_1 | -299.00 | 250      | 0    | .        | 900      |
| 59  | f1_mar_2 | shop2_2 | -623.89 | 99999999 | 0    | .        | 1450     |
| 60  | f1_apr_2 | shop2_2 | -549.68 | 99999999 | 0    | .        | 1450     |
| 61  | f1_may_2 | shop2_2 | -500.00 | 99999999 | 0    | .        | 1450     |
| 62  | f2_mar_2 | shop2_2 | -542.83 | 500      | 0    | .        | 1450     |
| 63  | f2_apr_2 | shop2_2 | -559.19 | 500      | 0    | .        | 1450     |
| 64  | f2_may_2 | shop2_2 | -519.06 | 500      | 0    | .        | 1450     |

| Production Planning/Inventory/Distribution<br>Using Constraints and Altering arc data |                |         |           |         |           |
|---|----------------|---------|-----------|---------|-----------|
| Obs   | _name_         | _FLOW_  | _FCOST_   | oldflow | oldfc     |
| 1   | prod f1 19 apl | 533.333 | 41920.00  | 533.333 | 41920.00  |
| 2   |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 3   | back f1 19 may | 0.000   | 0.00      | 0.000   | 0.00      |
| 4   |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 5   | prod f1 25 apl | 250.000 | 43625.00  | 250.000 | 43625.00  |
| 6   |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 7   | back f1 25 may | 0.000   | 0.00      | 0.000   | 0.00      |
| 8   |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 9   | prod f1 19 mar | 333.333 | 42633.33  | 333.333 | 42633.33  |
| 10  | back f1 19 apl | 20.000  | 672.00    | 20.000  | 672.00    |
| 11  |                | 40.000  | 400.00    | 40.000  | 400.00    |
| 12  | prod f1 25 mar | 400.000 | 87160.00  | 400.000 | 87160.00  |
| 13  | back f1 25 apl | 30.000  | 1152.00   | 30.000  | 1152.00   |
| 14  |                | 25.000  | 500.00    | 25.000  | 500.00    |
| 15  |                | 128.333 | 11562.83  | 128.333 | 11562.83  |
| 16  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 17  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 18  |                | 350.000 | 39655.00  | 350.000 | 39655.00  |
| 19  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 20  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 21  |                | 13.333  | 146.67    | 13.333  | 146.67    |
| 22  | prod f2 19 apl | 480.000 | 29952.00  | 480.000 | 29952.00  |
| 23  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 24  | back f2 19 may | 0.000   | 0.00      | 0.000   | 0.00      |
| 25  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 26  | prod f2 25 apl | 550.000 | 108185.00 | 577.500 | 113594.25 |
| 27  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 28  | back f2 25 may | 0.000   | 0.00      | 0.000   | 0.00      |
| 29  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 30  | prod f2 19 mar | 290.000 | 25520.00  | 290.000 | 25520.00  |
| 31  | back f2 19 apl | 0.000   | 0.00      | 0.000   | 0.00      |
| 32  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 33  | prod f2 25 mar | 650.000 | 118300.00 | 650.000 | 118300.00 |
| 34  | back f2 25 apl | 0.000   | 0.00      | 0.000   | 0.00      |
| 35  |                | 115.000 | 1840.00   | 115.000 | 1840.00   |
| 36  |                | 35.000  | 4508.00   | 35.000  | 4508.00   |
| 37  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 38  |                | 0.000   | 0.00      | 350.000 | 9100.00   |
| 39  |                | 150.000 | 27210.00  | 122.500 | 22221.50  |
| 40  |                | 0.000   | 0.00      | 0.000   | 0.00      |
| 41  |                | 143.333 | -46963.17 | 143.333 | -46963.16 |
| 42  |                | 250.000 | -75000.00 | 250.000 | -75000.00 |
| 43  |                | 13.333  | -3800.00  | 13.333  | -3800.00  |
| 44  |                | 250.000 | -74350.00 | 250.000 | -74350.00 |
| 45  |                | 243.333 | -70566.67 | 243.333 | -70566.67 |

| Production Planning/Inventory/Distribution<br>Using Constraints and Altering arc data |        |         |             |         |             |
|---|--------|---------|-------------|---------|-------------|
| Obs   | _name_ | _FLOW_  | _FCOST_     | oldflow | oldfc       |
| 46  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 47  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 48  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 49  |        | 350.000 | -180257.00  | 0.000   | 0.00        |
| 50  |        | 500.000 | -283915.00  | 500.000 | -283915.00  |
| 51  |        | 50.000  | -27109.50   | 400.000 | -216876.00  |
| 52  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 53  |        | 250.000 | -90685.00   | 250.000 | -90685.00   |
| 54  |        | 250.000 | -75000.00   | 250.000 | -75000.00   |
| 55  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 56  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 57  |        | 250.000 | -78000.00   | 250.000 | -78000.00   |
| 58  |        | 150.000 | -44850.00   | 150.000 | -44850.00   |
| 59  |        | 455.000 | -283869.95  | 455.000 | -283869.95  |
| 60  |        | 220.000 | -120929.60  | 220.000 | -120929.60  |
| 61  |        | 0.000   | 0.00        | 0.000   | 0.00        |
| 62  |        | 125.000 | -67853.75   | 125.000 | -67853.75   |
| 63  |        | 500.000 | -279595.00  | 177.500 | -99256.23   |
| 64  |        | 150.000 | -77859.00   | 472.500 | -245255.85  |
|   |        |         | =====       |         | =====       |
|   |        |         | -1295661.80 |         | -1282708.62 |

### Example 5.5: Nonarc Variables in the Side Constraints

You can verify that the FACT2 MAR GIZMO constraint has a left-hand-side activity of 3,470, which is not equal to the `_RHS_` of this constraint. Not all of the 3,750 chips that can be supplied to factory 2 for March production are used. It is suggested that all the possible chips be obtained in March and those not used be saved for April production. Because chips must be kept in an air-controlled environment, it costs one dollar to store each chip purchased in March until April. The maximum number of chips that can be stored in this environment at each factory is 150. In addition, a search of the parts inventory at factory 1 turned up 15 chips available for their March production.

Nonarc variables are used in the side constraints that handle the limitations of supply of Gizmo chips. A nonarc variable called `f1 unused chips` has as a value the number of chips that are not used at factory 1 in March. Another nonarc variable, `f2 unused chips`, has as a value the number of chips that are not used at factory 2 in March. `f1 chips from mar` has as a value the number of chips left over from March used for production at factory 1 in April. Similarly, `f2 chips from mar` has as a value the number of chips left over from March used for April production at factory 2 in April. The last two nonarc variables have objective function coefficients of 1 and upper bounds of 150. The Gizmo side constraints are

```

3*prod f1 19 mar + 4*prod f1 25 mar + f1 unused chips = 2615
3*prod f2 19 apl + 4*prod f2 25 apl + f2 unused chips = 3750
3*prod f1 19 apl + 4*prod f1 25 apl - f1 chips from mar = 2600
3*prod f2 19 apl + 4*prod f2 25 apl - f2 chips from mar = 3750
f1 unused chips + f2 unused chips -
f1 chips from mar - f2 chips from mar >= 0

```

The last side constraint states that the number of chips not used in March is not less than the number of chips left over from March and used in April. Here, this constraint is called CHIP LEFTOVER.

The following SAS code creates a new data set containing constraint data. It seems that most of the constraints are now equalities, so you specify `DEFCONTYPE=EQ` in the `PROC INTPOINT` statement from now on and provide constraint type data for constraints that are not “equal to” type, using the default `TYPEOBS` value `_TYPE_` as the `_COLUMN_` variable value to indicate observations that contain constraint type data. Also, from now on, the default `RHSOBS` value is used.

```

title2 'Nonarc Variables in the Side Constraints';
data con6;
  input _column_ &$17. _row_ &$15. _coef_ ;
  datalines;
prod f1 19 mar      FACT1 MAR GIZMO    3
prod f1 25 mar      FACT1 MAR GIZMO    4
f1 unused chips     FACT1 MAR GIZMO    1
_RHS_               FACT1 MAR GIZMO   2615
prod f2 19 mar      FACT2 MAR GIZMO    3
prod f2 25 mar      FACT2 MAR GIZMO    4
f2 unused chips     FACT2 MAR GIZMO    1
_RHS_               FACT2 MAR GIZMO   3750
prod f1 19 apl      FACT1 APL GIZMO    3
prod f1 25 apl      FACT1 APL GIZMO    4
f1 chips from mar   FACT1 APL GIZMO   -1
_RHS_               FACT1 APL GIZMO   2600
prod f2 19 apl      FACT2 APL GIZMO    3
prod f2 25 apl      FACT2 APL GIZMO    4
f2 chips from mar   FACT2 APL GIZMO   -1
_RHS_               FACT2 APL GIZMO   3750
f1 unused chips     CHIP LEFTOVER      1
f2 unused chips     CHIP LEFTOVER      1
f1 chips from mar   CHIP LEFTOVER     -1
f2 chips from mar   CHIP LEFTOVER     -1
_TYPE_              CHIP LEFTOVER      1
back f1 19 apl      TOTAL BACKORDER    1
back f1 25 apl      TOTAL BACKORDER    1
back f2 19 apl      TOTAL BACKORDER    1
back f2 25 apl      TOTAL BACKORDER    1
back f1 19 may      TOTAL BACKORDER    1
back f1 25 may      TOTAL BACKORDER    1
back f2 19 may      TOTAL BACKORDER    1
back f2 25 may      TOTAL BACKORDER    1
_TYPE_              TOTAL BACKORDER   -1
_RHS_               TOTAL BACKORDER    50
;

```

The nonarc variables f1 chips from mar and f2 chips from mar have objective function coefficients of 1 and upper bounds of 150. There are various ways in which this information can be furnished to `PROC INTPOINT`. If there were a `TYPE` list variable in the `CONDATA=` data set, observations could be in the form

| <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_ROW_</code> | <code>_COEF_</code> |
|-----------------------|---------------------|--------------------|---------------------|
| f1 chips from mar     | objfn               | .                  | 1                   |
| f1 chips from mar     | upperbd             | .                  | 150                 |

```
f2 chips from mar  objfn      .      1
f2 chips from mar  upperbd    .     150
```

It is desirable to assign ID list variable values to all the nonarc variables:

```
data arc6;
  input _tail_ $ _head_ $ _cost_ _capac_ _lo_ diagonal factory
        key_id $10. mth_made $ _name_&$17.;
datalines;
fact1_1 f1_apr_1 78.60 600 50 19 1 production April prod f1 19 apl
fact1_1 f1_mar_1 15.00 50 . 19 1 storage March .
fact1_1 f1_may_1 33.60 20 . 19 1 backorder May back f1 19 may
fact1_1 f2_apr_1 11.00 40 . 19 . f2_to_1 April .
fact1_2 f1_apr_2 174.50 550 50 25 1 production April prod f1 25 apl
fact1_2 f1_mar_2 20.00 40 . 25 1 storage March .
fact1_2 f1_may_2 49.20 15 . 25 1 backorder May back f1 25 may
fact1_2 f2_apr_2 21.00 25 . 25 . f2_to_1 April .
fact1_1 f1_mar_1 127.90 500 50 19 1 production March prod f1 19 mar
fact1_1 f1_apr_1 33.60 20 . 19 1 backorder April back f1 19 apl
fact1_1 f2_mar_1 10.00 40 . 19 . f2_to_1 March .
fact1_2 f1_mar_2 217.90 400 40 25 1 production March prod f1 25 mar
fact1_2 f1_apr_2 38.40 30 . 25 1 backorder April back f1 25 apl
fact1_2 f2_mar_2 20.00 25 . 25 . f2_to_1 March .
fact1_1 f1_may_1 90.10 400 50 19 1 production May .
fact1_1 f1_apr_1 12.00 50 . 19 1 storage April .
fact1_1 f2_may_1 13.00 40 . 19 . f2_to_1 May .
fact1_2 f1_may_2 113.30 350 40 25 1 production May .
fact1_2 f1_apr_2 18.00 40 . 25 1 storage April .
fact1_2 f2_may_2 13.00 25 . 25 . f2_to_1 May .
fact1_1 f2_apr_1 11.00 . . 19 . f1_to_2 April .
fact2_1 f2_apr_1 62.40 480 35 19 2 production April prod f2 19 apl
fact2_1 f2_mar_1 18.00 30 . 19 2 storage March .
fact2_1 f2_may_1 30.00 15 . 19 2 backorder May back f2 19 may
fact2_1 f1_apr_2 23.00 . . 25 . f1_to_2 April .
fact2_2 f2_apr_2 196.70 680 35 25 2 production April prod f2 25 apl
fact2_2 f2_mar_2 28.00 50 . 25 2 storage March .
fact2_2 f2_may_2 64.80 15 . 25 2 backorder May back f2 25 may
fact2_1 f1_mar_1 11.00 . . 19 . f1_to_2 March .
fact2_1 f2_mar_1 88.00 450 35 19 2 production March prod f2 19 mar
fact2_1 f2_apr_1 20.40 15 . 19 2 backorder April back f2 19 apl
fact2_1 f1_mar_2 23.00 . . 25 . f1_to_2 March .
fact2_2 f2_mar_2 182.00 650 35 25 2 production March prod f2 25 mar
fact2_2 f2_apr_2 37.20 15 . 25 2 backorder April back f2 25 apl
fact2_1 f1_may_1 16.00 . . 19 . f1_to_2 May .
fact2_1 f2_may_1 128.80 250 35 19 2 production May .
fact2_1 f2_apr_1 20.00 30 . 19 2 storage April .
fact2_1 f1_may_2 26.00 . . 25 . f1_to_2 May .
fact2_2 f2_may_2 181.40 550 35 25 2 production May .
fact2_2 f2_apr_2 38.00 50 . 25 2 storage April .
fact1_1 shop1_1 -327.65 250 . 19 1 sales March .
fact1_1 f1_apr_1 -300.00 250 . 19 1 sales April .
fact1_1 f1_may_1 -285.00 250 . 19 1 sales May .
fact2_1 f2_mar_1 -297.40 250 . 19 2 sales March .
fact2_1 f2_apr_1 -290.00 250 . 19 2 sales April .
```



```

f2_may_1 shop1_1 -292.00 250 . 19 2 sales May .
f1_mar_2 shop1_2 -559.76 . . 25 1 sales March .
f1_apr_2 shop1_2 -524.28 . . 25 1 sales April .
f1_may_2 shop1_2 -515.02 . . 25 1 sales May .
f2_mar_2 shop1_2 -567.83 500 . 25 2 sales March .
f2_apr_2 shop1_2 -542.19 500 . 25 2 sales April .
f2_may_2 shop1_2 -491.56 500 . 25 2 sales May .
f1_mar_1 shop2_1 -362.74 250 . 19 1 sales March .
f1_apr_1 shop2_1 -300.00 250 . 19 1 sales April .
f1_may_1 shop2_1 -245.00 250 . 19 1 sales May .
f2_mar_1 shop2_1 -272.70 250 . 19 2 sales March .
f2_apr_1 shop2_1 -312.00 250 . 19 2 sales April .
f2_may_1 shop2_1 -299.00 250 . 19 2 sales May .
f1_mar_2 shop2_2 -623.89 . . 25 1 sales March .
f1_apr_2 shop2_2 -549.68 . . 25 1 sales April .
f1_may_2 shop2_2 -500.00 . . 25 1 sales May .
f2_mar_2 shop2_2 -542.83 500 . 25 2 sales March .
f2_apr_2 shop2_2 -559.19 500 . 25 2 sales April .
f2_may_2 shop2_2 -519.06 500 . 25 2 sales May .
;

data arc6;
    set arc5;
    drop oldcost oldfc oldflow _flow_ _fcost_ ;
    run;

data arc6_b;
    input _name_ &$17. _cost_ _capac_ factory key_id $ ;
    datalines;
f1 unused chips . . 1 chips
f2 unused chips . . 2 chips
f1 chips from mar 1 150 1 chips
f2 chips from mar 1 150 2 chips
;

proc append force
    base=arc6 data=arc6_b;
run;

proc intpoint
    bytes=1000000
    printlevel2=2
    nodedata=node0 arcdata=arc6
    condata=con6 defcontype=eq sparseseconddata
    conout=arc7;
run;

```

The following messages appear on the SAS log:

```
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: Number of nonarc variables= 4 .
NOTE: Number of <= side constraints= 1 .
NOTE: Number of == side constraints= 4 .
NOTE: Number of >= side constraints= 1 .
NOTE: Number of side constraint coefficients= 24 .
NOTE: The following messages relate to the equivalent Linear Programming problem
      solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 1 .
NOTE: Number of == constraints= 25 .
NOTE: Number of >= constraints= 1 .
NOTE: Number of constraint coefficients= 160 .
NOTE: Number of variables= 72 .
NOTE: After preprocessing, number of <= constraints= 1.
NOTE: After preprocessing, number of == constraints= 24.
NOTE: After preprocessing, number of >= constraints= 1.
NOTE: The preprocessor eliminated 1 constraints from the problem.
NOTE: The preprocessor eliminated 9 constraint coefficients from the problem.
NOTE: 2 columns, 0 rows and 2 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 78 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 26 factor nodes make up 18 supernodes
NOTE: There are 101 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
```

| Iter | Complem_aff | Complem-ity | Duality_gap  | Tot_infeasb | Tot_infeasc | Tot_infeasd |
|------|-------------|-------------|--------------|-------------|-------------|-------------|
| 0    | -1.000000   | 210688061   | 0.904882     | 69336       | 35199       | 4398.024971 |
| 1    | 54066756    | 35459986    | 0.931873     | 5967.706945 | 3029.541352 | 935.225890  |
| 2    | 10266927    | 2957978     | 0.671565     | 0           | 0           | 36.655485   |
| 3    | 326659      | 314818      | 0.177750     | 0           | 0           | 3.893178    |
| 4    | 137432      | 83570       | 0.053111     | 0           | 0           | 0.852994    |
| 5    | 41386       | 26985       | 0.017545     | 0           | 0           | 0.204166    |
| 6    | 12451       | 6063.528974 | 0.003973     | 0           | 0           | 0.041229    |
| 7    | 2962.309960 | 1429.369437 | 0.000939     | 0           | 0           | 0.004395    |
| 8    | 352.469864  | 233.620884  | 0.000153     | 0           | 0           | 0.000297    |
| 9    | 115.012309  | 23.329492   | 0.000015331  | 0           | 0           | 0           |
| 10   | 1.754859    | 0.039304    | 2.5828276E-8 | 0           | 0           | 0           |

```
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 10
      iterations.
NOTE: Optimum reached.
NOTE: Objective= -1295542.717.
NOTE: The data set WORK.ARC7 has 68 observations and 14 variables.
NOTE: There were 68 observations read from the data set WORK.ARC6.
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 31 observations read from the data set WORK.CON6.
```

The optimal solution data set, CONOUT=ARC7, is given in [Output 5.5.1](#).

```
proc print data=arc7;
  var _tail_ _head_ _name_ _cost_ _capac_ _lo_
      _flow_ _fcost_;
  sum _fcost_;
run;
```

The optimal value of the nonarc variable f2 unused chips is 280. This means that although there are 3,750 chips that can be used at factory 2 in March, only 3,470 are used. As the optimal value of f1 unused chips is zero, all chips available for production in March at factory 1 are used. The nonarc variable f2 chips from mar also has zero optimal value. This means that the April production at factory 2 does not need any chips that could have been held in inventory since March. However, the nonarc variable f1 chips from mar has value of 20. Thus, 3,490 chips should be ordered for factory 2 in March. Twenty of these chips should be held in inventory until April, then sent to factory 1.

## Output 5.5.1 CONOUT=ARC7

| Production Planning/Inventory/Distribution<br>Nonarc Variables in the Side Constraints |          |          |                |         |          |      |         |           |
|--|----------|----------|----------------|---------|----------|------|---------|-----------|
| Obs  | _tail_   | _head_   | _name_         | _cost_  | _capac_  | _lo_ | _FLOW_  | _FCOST_   |
| 1  | fact1_1  | f1_apr_1 | prod f1 19 apl | 78.60   | 600      | 50   | 540.000 | 42444.00  |
| 2  | f1_mar_1 | f1_apr_1 |                | 15.00   | 50       | 0    | 0.000   | 0.00      |
| 3  | f1_may_1 | f1_apr_1 | back f1 19 may | 33.60   | 20       | 0    | 0.000   | 0.00      |
| 4  | f2_apr_1 | f1_apr_1 |                | 11.00   | 40       | 0    | 0.000   | 0.00      |
| 5  | fact1_2  | f1_apr_2 | prod f1 25 apl | 174.50  | 550      | 50   | 250.000 | 43625.01  |
| 6  | f1_mar_2 | f1_apr_2 |                | 20.00   | 40       | 0    | 0.000   | 0.00      |
| 7  | f1_may_2 | f1_apr_2 | back f1 25 may | 49.20   | 15       | 0    | 0.000   | 0.00      |
| 8  | f2_apr_2 | f1_apr_2 |                | 21.00   | 25       | 0    | 25.000  | 525.00    |
| 9  | fact1_1  | f1_mar_1 | prod f1 19 mar | 127.90  | 500      | 50   | 338.333 | 43272.81  |
| 10   | f1_apr_1 | f1_mar_1 | back f1 19 apl | 33.60   | 20       | 0    | 20.000  | 672.00    |
| 11   | f2_mar_1 | f1_mar_1 |                | 10.00   | 40       | 0    | 40.000  | 400.00    |
| 12   | fact1_2  | f1_mar_2 | prod f1 25 mar | 217.90  | 400      | 40   | 400.000 | 87159.99  |
| 13   | f1_apr_2 | f1_mar_2 | back f1 25 apl | 38.40   | 30       | 0    | 30.000  | 1152.00   |
| 14   | f2_mar_2 | f1_mar_2 |                | 20.00   | 25       | 0    | 25.000  | 500.00    |
| 15   | fact1_1  | f1_may_1 |                | 90.10   | 400      | 50   | 116.667 | 10511.68  |
| 16   | f1_apr_1 | f1_may_1 |                | 12.00   | 50       | 0    | 0.000   | 0.00      |
| 17   | f2_may_1 | f1_may_1 |                | 13.00   | 40       | 0    | 0.000   | 0.00      |
| 18   | fact1_2  | f1_may_2 |                | 113.30  | 350      | 40   | 350.000 | 39655.00  |
| 19   | f1_apr_2 | f1_may_2 |                | 18.00   | 40       | 0    | 0.000   | 0.00      |
| 20   | f2_may_2 | f1_may_2 |                | 13.00   | 25       | 0    | 0.000   | 0.00      |
| 21   | f1_apr_1 | f2_apr_1 |                | 11.00   | 99999999 | 0    | 20.000  | 220.00    |
| 22   | fact2_1  | f2_apr_1 | prod f2 19 apl | 62.40   | 480      | 35   | 480.000 | 29952.00  |
| 23   | f2_mar_1 | f2_apr_1 |                | 18.00   | 30       | 0    | 0.000   | 0.00      |
| 24   | f2_may_1 | f2_apr_1 | back f2 19 may | 30.00   | 15       | 0    | 0.000   | 0.00      |
| 25   | f1_apr_2 | f2_apr_2 |                | 23.00   | 99999999 | 0    | 0.000   | 0.00      |
| 26   | fact2_2  | f2_apr_2 | prod f2 25 apl | 196.70  | 680      | 35   | 577.500 | 113594.25 |
| 27   | f2_mar_2 | f2_apr_2 |                | 28.00   | 50       | 0    | 0.000   | 0.00      |
| 28   | f2_may_2 | f2_apr_2 | back f2 25 may | 64.80   | 15       | 0    | 0.000   | 0.00      |
| 29   | f1_mar_1 | f2_mar_1 |                | 11.00   | 99999999 | 0    | 0.000   | 0.00      |
| 30   | fact2_1  | f2_mar_1 | prod f2 19 mar | 88.00   | 450      | 35   | 290.000 | 25520.00  |
| 31   | f2_apr_1 | f2_mar_1 | back f2 19 apl | 20.40   | 15       | 0    | 0.000   | 0.00      |
| 32   | f1_mar_2 | f2_mar_2 |                | 23.00   | 99999999 | 0    | 0.000   | 0.00      |
| 33   | fact2_2  | f2_mar_2 | prod f2 25 mar | 182.00  | 650      | 35   | 650.000 | 118300.00 |
| 34   | f2_apr_2 | f2_mar_2 | back f2 25 apl | 37.20   | 15       | 0    | 0.000   | 0.00      |
| 35   | f1_may_1 | f2_may_1 |                | 16.00   | 99999999 | 0    | 115.000 | 1840.00   |
| 36   | fact2_1  | f2_may_1 |                | 128.80  | 250      | 35   | 35.000  | 4508.00   |
| 37   | f2_apr_1 | f2_may_1 |                | 20.00   | 30       | 0    | 0.000   | 0.00      |
| 38   | f1_may_2 | f2_may_2 |                | 26.00   | 99999999 | 0    | 0.000   | 0.00      |
| 39   | fact2_2  | f2_may_2 |                | 181.40  | 550      | 35   | 122.500 | 22221.50  |
| 40   | f2_apr_2 | f2_may_2 |                | 38.00   | 50       | 0    | 0.000   | 0.00      |
| 41   | f1_mar_1 | shop1_1  |                | -327.65 | 250      | 0    | 148.333 | -48601.35 |
| 42   | f1_apr_1 | shop1_1  |                | -300.00 | 250      | 0    | 250.000 | -75000.00 |
| 43   | f1_may_1 | shop1_1  |                | -285.00 | 250      | 0    | 1.667   | -475.01   |
| 44   | f2_mar_1 | shop1_1  |                | -297.40 | 250      | 0    | 250.000 | -74350.00 |
| 45   | f2_apr_1 | shop1_1  |                | -290.00 | 250      | 0    | 250.000 | -72500.00 |

## Output 5.5.1 continued

| Production Planning/Inventory/Distribution<br>Nonarc Variables in the Side Constraints |          |                   |        |         |          |      |             |
|--|----------|-------------------|--------|---------|----------|------|-------------|
| Obs  | _tail_   | _head_            | _name_ | _cost_  | _capac_  | _lo_ | _FCOST_     |
| 46   | f2_may_1 | shop1_1           |        | -292.00 | 250      | 0    | 0.000       |
| 47   | f1_mar_2 | shop1_2           |        | -559.76 | 99999999 | 0    | 0.000       |
| 48   | f1_apr_2 | shop1_2           |        | -524.28 | 99999999 | 0    | 0.000       |
| 49   | f1_may_2 | shop1_2           |        | -515.02 | 99999999 | 0    | 347.500     |
| 50   | f2_mar_2 | shop1_2           |        | -567.83 | 500      | 0    | 500.000     |
| 51   | f2_apr_2 | shop1_2           |        | -542.19 | 500      | 0    | 52.500      |
| 52   | f2_may_2 | shop1_2           |        | -491.56 | 500      | 0    | 0.000       |
| 53   | f1_mar_1 | shop2_1           |        | -362.74 | 250      | 0    | 250.000     |
| 54   | f1_apr_1 | shop2_1           |        | -300.00 | 250      | 0    | 250.000     |
| 55   | f1_may_1 | shop2_1           |        | -245.00 | 250      | 0    | 0.000       |
| 56   | f2_mar_1 | shop2_1           |        | -272.70 | 250      | 0    | 0.000       |
| 57   | f2_apr_1 | shop2_1           |        | -312.00 | 250      | 0    | 250.000     |
| 58   | f2_may_1 | shop2_1           |        | -299.00 | 250      | 0    | 150.000     |
| 59   | f1_mar_2 | shop2_2           |        | -623.89 | 99999999 | 0    | 455.000     |
| 60   | f1_apr_2 | shop2_2           |        | -549.68 | 99999999 | 0    | 245.000     |
| 61   | f1_may_2 | shop2_2           |        | -500.00 | 99999999 | 0    | 2.500       |
| 62   | f2_mar_2 | shop2_2           |        | -542.83 | 500      | 0    | 125.000     |
| 63   | f2_apr_2 | shop2_2           |        | -559.19 | 500      | 0    | 500.000     |
| 64   | f2_may_2 | shop2_2           |        | -519.06 | 500      | 0    | 122.500     |
| 65   |          | f1 chips from mar |        | 1.00    | 150      | 0    | 20.000      |
| 66   |          | f1 unused chips   |        | 0.00    | 99999999 | 0    | 0.001       |
| 67   |          | f2 chips from mar |        | 1.00    | 150      | 0    | 0.000       |
| 68   |          | f2 unused chips   |        | 0.00    | 99999999 | 0    | 280.000     |
|  |          |                   |        |         |          |      | =====       |
|  |          |                   |        |         |          |      | -1295542.72 |

## Example 5.6: Solving an LP Problem with Data in MPS Format

In this example, PROC INTPOINT is ultimately used to solve an LP. But prior to that, there is SAS code that is used to read a MPS format file and initialize an input SAS data set. MPS was an optimization package developed for IBM computers many years ago and the format by which data had to be supplied to that system became the industry standard for other optimization software packages, including those developed recently. The MPS format is described in Murtagh (1981). If you have an LP which has data in MPS format in a file /your-directory/your-filename.dat, then the following SAS code should be run:

```
filename w '/your-directory/your-filename.dat';
data raw;
  infile w lrecl=80 pad;
  input field1 $ 2-3 field2 $ 5-12 field3 $ 15-22
        field4 25-36 field5 $ 40-47 field6 50-61;
run;
%sasmpsxs;
data lp;
  set;
  if _type_="FREE" then _type_="MIN";
```

```

        if lag(_type_)="*HS" then _type_="RHS";
    run;
proc sort data=lp;
    by _col_;
run;

proc intpoint
    arcdata=lp
    condata=lp sparsesecondata rhsobs=rhs grouped=condata
    conout=solutn /* SAS data set for the optimal solution */
    bytes=20000000
    nnas=1700 ncoefs=4000 ncons=700
    printlevel2=2 memrep;
run;

proc lp
    data=lp sparsedata
    endpause time=3600 maxit1=100000 maxit2=100000;
run;
show status;
quit;

```

You will have to specify the appropriate path and file name in which your MPS format data resides.

SASMPSEX is a SAS macro provided within SAS/OR software. The MPS format resembles the [sparse](#) format of the [CONDATA=](#) data set for PROC INTPOINT. The SAS macro SASMPSEX examines the MPS data and transfers it into a SAS data set while automatically taking into account how the MPS format differs slightly from PROC INTPOINT's [sparse](#) format.

The parameters [NNAS=1700](#), [NCOEFS=4000](#), and [NCONS=700](#) indicate the approximate (overestimated) number of variables, coefficients and constraints this model has. You must change these to your problems dimensions. Knowing these, PROC INTPOINT is able to utilize memory better and read the data faster. These parameters are optional.

The PROC SORT preceding PROC INTPOINT is not necessary, but sorting the SAS data set can speed up PROC INTPOINT when it reads the data. After the sort, data for each column is grouped together. [GROUPED=condata](#) can be specified.

For small problems, presorting and specifying those additional options is not going to greatly influence PROC INTPOINT's run time. However, when problems are large, presorting and specifying those additional options can be very worthwhile.

If you generate the model yourself, you will be familiar enough with it to know what to specify for the [RHSOBS=](#) parameter. If the value of the SAS variable in the [COLUMN](#) list is equal to the character string specified as the [RHSOBS=](#) option, the data in that observation is interpreted as right-hand-side data as opposed to coefficient data. If you do not know what to specify for the [RHSOBS=](#) option, you should first run [PROC LP](#) and optionally set [MAXIT1=1](#) and [MAXIT2=1](#). PROC LP will output a Problem Summary that includes the line

```
Rhs Variable      rhs-charstr
```

[BYTES=20000000](#) is the size of working memory PROC INTPOINT is allowed.

The options `PRINTLEVEL2=2` and `MEMREP` indicate that you want to see an iteration log and messages about memory usage. Specifying these options is optional.

---

### Example 5.7: Converting to an MPS-Format SAS Data Set

This example demonstrates the use of the `MPSOUT=` option to convert a problem data set in PROC INTPOINT input format into an MPS-format SAS data set for use with the OPTLP procedure.

Suppose you want to solve a linear program with the following formulation:

$$\begin{array}{llllll}
 \text{min} & 2x_1 & - & 3x_2 & - & 4x_3 \\
 \text{subject to} & & - & 2x_2 & - & 3x_3 & \geq & -5 \\
 & x_1 & + & x_2 & + & 2x_3 & \leq & 4 \\
 & x_1 & + & 2x_2 & + & 3x_3 & \geq & 7 \\
 & & 0 & \leq & x_1 & \leq & 10 \\
 & & 0 & \leq & x_2 & \leq & 15 \\
 & & 0 & \leq & x_3 & \leq & 20
 \end{array}$$

You can save the LP in dense format by using the following DATA step:

```
data exdata;
  input x1 x2 x3 _type_ $ _rhs_;
datalines;
2 -3 -4 min .
. -2 -3 >= -5
1 1 2 <= 6
1 2 3 >= 7
10 15 20 upperbd .
;
```

If you decide to solve the problem by using the OPTLP procedure, you need to convert the data set `exdata` from dense format to MPS format. You can accomplish this by using the following statements:

```
proc intpoint condata=exdata mpsout=mpsdata bytes=100000;
run;
```

The MPS-format SAS data set mpsdata is shown in [Output 5.7.1](#).

**Output 5.7.1** Data Set mpsdata

| Obs | field1  | field2  | field3  | field4 | field5 | field6 |
|-----|---------|---------|---------|--------|--------|--------|
| 1   | NAME    |         | modname | .      |        | .      |
| 2   | ROWS    |         |         | .      |        | .      |
| 3   | MIN     | objfn   |         | .      |        | .      |
| 4   | G       | _OBS2_  |         | .      |        | .      |
| 5   | L       | _OBS3_  |         | .      |        | .      |
| 6   | G       | _OBS4_  |         | .      |        | .      |
| 7   | COLUMNS |         |         | .      |        | .      |
| 8   |         | x1      | objfn   | 2      | _OBS3_ | 1      |
| 9   |         | x1      | _OBS4_  | 1      |        | .      |
| 10  |         | x2      | objfn   | -3     | _OBS2_ | -2     |
| 11  |         | x2      | _OBS3_  | 1      | _OBS4_ | 2      |
| 12  |         | x3      | objfn   | -4     | _OBS2_ | -3     |
| 13  |         | x3      | _OBS3_  | 2      | _OBS4_ | 3      |
| 14  | RHS     |         |         | .      |        | .      |
| 15  |         |         | _OBS2_  | -5     | _OBS3_ | 6      |
| 16  |         |         | _OBS4_  | 7      |        | .      |
| 17  | BOUNDS  |         |         | .      |        | .      |
| 18  | UP      | bdsvect | x1      | 10     |        | .      |
| 19  | UP      | bdsvect | x2      | 15     |        | .      |
| 20  | UP      | bdsvect | x3      | 20     |        | .      |
| 21  | ENDATA  |         |         | .      |        | .      |

The constraint names \_OBS2\_, \_OBS3\_, and \_OBS4\_ are generated by the INTPOINT procedure. If you want to provide your own constraint names, use the [ROW](#) list variable in the [CONOUT=](#) data set. If you specify the problem data in sparse format instead of dense format, the MPSOUT= option produces the same MPS-format SAS data set shown in the preceding output.

Now that the problem data are in MPS format, you can solve the problem by using the OPTLP procedure. For more information, see Chapter 10, “The OPTLP Procedure” (*SAS/OR User’s Guide: Mathematical Programming*).



## Example 5.8: Migration to OPTMODEL: Production, Inventory, Distribution

The following example shows how to solve [Example 5.1](#) using PROC OPTMODEL. The input data sets are the same as in that example.

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called ARC1:

```
proc optmodel;
  set <str> NODES;
  num _supdem_ {NODES} init 0;
  read data node0 into NODES=[_node_] _supdem_;

  set <str,str> ARCS;
  num _lo_ {ARCS} init 0;
  num _capac_ {ARCS} init .;
  num _cost_ {ARCS};
  num diagonal {ARCS};
  num factory {ARCS};
  str key_id {ARCS};
  str mth_made {ARCS};
  str _name_ {ARCS};

  read data arc0 nomiss into ARCS=[_tail_ _head_] _lo_ _capac_ _cost_
    diagonal factory key_id mth_made _name_;
  NODES = NODES union (union {<i,j> in ARCS} {i,j});

  var Flow {<i,j> in ARCS} >= _lo_[i,j];
  for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
  min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
  con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
    - sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];

  num infinity = min {r in {}} r;
  num excess = sum {i in NODES} _supdem_[i];
  if (excess > 0) then do;
    /* change equality constraint to le constraint */
    for {i in NODES: _supdem_[i] > 0} balance[i].lb = -infinity;
  end;
  else if (excess < 0) then do;
    /* change equality constraint to ge constraint */
    for {i in NODES: _supdem_[i] < 0} balance[i].ub = infinity;
  end;

  solve;

  num _supply_ {<i,j> in ARCS} =
    (if _supdem_[i] ne 0 then _supdem_[i] else .);
  num _demand_ {<i,j> in ARCS} =
    (if _supdem_[j] ne 0 then -_supdem_[j] else .);
  num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

  create data arc1 from [_tail_ _head_]

```

```

      _cost_ _capac_ _lo_ _name_ _supply_ _demand_ _flow_=Flow _fcost_
      diagonal factory key_id mth_made;
quit;

```

The statements use both single-dimensional (NODES) and multiple-dimensional (ARCS) index sets, which are populated from the corresponding data set variables in the READ DATA statements. The `_SUPDEM_`, `_LO_`, and `_CAPAC_` parameters are given initial values, and the NOMISS option in the READ DATA statement tells OPTMODEL to read only the nonmissing values from the input data set. The balance constraint is initially declared as an equality, but depending on the total supply or demand, the sense of this constraint is changed to “ $\leq$ ” or “ $\geq$ ” by relaxing the constraint’s lower or upper bound, respectively. The ARC1 output data set contains the same information as in [Example 5.1](#).

The PROC PRINT statements are the same as in [Example 5.1](#):

```

proc print data=arc1 width=min;
  var _tail_ _head_ _cost_ _capac_ _lo_ _flow_ _fcost_
  diagonal factory key_id mth_made;
  sum _fcost_;
run;

```

The output is displayed in [Output 5.8.1](#).

### Output 5.8.1 Output Data Set

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem |          |          |         |     |    |     |           |    |   |            |       |
|---|----------|----------|---------|-----|----|-----|-----------|----|---|------------|-------|
|   |          |          |         |     |    |     |           | d  |   |            | m     |
|   |          |          |         |     |    |     |           | i  | f |            | t     |
|   |          |          |         |     |    |     |           | a  | a | k          | h     |
|   |          |          |         |     |    |     |           | g  | c | e          | —     |
| O   | a        | e        | o       | p   | l  | o   | s         | o  | n | y          | m     |
| b   | i        | a        | s       | a   | l  | s   | t         | a  | r | i          | d     |
| s   | —        | —        | —       | —   | —  | —   | —         | l  | y | d          | e     |
| 1   | fact1_1  | f1_mar_1 | 127.90  | 500 | 50 | 345 | 44125.50  | 19 | 1 | production | March |
| 2   | fact1_1  | f1_apr_1 | 78.60   | 600 | 50 | 600 | 47160.00  | 19 | 1 | production | April |
| 3   | fact1_1  | f1_may_1 | 95.10   | 400 | 50 | 50  | 4755.00   | 19 | 1 | production | May   |
| 4   | f1_mar_1 | f1_apr_1 | 15.00   | 50  | 0  | 0   | 0.00      | 19 | 1 | storage    | March |
| 5   | f1_apr_1 | f1_may_1 | 12.00   | 50  | 0  | 50  | 600.00    | 19 | 1 | storage    | April |
| 6   | f1_apr_1 | f1_mar_1 | 28.00   | 20  | 0  | 20  | 560.00    | 19 | 1 | backorder  | April |
| 7   | f1_may_1 | f1_apr_1 | 28.00   | 20  | 0  | 0   | 0.00      | 19 | 1 | backorder  | May   |
| 8   | f1_mar_1 | f2_mar_1 | 11.00   | .   | 0  | 0   | 0.00      | 19 | . | f1_to_2    | March |
| 9   | f1_apr_1 | f2_apr_1 | 11.00   | .   | 0  | 30  | 330.00    | 19 | . | f1_to_2    | April |
| 10  | f1_may_1 | f2_may_1 | 16.00   | .   | 0  | 100 | 1600.00   | 19 | . | f1_to_2    | May   |
| 11  | f1_mar_1 | shop1_1  | -327.65 | 250 | 0  | 155 | -50785.75 | 19 | 1 | sales      | March |
| 12  | f1_apr_1 | shop1_1  | -300.00 | 250 | 0  | 250 | -75000.00 | 19 | 1 | sales      | April |
| 13  | f1_may_1 | shop1_1  | -285.00 | 250 | 0  | 0   | 0.00      | 19 | 1 | sales      | May   |
| 14  | f1_mar_1 | shop2_1  | -362.74 | 250 | 0  | 250 | -90685.00 | 19 | 1 | sales      | March |
| 15  | f1_apr_1 | shop2_1  | -300.00 | 250 | 0  | 250 | -75000.00 | 19 | 1 | sales      | April |
| 16  | f1_may_1 | shop2_1  | -245.00 | 250 | 0  | 0   | 0.00      | 19 | 1 | sales      | May   |
| 17  | fact2_1  | f2_mar_1 | 88.00   | 450 | 35 | 290 | 25520.00  | 19 | 2 | production | March |
| 18  | fact2_1  | f2_apr_1 | 62.40   | 480 | 35 | 480 | 29952.00  | 19 | 2 | production | April |
| 19  | fact2_1  | f2_may_1 | 133.80  | 250 | 35 | 35  | 4683.00   | 19 | 2 | production | May   |
| 20  | f2_mar_1 | f2_apr_1 | 18.00   | 30  | 0  | 0   | 0.00      | 19 | 2 | storage    | March |
| 21  | f2_apr_1 | f2_may_1 | 20.00   | 30  | 0  | 15  | 300.00    | 19 | 2 | storage    | April |
| 22  | f2_apr_1 | f2_mar_1 | 17.00   | 15  | 0  | 0   | 0.00      | 19 | 2 | backorder  | April |
| 23  | f2_may_1 | f2_apr_1 | 25.00   | 15  | 0  | 0   | 0.00      | 19 | 2 | backorder  | May   |
| 24  | f2_mar_1 | f1_mar_1 | 10.00   | 40  | 0  | 40  | 400.00    | 19 | . | f2_to_1    | March |
| 25  | f2_apr_1 | f1_apr_1 | 11.00   | 40  | 0  | 0   | 0.00      | 19 | . | f2_to_1    | April |
| 26  | f2_may_1 | f1_may_1 | 13.00   | 40  | 0  | 0   | 0.00      | 19 | . | f2_to_1    | May   |
| 27  | f2_mar_1 | shop1_1  | -297.40 | 250 | 0  | 250 | -74350.00 | 19 | 2 | sales      | March |
| 28  | f2_apr_1 | shop1_1  | -290.00 | 250 | 0  | 245 | -71050.00 | 19 | 2 | sales      | April |
| 29  | f2_may_1 | shop1_1  | -292.00 | 250 | 0  | 0   | 0.00      | 19 | 2 | sales      | May   |
| 30  | f2_mar_1 | shop2_1  | -272.70 | 250 | 0  | 0   | 0.00      | 19 | 2 | sales      | March |
| 31  | f2_apr_1 | shop2_1  | -312.00 | 250 | 0  | 250 | -78000.00 | 19 | 2 | sales      | April |
| 32  | f2_may_1 | shop2_1  | -299.00 | 250 | 0  | 150 | -44850.00 | 19 | 2 | sales      | May   |
| 33  | fact1_2  | f1_mar_2 | 217.90  | 400 | 40 | 400 | 87160.00  | 25 | 1 | production | March |
| 34  | fact1_2  | f1_apr_2 | 174.50  | 550 | 50 | 550 | 95975.00  | 25 | 1 | production | April |
| 35  | fact1_2  | f1_may_2 | 133.30  | 350 | 40 | 40  | 5332.00   | 25 | 1 | production | May   |
| 36  | f1_mar_2 | f1_apr_2 | 20.00   | 40  | 0  | 0   | 0.00      | 25 | 1 | storage    | March |
| 37  | f1_apr_2 | f1_may_2 | 18.00   | 40  | 0  | 0   | 0.00      | 25 | 1 | storage    | April |
| 38  | f1_apr_2 | f1_mar_2 | 32.00   | 30  | 0  | 30  | 960.00    | 25 | 1 | backorder  | April |
| 39  | f1_may_2 | f1_apr_2 | 41.00   | 15  | 0  | 15  | 615.00    | 25 | 1 | backorder  | May   |
| 40  | f1_mar_2 | f2_mar_2 | 23.00   | .   | 0  | 0   | 0.00      | 25 | . | f1_to_2    | March |
| 41  | f1_apr_2 | f2_apr_2 | 23.00   | .   | 0  | 0   | 0.00      | 25 | . | f1_to_2    | April |
| 42  | f1_may_2 | f2_may_2 | 26.00   | .   | 0  | 0   | 0.00      | 25 | . | f1_to_2    | May   |
| 43  | f1_mar_2 | shop1_2  | -559.76 | .   | 0  | 0   | 0.00      | 25 | 1 | sales      | March |

**Output 5.8.1** *continued*

| Production Planning/Inventory/Distribution<br>Minimum Cost Flow problem |          |          |         |     |    |     |             |    |   |            |       |
|---|----------|----------|---------|-----|----|-----|-------------|----|---|------------|-------|
|   |          |          |         |     |    |     |             | d  | f |            | m     |
|   |          |          |         | c   |    | f   |             | i  | a | k          | t     |
|   | t        | h        | c       | a   |    | c   |             | g  | c | e          | h     |
|   | a        | e        | o       | p   | l  | o   |             | o  | t | y          | —     |
| O   | i        | a        | s       | a   | l  | o   | s           | n  | o | —          | a     |
| b   | l        | d        | t       | c   | o  | w   | t           | a  | r | i          | d     |
| s   | —        | —        | —       | —   | —  | —   | —           | l  | y | d          | e     |
| 44  | f1_apr_2 | shop1_2  | -524.28 | .   | 0  | 0   | 0.00        | 25 | 1 | sales      | April |
| 45  | f1_may_2 | shop1_2  | -475.02 | .   | 0  | 25  | -11875.50   | 25 | 1 | sales      | May   |
| 46  | f1_mar_2 | shop2_2  | -623.89 | .   | 0  | 455 | -283869.95  | 25 | 1 | sales      | March |
| 47  | f1_apr_2 | shop2_2  | -549.68 | .   | 0  | 535 | -294078.80  | 25 | 1 | sales      | April |
| 48  | f1_may_2 | shop2_2  | -460.00 | .   | 0  | 0   | 0.00        | 25 | 1 | sales      | May   |
| 49  | fact2_2  | f2_mar_2 | 182.00  | 650 | 35 | 645 | 117390.00   | 25 | 2 | production | March |
| 50  | fact2_2  | f2_apr_2 | 196.70  | 680 | 35 | 680 | 133756.00   | 25 | 2 | production | April |
| 51  | fact2_2  | f2_may_2 | 201.40  | 550 | 35 | 35  | 7049.00     | 25 | 2 | production | May   |
| 52  | f2_mar_2 | f2_apr_2 | 28.00   | 50  | 0  | 0   | 0.00        | 25 | 2 | storage    | March |
| 53  | f2_apr_2 | f2_may_2 | 38.00   | 50  | 0  | 0   | 0.00        | 25 | 2 | storage    | April |
| 54  | f2_apr_2 | f2_mar_2 | 31.00   | 15  | 0  | 0   | 0.00        | 25 | 2 | backorder  | April |
| 55  | f2_may_2 | f2_apr_2 | 54.00   | 15  | 0  | 15  | 810.00      | 25 | 2 | backorder  | May   |
| 56  | f2_mar_2 | f1_mar_2 | 20.00   | 25  | 0  | 25  | 500.00      | 25 | . | f2_to_1    | March |
| 57  | f2_apr_2 | f1_apr_2 | 21.00   | 25  | 0  | 0   | 0.00        | 25 | . | f2_to_1    | April |
| 58  | f2_may_2 | f1_may_2 | 43.00   | 25  | 0  | 0   | 0.00        | 25 | . | f2_to_1    | May   |
| 59  | f2_mar_2 | shop1_2  | -567.83 | 500 | 0  | 500 | -283915.00  | 25 | 2 | sales      | March |
| 60  | f2_apr_2 | shop1_2  | -542.19 | 500 | 0  | 375 | -203321.25  | 25 | 2 | sales      | April |
| 61  | f2_may_2 | shop1_2  | -461.56 | 500 | 0  | 0   | 0.00        | 25 | 2 | sales      | May   |
| 62  | f2_mar_2 | shop2_2  | -542.83 | 500 | 0  | 120 | -65139.60   | 25 | 2 | sales      | March |
| 63  | f2_apr_2 | shop2_2  | -559.19 | 500 | 0  | 320 | -178940.80  | 25 | 2 | sales      | April |
| 64  | f2_may_2 | shop2_2  | -489.06 | 500 | 0  | 20  | -9781.20    | 25 | 2 | sales      | May   |
|   |          |          |         |     |    |     | =====       |    |   |            |       |
|   |          |          |         |     |    |     | -1281110.35 |    |   |            |       |

The optimal objective value is the same as in [Example 5.1](#). The log is displayed in [Output 5.8.2](#).

### Output 5.8.2 OPTMODEL Log

```
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 64 observations read from the data set WORK.ARC0.
NOTE: The problem has 64 variables (0 free, 0 fixed).
NOTE: The problem has 20 linear constraints (4 LE, 16 EQ, 0 GE, 0 range).
NOTE: The problem has 128 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 0 variables and 0 constraints.
NOTE: The OPTLP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 64 variables, 20 constraints, and 128
      constraint coefficients.
NOTE: The DUAL SIMPLEX solver is called.
      Objective
Phase Iteration Value
      2          1   -2952213
      2         30   -1281110
NOTE: Optimal.
NOTE: Objective = -1281110.35.
NOTE: The data set WORK.ARC1 has 64 observations and 14 variables.
```

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# Chapter 6

## The LP Procedure

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---

## Overview: LP Procedure

The LP procedure solves linear programs, integer programs, and mixed-integer programs. It also performs parametric programming, range analysis, and reports on solution sensitivity to changes in the right-hand-side constants and price coefficients.

The LP procedure provides various control options and solution strategies. It also provides the functionality to produce various kinds of intermediate and final solution information. The procedure's interactive features enable you to take control of the problem solving process. During linear or integer iterations, for example, you can stop the procedure at intermediate stages and examine current results. If necessary, you can change options or strategies and resume the execution of the procedure.

The LP procedure is used to optimize a linear function subject to linear and integer constraints. Specifically, the LP procedure solves the general mixed-integer program of the form



$$\begin{aligned}
& \text{minimize} && c^T x \\
& \text{subject to} && Ax \{ \geq, =, \leq \} b \\
& && \ell \leq x \leq u \\
& && x_i \text{ is integer, } i \in \mathcal{S}
\end{aligned}$$

where

- $A$  is an  $m \times n$  matrix of technological coefficients
- $b$  is an  $m \times 1$  matrix of right-hand-side (RHS) constants
- $c$  is an  $n \times 1$  matrix of objective function coefficients
- $x$  is an  $n \times 1$  matrix of structural variables
- $\ell$  is an  $n \times 1$  matrix of lower bounds on  $x$
- $u$  is an  $n \times 1$  matrix of upper bounds on  $x$
- $\mathcal{S}$  is a subset of the set of indices  $\{1, \dots, n\}$

Linear programs (when  $\mathcal{S}$  is empty) are denoted by (LP). For these problems, the procedure employs the two-phase revised simplex method, which uses the Bartels-Golub update of the LU decomposed basis matrix to pivot between feasible solutions (Bartels 1971). In phase 1, PROC LP finds a basic feasible solution to (LP), while in phase 2, PROC LP finds an optimal solution,  $x^{opt}$ . The procedure implicitly handles unrestricted variables, lower-bounded variables, upper-bounded variables, and ranges on constraints. When no explicit lower bounds are specified, PROC LP assumes that all variables are bounded below by zero.

When a variable is specified as an integer variable,  $\mathcal{S}$  has at least one element. The procedure then uses the branch-and-bound technique for optimization.

The relaxed problem (the problem with no integer constraints) is solved initially using the primal algorithm described previously. Constraints are added in defining the subsequent descendant problems in the branch-and-bound tree. These problems are then solved using the dual simplex algorithm. Dual pivots are referred to as phase 3 pivots.

The preprocessing option enables the procedure to identify redundant and infeasible constraints, fix variables, and reduce the feasible region before solving a problem. For linear programs, the option often can reduce the number of constraints and variables, leading to a quicker elapsed solution time and improved reliability. For integer programs, it often reduces the gap between an integer program and its relaxed linear program, which will likely lead to a reduced branch-and-bound tree and a quicker CPU time. In general, it provides users an alternative to solving large, complicated operations research problems.

The LP procedure can also analyze the sensitivity of the solution  $x^{opt}$  to changes in both the objective function and the right-hand-side constants. There are three techniques available for this analysis: sensitivity analysis, parametric programming, and range analysis. Sensitivity analysis enables you to examine the size of a perturbation to the right-hand-side or objective vector by an arbitrary change vector for which the basis of the current optimal solution remains optimal.

Parametric programming, on the other hand, enables you to specify the size of the perturbation beforehand and examine how the optimal solution changes as the desired perturbation is realized. With this technique,

the procedure pivots to maintain optimality as the right-hand-side or objective vector is perturbed beyond the range for which the current solution is optimal. Range analysis is used to examine the range of each right-hand-side value or objective coefficient for which the basis of the current optimal solution remains optimal.

The LP procedure can also save both primal and dual solutions, the current tableau, and the branch-and-bound tree in SAS data sets. This enables you to generate solution reports and perform additional analyses with the SAS System. Although PROC LP reports solutions, this feature is particularly useful for reporting solutions in formats tailored to your specific needs. Saving computational results in a data set also enables you to continue executing a problem not solved because of insufficient time or other computational problems.

The LP procedure uses the Output Delivery System (ODS), a SAS subsystem that provides capabilities for displaying and controlling the output from SAS procedures. ODS enables you to modify the headers, column names, data formats, and layouts of the output tables in PROC LP.

There are no restrictions on the problem size in the LP procedure. The number of constraints and variables in a problem that PROC LP can solve depends on the host platform, the available memory, and the available disk space for utility data sets.

You can also solve LP problems by using the OPTLP procedure. The OPTLP procedure requires a linear program to be specified using a SAS data set that adheres to the MPS format, a widely accepted format in the optimization community. You can use the `MPSOUT=` option in the LP procedure to convert typical PROC LP format data sets into MPS-format SAS data sets.

---

## Getting Started: LP Procedure

PROC LP expects the definition of one or more linear, integer, or mixed-integer programs in an input data set. There are two formats, a dense format and a sparse format, for this data set.

In the dense format, a model is expressed in a similar way as it is formulated. Each SAS variable corresponds to a model's column, and each SAS observation corresponds to a model's row. A SAS variable in the input data set is one of the following:

- a `type` variable
- an `id` variable
- a `structural` variable
- a `right-hand-side` variable
- a `right-hand-side sensitivity analysis` variable or
- a `range` variable

The type variable tells PROC LP how to interpret the observation as a part of the mathematical programming problem. It identifies and classifies objectives, constraints, and the rows that contain information of variables like types, bounds, and so on. PROC LP recognizes the following keywords as values for the type variable: MIN, MAX, EQ, LE, GE, SOSEQ, SOSLE, UNRSTRT, LOWERBD, UPPERBD, FIXED, INTEGER, BINARY, BASIC, PRICESEN, and FREE. The values of the id variable are the names of the rows in the model. The other variables identify and classify the columns with numerical values.

The sparse format to PROC LP is designed to enable you to specify only the nonzero coefficients in the description of linear programs, integer programs, and mixed-integer programs. The SAS data set that describes the sparse model must contain at least four SAS variables:

- a **type** variable
- a **column** variable
- a **row** variable and
- a **coefficient** variable

Each observation in the data set associates a type with a row or a column, or defines a coefficient or a numerical value in the model, or both. In addition to the keywords in the dense format, PROC LP also recognizes the keywords RHS, RHSEN, and RANGE as values of the type variable. The values of the row and column variables are the names of the rows and columns in the model. The values of the coefficient variables give the coefficients or other numerical data. The SAS data set can contain multiple pairs of row and coefficient variables. In this way, more information about the model can be specified in each observation in the data set. See the section “[Sparse Data Input Format](#)” on page 207 for further discussion.

With both the dense and sparse formats for model specification, the observation order is not important. This feature is particularly useful when using the sparse model input.

---

## An Introductory Example

A simple blending problem illustrates the dense and sparse input formats and the use of PROC LP. A step in refining crude oil into finished oil products involves a distillation process that splits crude into various streams. Suppose there are three types of crude available: Arabian light, Arabian heavy, and Brega. These types of crude are distilled into light naphtha, intermediate naphtha, and heating oil. These in turn are blended into jet fuel using one of two recipes. What amounts of the three crudes maximize the profit from producing jet fuel? A formulation to answer this question is as follows:

$$\text{maximize} \quad -175 a_{\text{light}} - 165 a_{\text{heavy}} - 205 b_{\text{rega}} + 300 \text{jet}_1 + 300 \text{jet}_2$$

```

subject to .035 a_light + .03 a_heavy + .045 brega = naphthal
           .1 a_light + .075 a_heavy + .135 brega = naphthai
           .39 a_light + .3 a_heavy + .43 brega = heatingo
           .3 naphthai + .7 heatingo = jet_1
           .2 naphthal + .8 heatingo = jet_2
           a_light ≤ 110
           a_heavy ≤ 165
           brega ≤ 80
           a_light, a_heavy, brega, naphthai,
           naphthal, heatingo, jet_1, jet_2 ≥ 0

```

The following data set gives the representation of this formulation. Notice that the variable names are the structural variables, the rows are the constraints, and the coefficients are given as the values for the structural variables.

```

data;
  input _id_ $17.
        a_light a_heavy brega naphthal naphthai
        heatingo jet_1 jet_2
        _type_ $ _rhs_;
  datalines;
profit          -175 -165 -205  0  0  0 300 300 max      .
naphtha_l_conv  .035 .030 .045 -1  0  0  0  0 eq      0
naphtha_i_conv  .100 .075 .135  0 -1  0  0  0 eq      0
heating_o_conv  .390 .300 .430  0  0 -1  0  0 eq      0
recipe_1        0    0    0  0 .3 .7 -1  0 eq      0
recipe_2        0    0    0 .2  0 .8  0 -1 eq      0
available       110  165   80  .  .  .  .  . upperbd .
;

```

The same model can be specified in the sparse format, as follows. This format enables you to omit the zero coefficients.

```

data;
  format _type_ $8. _col_ $8. _row_ $16. ;
  input _type_ $ _col_ $ _row_ $ _coef_ ;
  datalines;
max          .          profit          .
eq           .          napha_l_conv     .
eq           .          napha_i_conv     .
eq           .          heating_oil_conv .
eq           .          recipe_1         .
eq           .          recipe_2         .
upperbd      .          available        .
.            a_light    profit           -175
.            a_light    napha_l_conv     .035
.            a_light    napha_i_conv     .100

```

```

.      a_light      heating_oil_conv      .390
.      a_light      available             110
.      a_heavy      profit                -165
.      a_heavy      napha_l_conv          .030
.      a_heavy      napha_i_conv          .075
.      a_heavy      heating_oil_conv      .300
.      a_heavy      available             165
.      brega        profit                -205
.      brega        napha_l_conv          .045
.      brega        napha_i_conv          .135
.      brega        heating_oil_conv      .430
.      brega        available             80
.      naphthal     napha_l_conv          -1
.      naphthal     recipe_2              .2
.      naphthai     napha_i_conv          -1
.      naphthai     recipe_1              .3
.      heatingo     heating_oil_conv      -1
.      heatingo     recipe_1              .7
.      heatingo     recipe_2              .8
.      jet_1        profit                300
.      jet_1        recipe_1              -1
.      jet_2        profit                300
.      jet_2        recipe_2              -1
.      _rhs_        recipe_1              0
;

```

Because the input order of the model into PROC LP is unimportant, this model can be specified in sparse input in arbitrary row order. [Example 6.2](#) in the section “[Examples: LP Procedure](#)” on page 238 demonstrates this.

The dense and sparse forms of model input give you flexibility to generate models using the SAS language. The dense form of the model is solved with the statements

```

proc lp;
run;

```

The sparse form is solved with the statements

```

proc lp sparsedata;
run;

```

[Example 6.1](#) and [Example 6.2](#) in the section “[Examples: LP Procedure](#)” on page 238 continue with this problem.

## Problem Input

As default, PROC LP uses the most recently created SAS data set as the problem input data set. However, if you want to input the problem from a specific SAS data set, use the [DATA=](#) option. For example, if the previous dense form data set has the name DENSE, the PROC LP statements can be written as

```

proc lp data=dense;
run;

```

## Problem Definition Statements

In the previous dense form data set, the `_ID_`, `_TYPE_`, and `_RHS_` variables are special variables in PROC LP. They stand for id variable, type variable, and right-hand-side variable. If you replace those variable names with, for example, `ROWNAME`, `TYPE`, and `RHS`, you need the problem definition statements (`ID`, `TYPE` and `RHS`) in PROC LP:

```
proc lp;
  id rowname;
  type type;
  rhs rhs;
run;
```

Other special variables for the dense format are `_RHSEN_` and `_RANGE_`, which identify the vectors for the right-hand-side sensitivity and range analyses. The corresponding statements are the `RHSEN` and `RANGE` statements. (Notice that a variable name can be identical to a statement name.)

In the same way, if you replace the variables `_COL_`, `_ROW_`, `_TYPE_`, and `_COEF_` in the previous sparse form data set by `COLUMN`, `ROW`, `TYPE`, and `COEF`, you need the problem definition statements (`COL`, `ROW`, `TYPE`, and `COEF`) in PROC LP.

```
proc lp sparsedata;
  col column;
  row row;
  type type;
  coef coef;
run;
```

In the sparse form data set, the value `'_RHS_'` under the variable `_COL_` is a special column name, which represents the model's right-hand-side column. If you replace it by a value `'R'`, the PROC LP statements would be

```
proc lp sparsedata;
  rhs r;
run;
```

Other special column names for the sparse format are `'_RHSEN_'` and `'_RANGE_'`. The corresponding statements are the `RHSEN` and `RANGE` statements.

PROC LP is case insensitive to variable names and all character values, including the row and column names in the sparse format. The order of the problem definition statements is not important.

For the dense format, a model's row names appear as character values in a SAS data set. For the sparse format, both the row and the column names of the model appear as character values in the data set. Thus, you can put spaces or other special characters in the names. When referring to these names in the problem definition statement or other LP statements, you must use single or double quotes around them. For example, if you replace `'_RHS_'` by `'R H S'` in the previous sparse form data set, the PROC LP statements would become

```
proc lp sparsedata;
    rhs "r h s";
run;
```

## LP Options

The specifications **SPARSEDATA** and **DATA=** in the previous examples are PROC LP options. PROC LP options include

- data set options
- display control options
- interactive control options
- preprocessing control options
- branch-and-bound control options
- sensitivity/parametric/ranging control options
- simplex algorithm control options

## Interactive Processing

Interactive control options include **READPAUSE**, **ENDPAUSE**, and so forth. You can run PROC LP interactively using those options. For example, for the blending problem example in the dense form, you can first pause the procedure before iterations start with the **READPAUSE** option. The PROC LP statements are

```
proc lp readpause;
run;
```

When the procedure pauses, you run the **PRINT** statement to display the initial technological matrix and see if the input is correct. Then you run the **PIVOT** statement to do one simplex pivot and pause. After that you use the **SHOW** statement to check the current solution status. Then you apply the **RESET** statement to tell the procedure to stop as soon as it finds a solution. Now you use the **RUN** statement to continue the execution. When the procedure stops, you run the **PRINT** statement again to do a price range analysis and **QUIT** the procedure. Use a SAS **%PUT** statement to display the contents of PROC LP's macro variable, **\_ORLP\_**, which contains iterations and solution information. What follows are the complete statements in batch mode:

```
proc lp readpause;
run;
print matrix(,); /* display all rows and columns. */
pivot;
show status;
reset endpause;
run;
print rangeprice;
quit;
%put &_orlp_;
```

**NOTE:** You can force PROC LP to pause during iterations by using the CTRL-BREAK key.

## An Integer Programming Example

The following is a simple mixed-integer programming problem. Details can be found in [Example 6.8](#) in the section “[Examples: LP Procedure](#)” on page 238.

```
data;
  format _row_ $10.;
  input _row_ $ choco gumdr ichoco igumdr _type_ $ _rhs_;
  datalines;
object      .25      .75      -100      -75 max      .
cooking      15      40      0      0 1e      27000
color        0 56.25      0      0 1e      27000
package     18.75      0      0      0 1e      27000
condiments   12      50      0      0 1e      27000
chocolate    1      0 -10000      0 1e      0
gum          0      1      0 -10000 1e      0
only_one     0      0      1      1 eq      1
binary       .      .      1      2 binary .
;
```

The row with ‘binary’ type indicates that this problem is a mixed-integer program and all the integer variables are binary. The integer values of the row set an ordering for PROC LP to pick the branching variable when **VARSELECT=PRIOR** is chosen. Smaller values will have higher priorities. The **\_ROW\_** variable here is an alias of the **\_ID\_** variable.

This problem can be solved with the following statements:

```
proc lp canselect=lifo backtrack=obj varselect=far endpause;
run;
quit;
%put &_orlp_;
```

The options **CANSELECT=**, **BACKTRACK=**, and **VARSELECT=** specify the rules for picking the next active problem and the rule to choose the branching variable. In this example, the values LIFO, OBJ and FAR serve as the default values, so the three options can be omitted from the PROC LP statement. The following is the output from the %PUT statement:

```
STATUS=SUCCESSFUL PHASE=3 OBJECTIVE=285 P_FEAS=YES D_FEAS=YES INT_ITER=3
INT_FEAS=2 ACTIVE=0 INT_BEST=285 PHASE1_ITER=0 PHASE2_ITER=5
PHASE3_ITER=5
```

## Preprocessing

Using the **PREPROCESS=** option, you can apply the preprocessing techniques to pre-solve and then solve the preceding mixed-integer program:



```
proc lp preprocess=1 endpause;
run;
quit;
%put &_orlp_;
```

The preprocessing statistics are written to the SAS log file as follows:

```
NOTE: Preprocessing 1 ...
NOTE:      2 upper bounds decreased.
NOTE:      2 coefficients reduced.
NOTE: Preprocessing 2 ...
NOTE:      2 constraints eliminated.
NOTE: Preprocessing done.
```

The new output `_ORLP_` is as follows:

```
STATUS=SUCCESSFUL PHASE=3 OBJECTIVE=285 P_FEAS=YES D_FEAS=YES INT_ITER=0
      INT_FEAS=1 ACTIVE=0 INT_BEST=285 PHASE1_ITER=0 PHASE2_ITER=5
      PHASE3_ITER=0
```

In this example, the number of integer iterations (INT\_ITER=) is zero, which means that the preprocessing has reduced the gap between the relaxed linear problem and the mixed-integer program to zero.

---

## An MPS Format to Sparse Format Conversion Example

If your model input is in [MPS input format](#), you can convert it to the sparse input format of PROC LP using the SAS macro function SASMPXS. For example, if you have an MPS file called MODEL.MPS and it is stored in the directory C:\OR on a PC, the following program can help you to convert the file and solve the problem.

```
%sasmpxs(mpsfile="c:\or\model.mps",lpdata=lp);

data;
  set lp;
  retain i 1;
  if _type_="FREE" and i=1 then
    do;
      _type_="MIN";
      i=0;
    end;
run;

proc lp sparsedata;
run;
```

In the MPS input format, all objective functions, price change rows, and free rows have the type ‘N’. The SASMPXS macro marks them as ‘FREE’ rows. After the conversion, you must run a DATA step to identify the objective rows and price change rows. In this example, assume that the problem is one of minimization and the first ‘FREE’ row is an objective row.

---

## Syntax: LP Procedure

Below are statements used in PROC LP, listed in alphabetical order as they appear in the text that follows.

```

PROC LP options ;
  COEF variables ;
  COL variable ;
  ID variable(s) ;
  IPIVOT ; ;
  PIVOT ; ;
  PRINT options ;
  QUIT options ;
  RANGE variable ;
  RESET options ;
  RHS variables ;
  RHSSEN variables ;
  ROW variable(s) ;
  RUN ; ;
  SHOW options ;
  TYPE variable ;
  VAR variables ;

```

The TYPE, ID (or ROW), VAR, RHS, RHSSEN, and RANGE statements are used for identifying variables in the problem data set when the model is in the dense input format. In the dense input format, a model's variables appear as variables in the problem data set. The TYPE, ID (or ROW), and RHS statements can be omitted if the input data set contains variables \_TYPE\_, \_ID\_ (or \_ROW\_), and \_RHS\_; otherwise, they must be used. The VAR statement is optional. When it is omitted, PROC LP treats all numeric variables that are not explicitly or implicitly included in RHS, RHSSEN, and RANGE statements as structural variables. The RHSSEN and RANGE statements are optional statements for sensitivity and range analyses. They can be omitted if the input data set contains the \_RHSSEN\_ and \_RANGE\_ variables.

The TYPE, COL, ROW (or ID), COEF, RHS, RHSSEN, and RANGE statements are used for identifying variables in the problem data set when the model is in the sparse input format. In the sparse input format, a model's rows and columns appear as observations in the problem data set. The TYPE, COL, ROW (or ID), and COEF statements can be omitted if the input data set contains the \_TYPE\_ and \_COL\_ variables, as well as variables beginning with the prefixes \_ROW\_ (or \_ID\_) and \_COEF\_. Otherwise, they must be used. The RHS, RHSSEN, and RANGE statements identify the corresponding columns in the model. These statements can be omitted if there are observations that contain the RHS, RHSSEN, and RANGE types or the \_RHS\_, \_RHSSEN\_, and \_RANGE\_ column values.

The SHOW, RESET, PRINT, QUIT, PIVOT, IPIVOT, and RUN statements are especially useful when executing PROC LP interactively. However, they can also be used in batch mode.

## Functional Summary

The statements and options available with PROC LP are summarized by purpose in the following table.

**Table 6.1** Functional Summary

| Description   | Statement | Option      |
|---|-----------|-------------|
| <b>Interactive Statements:</b>  |           |             |
| Perform one integer pivot and pause   | IPIVOT    |             |
| Perform one simplex pivot and pause   | PIVOT     |             |
| Display information at current iteration  | PRINT     |             |
| Terminate processing immediately  | QUIT      |             |
| Reset options specified   | RESET     |             |
| Start or resume optimization  | RUN       |             |
| Show settings of options  | SHOW      |             |
| <b>Variable Lists:</b>  |           |             |
| Variables that contain coefficients (sparse)  | COEF      |             |
| Variable that contains column names (sparse)  | COL       |             |
| Alias for the ROW statement   | ID        |             |
| Variable (column) that contains the range constant for the dense (sparse) format                                  | RANGE     |             |
| Variables (columns) that contains RHS constants for the dense (sparse) format                                     | RHS       |             |
| Variables (columns) that define RHS change vectors for the dense (sparse) format                                  | RHSEN     |             |
| Variable that contains names of constraints and objective functions (names of rows) for the dense (sparse) format | ROW       |             |
| Variable that contains the type of each observation   | TYPE      |             |
| Structural variables (dense)  | VAR       |             |
| <b>Data Set Options:</b>  |           |             |
| Active nodes input data set   | PROC LP   | ACTIVEIN=   |
| Active nodes output data set  | PROC LP   | ACTIVEOUT=  |
| Input data set  | PROC LP   | DATA=       |
| Dual output data set  | PROC LP   | DUALOUT=    |
| Primal input data set   | PROC LP   | PRIMALIN=   |
| Primal output data set  | PROC LP   | PRIMALOUT=  |
| Sparse format data input flag   | PROC LP   | SPARSEDATA  |
| Tableau output data set   | PROC LP   | TABLEAUOUT= |
| Convert sparse or dense format input data set into MPS-format output data set                                     | PROC LP   | MPSOUT=     |
| <b>Display Control Options:</b>   |           |             |
| Display iteration log   | PROC LP   | FLOW        |

| Description                                      | Statement | Option          |
|--|-----------|-----------------|
| Nonzero tolerance displaying                     | PROC LP   | FUZZ=           |
| Inverse of FLOW option                           | PROC LP   | NOFLOW          |
| Inverse of PARAPRINT option                      | PROC LP   | NOPARAPRINT     |
| Omit some displaying                             | PROC LP   | NOPRINT         |
| Inverse of TABLEAUPRINT                          | PROC LP   | NOTABLEAUPRINT  |
| Parametric programming displaying                | PROC LP   | PARAPRINT       |
| Inverse of NOPRINT                               | PROC LP   | PRINT           |
| Iteration frequency of display                   | PROC LP   | PRINTFREQ=      |
| Level of display desired                         | PROC LP   | PRINTLEVEL=     |
| Display the final tableau                        | PROC LP   | TABLEAUPRINT    |
| <b>Interactive Control Options:</b>              |           |                 |
| Pause before displaying the solution             | PROC LP   | ENDPAUSE        |
| Pause after first feasible solution              | PROC LP   | FEASIBLEPAUSE   |
| Pause frequency of integer solutions             | PROC LP   | IFEASIBLEPAUSE= |
| Pause frequency of integer iterations            | PROC LP   | IPAUSE=         |
| Inverse of ENDPAUSE                              | PROC LP   | NOENDPAUSE      |
| Inverse of FEASIBLEPAUSE                         | PROC LP   | NOFEASIBLEPAUSE |
| Pause frequency of iterations                    | PROC LP   | PAUSE=          |
| Pause if within specified proximity              | PROC LP   | PROXIMITYPAUSE= |
| Pause after data are read                        | PROC LP   | READPAUSE       |
| <b>Preprocessing Control Options:</b>            |           |                 |
| Do not perform preprocessing                     | PROC LP   | NOPREPROCESS    |
| Preprocessing error tolerance                    | PROC LP   | PEPSILON=       |
| Limit preprocessing iterations                   | PROC LP   | PMAXIT=         |
| Perform preprocessing techniques                 | PROC LP   | PREPROCESS      |
| <b>Branch-and-Bound (BB) Control Options:</b>    |           |                 |
| Perform automatic node selection technique       | PROC LP   | AUTO            |
| Backtrack strategy to be used                    | PROC LP   | BACKTRACK=      |
| Branch on binary variables first                 | PROC LP   | BINFST          |
| Active node selection strategy                   | PROC LP   | CANSELECT=      |
| Comprehensive node selection control parameter   | PROC LP   | CONTROL=        |
| Backtrack related technique                      | PROC LP   | DELTAIT=        |
| Measure for pruning BB tree                      | PROC LP   | DOBJECTIVE=     |
| Integer tolerance                                | PROC LP   | IEPSILON=       |
| Limit integer iterations                         | PROC LP   | IMAXIT=         |
| Measure for pruning BB tree                      | PROC LP   | IOBJECTIVE=     |
| Order of two branched nodes in adding to BB tree | PROC LP   | LIFOTYPE=       |
| Inverse of AUTO                                  | PROC LP   | NOAUTO          |
| Inverse of BINFST                                | PROC LP   | NOBINFST        |
| Inverse of POSTPROCESS                           | PROC LP   | NOPOSTPROCESS   |
| Limit number of branching variables              | PROC LP   | PENALTYDEPTH=   |
| Measure for pruning BB tree                      | PROC LP   | POBJECTIVE=     |

| Description   | Statement | Option           |
|---|-----------|------------------|
| Perform variables fixing technique  | PROC LP   | POSTPROCESS      |
| Percentage used in updating WOBJECTIVE  | PROC LP   | PWOBJECTIVE=     |
| Compression algorithm for storing active nodes  | PROC LP   | TREETYPE=        |
| Branching variable selection strategy   | PROC LP   | VARSELECT=       |
| Delay examination of some active nodes  | PROC LP   | WOBJECTIVE=      |
| <b>Sensitivity/Parametric/Ranging Control Options:</b>                                  |           |                  |
| Inverse of RANGEPRICE   | PROC LP   | NORANGEPRICE     |
| Inverse of RANGERHS   | PROC LP   | NORANGERHS       |
| Limit perturbation of the price vector  | PROC LP   | PRICEPHI=        |
| Range analysis on the price coefficients  | PROC LP   | RANGEPRICE       |
| Range analysis on the RHS vector  | PROC LP   | RANGERHS         |
| Limit perturbation of the RHS vector  | PROC LP   | RHSPHI=          |
| <b>Simplex Algorithm Control Options:</b>   |           |                  |
| Use devex method  | PROC LP   | DEVEX            |
| General error tolerance   | PROC LP   | EPSILON=         |
| Perform goal programming  | PROC LP   | GOALPROGRAM      |
| Largest number used in computation  | PROC LP   | INFINITY=        |
| Reinversion frequency   | PROC LP   | INVREQ=          |
| Reinversion tolerance   | PROC LP   | INVTOL=          |
| Simultaneously set MAXIT1, MAXIT2, MAXIT3 and IMAXIT values                             | PROC LP   | MAXIT=           |
| Limit phase 1 iterations  | PROC LP   | MAXIT1=          |
| Limit phase 2 iterations  | PROC LP   | MAXIT2=          |
| Limit phase 3 iterations  | PROC LP   | MAXIT3=          |
| Inverse of devex  | PROC LP   | NODEVEX          |
| Restore basis after parametric programming  | PROC LP   | PARARESTORE      |
| Weight of the phase 2 objective function in phase 1                                     | PROC LP   | PHASEMIX=        |
| Multiple pricing strategy   | PROC LP   | PRICETYPE=       |
| Number of columns to subset in multiple pricing   | PROC LP   | PRICE=           |
| Limit the number of iterations randomly selecting each entering variable during phase 1 | PROC LP   | RANDOMPRICEMULT= |
| Zero tolerance in ratio test  | PROC LP   | REPSILON=        |
| Scaling type to be performed  | PROC LP   | SCALE=           |
| Zero tolerance in LU decomposition  | PROC LP   | SMALL=           |
| Time pause limit  | PROC LP   | TIME=            |
| Control pivoting during LU decomposition  | PROC LP   | U=               |

**RESET Statement Options:**

The RESET statement supports the same options as the PROC LP statement except for the DATA=, PRIMALIN=, and ACTIVEIN= options, and supports the following additional options:

|   |       |        |
|---|-------|--------|
| New variable lower bound during phase 3 | RESET | LOWER= |
|---|-------|--------|

| Description   | Statement | Option               |
|---|-----------|----------------------|
| New variable upper bound during phase 3                                       | RESET     | UPPER=               |
| <b>PRINT Statement Options:</b>   |           |                      |
| Display the best integer solution   | PRINT     | BEST                 |
| Display variable summary for specified columns                                | PRINT     | COLUMN               |
| Display variable summary and price sensitivity analysis for specified columns | PRINT     | COLUMN / SENSITIVITY |
| Display variable summary for integer variables                                | PRINT     | INTEGER              |
| Display variable summary for nonzero integer variables                        | PRINT     | INTEGER_NONZEROS     |
| Display variable summary for integer variables with zero activity             | PRINT     | INTEGER_ZEROS        |
| Display submatrix for specified rows and columns                              | PRINT     | MATRIX               |
| Display formatted submatrix for specified rows and columns                    | PRINT     | MATRIX / PICTURE     |
| Display variable summary for continuous variables                             | PRINT     | NONINTEGER           |
| Display variable summary for nonzero continuous variables                     | PRINT     | NONINTEGER_NONZEROS  |
| Display variable summary for variables with nonzero activity                  | PRINT     | NONZEROS             |
| Display price sensitivity analysis or price parametric programming            | PRINT     | PRICESEN             |
| Display price range analysis  | PRINT     | RANGEPRICE           |
| Display RHS range analysis  | PRINT     | RANGERHS             |
| Display RHS sensitivity analysis or RHS parametric programming                | PRINT     | RHSEN                |
| Display constraint summary for specified rows                                 | PRINT     | ROW                  |
| Display constraint summary and RHS sensitivity analysis for specified rows    | PRINT     | ROW / SENSITIVITY    |
| Display solution, variable, and constraint summaries                          | PRINT     | SOLUTION             |
| Display current tableau   | PRINT     | TABLEAU              |
| Display variables with zero activity  | PRINT     | ZEROS                |
| <b>SHOW Statement Options:</b>  |           |                      |
| Display options applied   | SHOW      | OPTIONS              |
| Display status of the current solution  | SHOW      | STATUS               |
| <b>QUIT Statement Option:</b>   |           |                      |
| Save the defined output data sets and then terminate PROC LP                  | QUIT      | / SAVE               |

## PROC LP Statement

**PROC LP** *options* ;

This statement invokes the procedure. The following options can appear in the PROC LP statement.

### Data Set Options

**ACTIVEIN=SAS-data-set**

names the SAS data set containing the active nodes in a branch-and-bound tree that is to be used to restart an integer program.

**ACTIVEOUT=SAS-data-set**

names the SAS data set in which to save the current branch-and-bound tree of active nodes.

**DATA=SAS-data-set**

names the SAS data set containing the problem data. If the DATA= option is not specified, PROC LP uses the most recently created SAS data set.

**DUALOUT=SAS-data-set**

names the SAS data set that contains the current dual solution (shadow prices) on termination of PROC LP. This data set contains the current dual solution only if PROC LP terminates successfully.

**MPSOUT=SAS-data-set**

names the SAS data set that contains converted sparse or dense format input data in MPS format. Invoking this option directs the LP procedure to halt before attempting optimization. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*).

**PRIMALIN=SAS-data-set**

names the SAS data set that contains a feasible solution to the problem defined by the [DATA=](#) data set. The data set specified in the PRIMALIN= option should have the same format as a data set saved using the [PRIMALOUT=](#) option. Specifying the PRIMALIN= option is particularly useful for continuing iteration on a problem previously attempted. It is also useful for performing sensitivity analysis on a previously solved problem.

**PRIMALOUT=SAS-data-set**

names the SAS data set that contains the current primal solution when PROC LP terminates.

**SPARSEDATA**

tells PROC LP that the data are in the sparse input format. If this option is not specified, PROC LP assumes that the data are in the dense input format. See the section “[Sparse Data Input Format](#)” on page 207 for information about the sparse input format.

**TABLEAUOUT=SAS-data-set**

names the SAS data set in which to save the final tableau.

## Display Control Options

### FLOW

requests that a journal of pivot information (the Iteration Log) be displayed after every **PRINTFREQ=** iterations. This includes the names of the variables entering and leaving the basis, the reduced cost of the entering variable, and the current objective value.

### FUZZ=*e*

displays all numbers within *e* of zero as zeros. The default value is 1.0E–10.

### NOFLOW

is the inverse of the **FLOW** option.

### NOPARAPRINT

is the inverse of the **PARAPRINT** option.

### NOPRINT

suppresses the display of the Variable, Constraint, and Sensitivity Analysis summaries. This option is equivalent to the **PRINTLEVEL=0** option.

### NOTABLEUPRINT

is the inverse of the **TABLEAUPRINT** option.

### PARAPRINT

indicates that the solution be displayed at each pivot when performing parametric programming.

### PRINT

is the inverse of the **NOPRINT** option.

### PRINTFREQ=*m*

indicates that after every *m*th iteration, a line in the (Integer) Iteration Log be displayed. The default value is 1.

### PRINTLEVEL=*i*

indicates the amount of displaying that the procedure should perform.

**PRINTLEVEL=-2**      only messages to the SAS log are displayed

**PRINTLEVEL=-1**      is equivalent to **NOPRINT** unless the problem is infeasible. If it is infeasible, the infeasible rows are displayed in the Constraint Summary along with the Infeasible Information Summary.

**PRINTLEVEL=0**      is identical to **NOPRINT**

**PRINTLEVEL=1**      all output is displayed

The default value is 1.

### TABLEAUPRINT

indicates that the final tableau be displayed.



## Interactive Control Options

### ENDPAUSE

requests that PROC LP pause before displaying the solution. When this pause occurs, you can enter the **RESET**, **SHOW**, **PRINT**, **RUN**, and **QUIT** statements.

### FEASIBLEPAUSE

requests that PROC LP pause after a feasible (not necessarily integer feasible) solution has been found. At a pause, you can enter the **RESET**, **SHOW**, **PRINT**, **PIVOT**, **RUN**, and **QUIT** statements.

### IFEASIBLEPAUSE=*n*

requests that PROC LP pause after every *n* integer feasible solutions. At a pause, you can enter the **RESET**, **SHOW**, **PRINT**, **IPIVOT**, **PIVOT**, **RUN**, and **QUIT** statements. The default value is 99999999.

### IPAUSE=*n*

requests that PROC LP pause after every *n* integer iterations. At a pause, you can enter **RESET**, **SHOW**, **PRINT**, **IPIVOT**, **PIVOT**, **RUN**, and **QUIT** statements. The default value is 99999999.

### NOENDPAUSE

is the inverse of the **ENDPAUSE** option.

### NOFEASIBLEPAUSE

is the inverse of the **FEASIBLEPAUSE** option.

### PAUSE=*n*

requests that PROC LP pause after every *n* iterations. At a pause, you can enter the **RESET**, **SHOW**, **PRINT**, **IPIVOT**, **PIVOT**, **RUN**, and **QUIT** statements. The default value is 99999999.

### PROXIMITYPAUSE=*r*

causes the procedure to pause if at least one integer feasible solution has been found and the objective value of the current best integer solution can be determined to be within *r* units of the optimal integer solution. This distance, called proximity, is also displayed on the Integer Iteration Log. Note that the proximity is calculated using the minimum (maximum if the problem is maximization) objective value among the nodes that remain to be explored in the branch-and-bound tree as a bound on the value of the optimal integer solution. Following the first **PROXIMITYPAUSE=** pause, in order to avoid a pause at every iteration thereafter, it is recommended that you reduce this measure through the use of a **RESET** statement. Otherwise, if any other option or statement that causes the procedure to pause is used while the **PROXIMITYPAUSE=** option is in effect, pause interferences may occur. When this pause occurs, you can enter the **RESET**, **SHOW**, **PRINT**, **IPIVOT**, **PIVOT**, **RUN**, and **QUIT** statements. The default value is 0.

### READPAUSE

requests that PROC LP pause after the data have been read and the initial basis inverted. When this pause occurs, you can enter the **RESET**, **SHOW**, **PRINT**, **IPIVOT**, **PIVOT**, **RUN**, and **QUIT** statements.

## Preprocessing Control Options

### NOPREPROCESS

is the inverse of the **PREPROCESS** option.

**PEPSILON=*e***

specifies a positive number close to zero. This value is an error tolerance in the preprocessing. If the value is too small, any marginal changes may cause the preprocessing to repeat itself. However, if the value is too large, it may alter the optimal solution or falsely claim that the problem is infeasible. The default value is 1.0E–8.

**PMAXIT=*n***

performs at most *n* preprocessings. Preprocessing repeats itself if it improves some bounds or fixes some variables. However when a problem is large and dense, each preprocessing may take a significant amount of CPU time. This option limits the number of preprocessings PROC LP performs. It can also reduce the build-up of round-off errors. The default value is 100.

**PREPROCESS**

performs preprocessing techniques. See the section “[Preprocessing](#)” on page 215 for further discussion.

## Branch-and-Bound Algorithm Control Options

**AUTO, AUTO(*m,n*)**

automatically sets and adjusts the value of the **CONTROL=** option. Initially, it sets **CONTROL=0.70**, concentrating on finding an integer feasible solution or an upper bound. When an upper bound is found, it sets **CONTROL=0.5**, concentrating on efficiency and lower bound improvement. When the number of active problems exceeds *m*, it starts to gradually increase the value of the **CONTROL=** option to keep the size of active problems under control. When total active problems exceed *n*, **CONTROL=1** will keep the active problems from growing further. You can alter the automatic process by resetting the value of the **CONTROL=** option interactively.

The default values of *m* and *n* are 20000 and 250000, respectively. You can change the two values according to your computer’s space and memory capacities.

**BACKTRACK=*rule***

specifies the rule used to choose the next active problem when backtracking is required. One of the following can be specified:

- BACKTRACK=*LIFO*
- BACKTRACK=*FIFO*
- BACKTRACK=*OBJ*
- BACKTRACK=*PROJECT*
- BACKTRACK=*PSEUDOC*
- BACKTRACK=*ERROR*

The default value is *OBJ*. See the section “[Integer Programming](#)” on page 216 for further discussion.

**BINFST**

requests that PROC LP branch on binary variables first when integer and binary variables are present. The reasoning behind this is that a subproblem will usually be fathomed or found integer feasible after less than 20% of its variables have been fixed. Considering binary variables first attempts to reduce the size of the branch-and-bound tree. It is a heuristic technique.

**CANSELECT=rule**

specifies the rule used to choose the next active problem when backtracking is not required or used. One of the following can be specified:

- CANSELECT=LIFO
- CANSELECT=FIFO
- CANSELECT=OBJ
- CANSELECT=PROJECT
- CANSELECT=PSEUDOC
- CANSELECT=ERROR

The default value is *LIFO*. See the section “[Integer Programming](#)” on page 216 for further discussion.

**CONTROL=r**

specifies a number between 0 and 1. This option combines [CANSELECT=](#) and other rules to choose the next active problem. It takes into consideration three factors: efficiency, improving lower bounds, and improving upper bounds. When  $r$  is close to 0, PROC LP concentrates on improving lower bounds (upper bounds for maximization). However, the efficiency per integer iteration is usually the worst. When  $r$  is close to 1, PROC LP concentrates on improving upper bounds (lower bounds for maximization). In addition, the growth of active problems will be controlled and stopped at  $r = 1$ . When its value is around 0.5, PROC LP will be in the most efficient state in terms of CPU time and integer number of iterations. The [CONTROL=](#) option will be automatically adjusted when the [AUTO](#) option is applied.

**DELTAIT=r**

is used to modify the exploration of the branch-and-bound tree. If more than  $r$  integer iterations have occurred since the last integer solution was found, then the procedure uses the backtrack strategy in choosing the next node to be explored. The default value is 3 times the number of integer variables.

**DOBJECTIVE=r**

specifies that PROC LP should discard active nodes that cannot lead to an integer solution with the objective at least as small (or as large for maximizations) as the objective of the relaxed problem plus (minus)  $r$ . The default value is  $+\infty$ .

**IEPSILON=e**

requests that PROC LP consider an integer variable as having an integer value if its value is within  $e$  units of an integer. The default value is  $1.0\text{E}-7$ .

**IMAXIT=n**

performs at most  $n$  integer iterations. The default value is 100.

**IOBJECTIVE=r**

specifies that PROC LP should discard active nodes unless the node could lead to an integer solution with the objective smaller (or larger for maximizations) than  $r$ . The default value is  $+\infty$  for minimization ( $-\infty$  for maximization).

**LIFOTYPE=*c***

specifies the order in which to add the two newly branched active nodes to the LIFO list.

|            |  |
|------------|--|
| LIFOTYPE=0 | add the node with minimum penalty first  |
| LIFOTYPE=1 | add the node with maximum penalty first  |
| LIFOTYPE=2 | add the node resulting from adding $x_i \geq \lceil x^{opt}(k)_i \rceil$ first   |
| LIFOTYPE=3 | add the node resulting from adding $x_i \leq \lfloor x^{opt}(k)_i \rfloor$ first |

The default value is 0.

**NOAUTO**

is the inverse of the **AUTO** option.

**NOBINFST**

is the inverse of the **BINFST** option.

**NOPOSTPROCESS**

is the inverse of the **POSTPROCESS** option.

**PENALTYDEPTH=*m***

requests that PROC LP examine  $m$  variables as branching candidates when **VARSELECT=PENALTY**. If the **PENALTYDEPTH=** option is not specified when **VARSELECT=PENALTY**, then all of the variables are considered branching candidates. The default value is the number of integer variables. See the section “**Integer Programming**” on page 216 for further discussion.

**POBJECTIVE=*r***

specifies that PROC LP should discard active nodes that cannot lead to an integer solution with objective at least as small as  $o + |o| \times r$  (at least as large as  $o - |o| \times r$  for maximizations) where  $o$  is the objective of the relaxed noninteger constrained problem. The default value is  $+\infty$ .

**POSTPROCESS**

attempts to fix binary variables globally based on the relationships among the reduced cost and objective value of the relaxed problem and the objective value of the current best integer feasible solution.

**PWOBJECTIVE=*r***

specifies a percentage for use in the automatic update of the **WOBJECTIVE=** option. If the **WOBJECTIVE=** option is not specified in PROC LP, then when an integer feasible solution is found, the value of the option is updated to be  $b + q \times r$  where  $b$  is the best bound on the value of the optimal integer solution and  $q$  is the current proximity. Note that for maximizations,  $b - q \times r$  is used. The default value is 0.95.

**TREETYPE=*i***

specifies a data compression algorithm.

|            |   |
|------------|---|
| TREETYPE=0 | no data compression                             |
| TREETYPE=1 | Huffman coding compression routines             |
| TREETYPE=2 | adaptive Huffman coding compression routines    |
| TREETYPE=3 | adaptive arithmetic coding compression routines |

For IP or MIP problems, the basis and bounds information of each active node is saved to a utility file. When the number of active nodes increases, the size of the utility file becomes larger and larger. If PROC LP runs into a disk problem, like “disk full ...” or “writing failure ...”, you can use this option to compress the utility file. For more information on the data compression routines, refer to Nelson (1992). The default value is 0.

**VARSELECT=rule**

specifies the rule used to choose the branching variable on an integer iteration.

- VARSELECT=CLOSE
- VARSELECT=PRIOR
- VARSELECT=PSEUDOC
- VARSELECT=FAR
- VARSELECT=PRICE
- VARSELECT=PENALTY

The default value is FAR. See the section “[Integer Programming](#)” on page 216 for further discussion.

**WOBJECTIVE=r**

specifies that PROC LP should delay examination of active nodes that cannot lead to an integer solution with objective at least as small (as large for maximizations) as  $r$ , until all other active nodes have been explored. The default value is  $+\infty$  for minimization ( $-\infty$  for maximization).

## Sensitivity/Parametric/Ranging Control Options

**NORANGEPRICE**

is the inverse of the [RANGEPRICE](#) option.

**NORANGERHS**

is the inverse of the [RANGERHS](#) option.

**PRICEPHI= $\Phi$**

specifies the limit for parametric programming when perturbing the price vector. See the section “[Parametric Programming](#)” on page 226 for further discussion. See [Example 6.5](#) for an illustration of this option.

**RANGEPRICE**

indicates that range analysis is to be performed on the price coefficients. See the section “[Range Analysis](#)” on page 225 for further discussion.

**RANGERHS**

indicates that range analysis is to be performed on the right-hand-side vector. See the section “[Range Analysis](#)” on page 225 for further discussion.

**RHSPHI= $\Phi$**

specifies the limit for parametric programming when perturbing the right-hand-side vector. See the section “[Parametric Programming](#)” on page 226 for further discussion.

## Simplex Algorithm Control Options

### DEVEX

indicates that the devex method of weighting the reduced costs be used in pricing (Harris 1975).

### EPSILON=*e*

specifies a positive number close to zero. It is used in the following instances:

During phase 1, if the sum of the basic artificial variables is within *e* of zero, the current solution is considered feasible. If this sum is not exactly zero, then there are artificial variables within *e* of zero in the current solution. In this case, a note is displayed on the SAS log.

During phase 1, if all reduced costs are  $\leq e$  for nonbasic variables at their lower bounds and  $\geq e$  for nonbasic variables at their upper bounds and the sum of infeasibilities is greater than *e*, then the problem is considered infeasible. If the maximum reduced cost is within *e* of zero, a note is displayed on the SAS log.

During phase 2, if all reduced costs are  $\leq e$  for nonbasic variables at their lower bounds and  $\geq e$  for nonbasic variables at their upper bounds, then the current solution is considered optimal.

During phases 1, 2, and 3, the EPSILON= option is also used to test if the denominator is different from zero before performing the ratio test to determine which basic variable should leave the basis.

The default value is 1.0E-8.

### GOALPROGRAM

specifies that multiple objectives in the input data set are to be treated as sequential objectives in a goal-programming model. The value of the right-hand-side variable in the objective row gives the priority of the objective. Lower numbers have higher priority.

### INFINITY=*r*

specifies the largest number PROC LP uses in computation. The INFINITY= option is used to determine when a problem has an unbounded variable value. The default value is the largest double precision number.<sup>1</sup>

### INVREQ=*m*

reinverts the current basis matrix after *m* major and minor iterations. The default value is 100.

### INTOL=*r*

reinverts the current basis matrix if the largest element in absolute value in the decomposed basis matrix is greater than *r*. If after reinversion this condition still holds, then the value of the INTOL= option is increased by a factor of 10 and a note indicating this modification is displayed on the SAS log. When *r* is frequently exceeded, this may be an indication of a numerically unstable problem. The default value is 1000.

### MAXIT=*n*

simultaneously sets the values of the MAXIT1=, MAXIT2=, MAXIT3=, and IMAXIT= options.

### MAXIT1=*n*

performs at most  $n \geq 0$  phase 1 iterations. The default value is 100.

---

<sup>1</sup>This value is system dependent.

**MAXIT2=*n***

performs at most  $n \geq 0$  phase 2 iterations. If MAXIT2=0, then only phase 1 is entered so that on successful termination PROC LP will have found a feasible, but not necessarily optimal, solution. The default value is 100.

**MAXIT3=*n***

performs at most  $n \geq 0$  phase 3 iterations. All dual pivots are counted as phase 3 pivots. The default value is 99999999.

**NODEVEX**

is the inverse of the [DEVEX](#) option.

**PARARESTORE**

indicates that following a parametric programming analysis, PROC LP should restore the basis.

**PHASEMIX=*r***

specifies a number between 0 and 1. When the number is positive, PROC LP tries to improve the objective function of phase 2 during phase 1. The PHASEMIX= option is a weight factor of the phase 2 objective function in phase 1. The default value is 0.

**PRICE=*m***

specifies the number of columns to subset when multiple pricing is used in selecting the column to enter the basis (Greenberg 1978). The type of suboptimization used is determined by the [PRICETYPE=](#) option. See the section “[Pricing](#)” on page 214 for a description of this process.

**PRICETYPE=*pricetype***

specifies the type of multiple pricing to be performed. If this option is specified and the [PRICE=](#) option is not specified, then [PRICE=](#) is assumed to be 10. Valid values for the PRICETYPE= option are

- [PRICETYPE=COMPLETE](#)
- [PRICETYPE=DYNAMIC](#)
- [PRICETYPE=NONE](#)
- [PRICETYPE=PARTIAL](#)

The default value is PARTIAL. See the section “[Pricing](#)” on page 214 for a description of this process.

**RANDOMPRICEMULT=*r***

specifies a number between 0 and 1. This option sets a limit, in phase 1, on the number of iterations when PROC LP will randomly pick the entering variables. The limit equals  $r$  times the number of nonbasic variables, or the number of basic variables, whichever is smaller. The default value of the RANDOMPRICEMULT= option is 0.01.

**REPSILON=*e***

specifies a positive number close to zero. The REPSILON= option is used in the ratio test to determine which basic variable is to leave the basis. The default value is 1.0E-10.

**SCALE=*scale***

specifies the type of scaling to be used. Valid values for the SCALE= option are

- [SCALE=BOTH](#)

- SCALE=COLUMN
- SCALE=NONE
- SCALE=ROW

The default value is BOTH. See the section “[Scaling](#)” on page 215 for further discussion.

#### **SMALL=e**

specifies a positive number close to zero. Any element in a matrix with a value less than *e* is set to zero. The default value is machine dependent.

#### **TIME=t**

checks at each iteration to see if *t* seconds have elapsed since PROC LP began. If more than *t* seconds have elapsed, the procedure pauses and displays the current solution. The default value is 120 seconds.

#### **U=r**

enables PROC LP to control the choice of pivots during LU decomposition and updating the basis matrix. The variable *r* should take values between [EPSILON](#) and 1.0 because small values of *r* bias the algorithm toward maintaining sparsity at the expense of numerical stability and vice versa. The more sparse the decomposed basis is, the less time each iteration takes. The default value is 0.1.

---

## **COEF Statement**

**COEF** *variables* ;

For the sparse input format, the COEF statement specifies the numeric variables in the problem data set that contain the coefficients in the model. The value of the coefficient variable in a given observation is the value of the coefficient in the column and row specified in the COLUMN and ROW variables in that observation. For multiple ROW variables, the LP procedure maps the ROW variables to the COEF variables on the basis of their order in the COEF and [ROW](#) statements. There must be the same number of COEF variables as ROW variables. If the COEF statement is omitted, the procedure looks for the default variable names that have the prefix \_COEF.

---

## **COL Statement**

**COL** *variable* ;

For the sparse input format, the COL statement specifies a character variable in the problem data set that contains the names of the columns in the model. Columns in the model are either structural variables, right-hand-side vectors, right-hand-side change vectors, or a range vector. The COL variable must be a character variable. If the COL statement is omitted, the LP procedure looks for the default variable name \_COL\_.

---

## **ID Statement**

**ID** *variable(s)* ;



For the dense input format, the ID statement specifies a character variable in the problem data set that contains a name for each constraint coefficients row, objective coefficients row, and variable definition row. If the ID statement is omitted, the LP procedure looks for the default variable name, `_ID_`. If this variable is not in the problem data set, the procedure assigns the default name `_OBSxx_` to each row, where `xx` specifies the observation number in the problem data set.

For the sparse input format, the ID statement specifies the character variables in the problem data set that contain the names of the rows in the model. Rows in the model are one of the following types: constraints, objective functions, bounding rows, or variable describing rows. The ID variables must be character variables. There must be the same number of ID variables as variables specified in the [COEF](#) statement. If the ID statement is omitted, the LP procedure looks for the default variable names having the prefix `_ID`.

**NOTE:** The ID statement is an alias for the [ROW](#) statement.

---

## IPIVOT Statement

**IPIVOT ;**

The IPIVOT statement causes the LP procedure to execute one integer branch-and-bound pivot and pause. If you use the IPIVOT statement while the [PROXIMITYPAUSE=](#) option is in effect, pause interferences may occur. To avoid such interferences, you must either reset the [PROXIMITYPAUSE](#) value or submit IPIVOT; RUN; instead of IPIVOT;.

---

## PIVOT Statement

**PIVOT ;**

The PIVOT statement causes the LP procedure to execute one simplex pivot and pause.

---

## PRINT Statement

**PRINT options ;**

The PRINT statement is useful for displaying part of a solution summary, examining intermediate tableaus, performing sensitivity analysis, and using parametric programming. In the options, the `colnames` and `rownames` lists can be empty, in which case the LP procedure displays tables with all columns or rows, or both. If a column name or a row name has spaces or other special characters in it, the name must be enclosed in single or double quotes when it appears in the argument.

The options that can be used with this statement are as follows.

### **BEST**

displays a Solution, Variable, and Constraint Summary for the best integer solution found.

### **COLUMN(*colnames*) / SENSITIVITY**

displays a Variable Summary containing the logical and structural variables listed in the `colnames` list. If the `/ SENSITIVITY` option is included, then sensitivity analysis is performed on the price coefficients for the listed `colnames` structural variables.

**INTEGER**

displays a Variable Summary containing only the integer variables.

**INTEGER\_NONZEROS**

displays a Variable Summary containing only the integer variables with nonzero activity.

**INTEGER\_ZEROS**

displays a Variable Summary containing only the integer variables with zero activity.

**MATRIX(rownames,colnames) / PICTURE**

displays the submatrix of the matrix of constraint coefficients defined by the rownames and colnames lists. If the / PICTURE option is included, then the formatted submatrix is displayed. The format used is summarized in [Table 6.2](#).

**Table 6.2** Format Summary

| Condition on the Coefficient x |        |                   |         | Symbols Printed |     |
|--------------------------------|--------|-------------------|---------|-----------------|-----|
|                                |        | $\text{abs}(x) =$ | 0       |                 | “ ” |
| 0                              | <      | $\text{abs}(x) <$ | .000001 | $\text{sgn}(x)$ | “Z” |
| .000001                        | $\leq$ | $\text{abs}(x) <$ | .00001  | $\text{sgn}(x)$ | “Y” |
| .00001                         | $\leq$ | $\text{abs}(x) <$ | .0001   | $\text{sgn}(x)$ | “X” |
| .0001                          | $\leq$ | $\text{abs}(x) <$ | .001    | $\text{sgn}(x)$ | “W” |
| .001                           | $\leq$ | $\text{abs}(x) <$ | .01     | $\text{sgn}(x)$ | “V” |
| .01                            | $\leq$ | $\text{abs}(x) <$ | .1      | $\text{sgn}(x)$ | “U” |
| .1                             | $\leq$ | $\text{abs}(x) <$ | 1       | $\text{sgn}(x)$ | “T” |
|                                |        | $\text{abs}(x) =$ | 1       | $\text{sgn}(x)$ | “1” |
| 1                              | <      | $\text{abs}(x) <$ | 10      | $\text{sgn}(x)$ | “A” |
| 10                             | $\leq$ | $\text{abs}(x) <$ | 100     | $\text{sgn}(x)$ | “B” |
| 100                            | $\leq$ | $\text{abs}(x) <$ | 1000    | $\text{sgn}(x)$ | “C” |
| 1000                           | $\leq$ | $\text{abs}(x) <$ | 10000   | $\text{sgn}(x)$ | “D” |
| 10000                          | $\leq$ | $\text{abs}(x) <$ | 100000  | $\text{sgn}(x)$ | “E” |
| 100000                         | $\leq$ | $\text{abs}(x) <$ | 1.0E06  | $\text{sgn}(x)$ | “F” |

**NONINTEGER**

displays a Variable Summary containing only the continuous variables.

**NONINTEGER\_NONZEROS**

displays a Variable Summary containing only the continuous variables with nonzero activity.

**NONZEROS**

displays a Variable Summary containing only the variables with nonzero activity.

**PRICESEN**

displays the results of parametric programming for the current value of the **PRICEPHI=** option, the price coefficients, and all of the price change vectors.

**RANGEPRICE**

performs range analysis on the price coefficients.

**RANGERHS**

performs range analysis on the right-hand-side vector.

**RHSEN**

displays the results of parametric programming for the current value of the **RHSPHI=** option, the right-hand-side coefficients, and all of the right-hand-side change vectors.

**ROW(rownames) / SENSITIVITY**

displays a constraint summary containing the rows listed in the rowname list. If the / SENSITIVITY option is included, then sensitivity analysis is performed on the right-hand-side coefficients for the listed rownames.

**SOLUTION**

displays the Solution Summary, including the Variable Summary and the Constraint Summary.

**TABLEAU**

displays the current tableau.

**ZEROS**

displays a Variable Summary containing only the variables with zero activity. This may be useful in the analysis of ON/OFF, ZERO/ONE, scheduling, and assignment applications.

---

## QUIT Statement

**QUIT** *options* ;

The QUIT statement causes the LP procedure to terminate processing immediately. No further displaying is performed and no output data sets are created.

The QUIT/SAVE statement causes the LP procedure to save the output data sets, defined in the **PROC LP** statement or in the **RESET** statement, and then terminate the procedure.

---

## RANGE Statement

**RANGE** *variable* ;

For the dense input format, the RANGE statement identifies the variable in the problem data set that contains the range coefficients. These coefficients enable you to specify the feasible range of a row. For example, if the  $i$ th row is

$$a^T x \leq b_i$$

and the range coefficient for this row is  $r_i > 0$ , then all values of  $x$  that satisfy

$$b_i - r_i \leq a^T x \leq b_i$$

are feasible for this row. [Table 6.3](#) shows the bounds on a row as a function of the row type and the sign on a nonmissing range coefficient  $r$ .

**Table 6.3** Interpretation of the Range Coefficient

| $r$      | _TYPE_ | Bounds    |           |
|----------|--------|-----------|-----------|
|          |        | Lower     | Upper     |
| $\neq 0$ | LE     | $b -  r $ | $b$       |
| $\neq 0$ | GE     | $b$       | $b +  r $ |
| $> 0$    | EQ     | $b$       | $b + r$   |
| $< 0$    | EQ     | $b + r$   | $b$       |

If you include a range variable in the model and have a missing value or zero for it in a constraint row, then that constraint is treated as if no range variable had been included.

If the RANGE statement is omitted, the LP procedure assumes that the variable named `_RANGE_` contains the range coefficients.

For the sparse input format, the RANGE statement gives the name of a column in the problem data set that contains the range constants. If the RANGE statement is omitted, then the LP procedure assumes that the column named `_RANGE_` or the column with the 'RANGE' keyword in the problem data set contains the range constants.

---

## RESET Statement

**RESET** *options* ;

The RESET statement is used to change options after the LP procedure has started execution.

All of the options that can be set in the PROC LP statement can also be reset with the RESET statement, except for the `DATA=`, the `PRIMALIN=`, and the `ACTIVEIN=` options. In addition to the options available with the PROC LP statement, the following two options can be used.

**LOWER(colnames)=*n*;**

During phase 3, this sets the lower bound on all of the structural variables listed in the `colnames` list to an integer value *n*. This may contaminate the branch-and-bound tree. All nodes that descend from the current problem have lower bounds that may be different from those input in the problem data set.

**UPPER(colnames)=*n*;**

During phase 3, this sets the upper bound on all of the structural variables listed in the `colnames` list to an integer value *n*. This may contaminate the branch-and-bound tree. All nodes that descend from the current problem have upper bounds that may be different from those input in the problem data set.

Note that the LOWER= and UPPER= options only apply to phase 3 for integer problems. Therefore, they should only be applied once the integer iterations have started; if they are applied before then, they will be ignored.

---

## RHS Statement

**RHS** *variables* ;

For the dense input format, the RHS statement identifies variables in the problem data set that contain the right-hand-side constants of the linear program. Only numeric variables can be specified. If more than one variable is included in the RHS statement, the LP procedure assumes that problems for several linear programs are defined in the problem data set. A new linear program is defined for each variable in the RHS list. If the RHS statement is omitted, the procedure assumes that a variable named `_RHS_` contains the right-hand-side constants.

For the sparse input format, the RHS statement gives the names of one or more columns in the problem data set that are to be considered as right-hand-side constants. If the RHS statement is omitted, then the LP procedure assumes that the column named `_RHS_` or columns with the 'RHS' keyword in the problem data set contain the right-hand-side constants. See the section “[Sparse Data Input Format](#)” on page 207 for further discussion.

As default, the LP procedure assumes that the RHS constant is a zero vector for the dense and sparse input formats.

---

## RHSEN Statement

**RHSEN** *variables* ;

For the dense input format, the RHSEN statement identifies variables in the problem data set that define change vectors for examining the sensitivity of the optimal solution to changes in the RHS constants. If the RHSEN statement is omitted, then the LP procedure assumes that a variable named `_RHSEN_` contains a right-hand-side change vector.

For the sparse input format, the RHSEN statement gives the names of one or more columns in the problem data set that are to be considered as change vectors. If the RHSEN statement is omitted, then the LP procedure assumes that the column named `_RHSEN_` or columns with the 'RHSEN' keyword in the problem data set contain the right-hand-side change vectors. For further information, see the section “[Sparse Data Input Format](#)” on page 207, the section “[Right-Hand-Side Sensitivity Analysis](#)” on page 223, and the section “[Right-Hand-Side Parametric Programming](#)” on page 226.

---

## ROW Statement

**ROW** *variable(s)* ;

For the dense input format, the ROW statement specifies a character variable in the problem data set that contains a name for each row of constraint coefficients, each row of objective coefficients and each variable describing row. If the ROW statement is omitted, the LP procedure looks for the default variable name, `_ROW_`. If there is no such variable in the problem data set, the procedure assigns the default name `_OBSxx_` to each row, where *xx* specifies the observation number in the problem data set.

For the sparse input format, the ROW statement specifies the character variables in the problem data set that contain the names of the rows in the model. Rows in the model are one of the following types: constraints, objective functions, bounding rows, or variable describing rows. The ROW variables must be character variables. There must be the same number of ROW variables as variables specified in the [COEF](#) statement. If the ROW statement is omitted, the LP procedure looks for the default variable names having the prefix `_ROW_`.

---

## RUN Statement

**RUN ;**

The RUN statement causes optimization to be started or resumed.

The TITLE or OPTIONS statement should not appear between PROC LP and RUN statements.

---

## SHOW Statement

**SHOW options ;**

The SHOW statement specifies that the LP procedure display either the *current options* or the *current solution status* on the SAS log.

### OPTIONS

requests that the current options be displayed on the SAS log.

### STATUS

requests that the status of the current solution be displayed on the SAS log.

---

## TYPE Statement

**TYPE variable ;**

The TYPE statement specifies a character variable in the problem data set that contains the type identifier for each observation. This variable has keyword values that specify how the LP procedure should interpret the observation. If the TYPE statement is omitted, the procedure assumes that a variable named `_TYPE_` contains the type keywords.

For the dense input format, the type variable identifies the constraint and objective rows and rows that contain information about the variables. The type variable should have nonmissing values in all observations.

For the sparse input format, the type variable identifies a model's rows and columns. In an observation, a nonmissing type is associated with either a row or a column. If there are many columns sharing the same type, you can define a row of that type. Then, any nonmissing values in that row set the types of the corresponding columns.

The following are valid values for the TYPE variable in an observation:

|               |  |
|---------------|--|
| MIN           | contains the price coefficients of an objective row, for example, $c$ in the problem (MIP), to be minimized. |
| MAX           | contains the price coefficients of an objective row, for example, $c$ , to be maximized.                     |
| EQ (=)        | contains coefficients of an equality constrained row.  |
| LE ( $\leq$ ) | contains coefficients of an inequality, less than or equal to, constrained row.                              |
| GE ( $\geq$ ) | contains coefficients of an inequality, greater than or equal to, constrained row.                           |

|                     |   |
|---------------------|---|
| SOSEQ               | identifies the row as specifying a special ordered set. The variables flagged in this row are members of a set <i>exactly one</i> of which must be above its lower bound in the optimal solution. Note that variables in this type of special ordered set must be <i>integer</i> .  |
| SOSLE               | identifies the row as specifying a special ordered set. The variables flagged in this row are members of a set in which only one can be above its lower bound in the optimal solution.  |
| UNRSTRT<br>UNRSTRCT | identifies those structural variables to be considered as unrestricted variables. These are variables for which $\ell_i = -\infty$ and $u_i = +\infty$ . Any variable that has a 1 in this observation is considered an unrestricted variable.  |
| LOWERBD             | identifies lower bounds on the structural variables. If all structural variables are to be nonnegative, that is, $\ell_i = 0$ , then you do not need to include an observation with the 'LOWERBD' keyword in a variable specified in the TYPE statement. Missing values for variables in a lower-bound row indicate that the variable has lower bound equal to zero.<br><b>NOTE:</b> A variable with lower or upper bounds cannot be identified as unrestricted.  |
| UPPERBD             | identifies upper bounds $u_i$ on the structural variables. For each structural variable that is to have an upper bound $u_i = +\infty$ , the observation must contain a missing value or the current value of INFINITY. All other values are interpreted as upper bounds, including 0.  |
| FIXED               | identifies variables that have fixed values. A nonmissing value in a row with 'FIXED' type keyword gives the constant value of that variable.   |
| INTEGER             | identifies variables that are integer-constrained. In a feasible solution, these variables must have integer values. A missing value in a row with 'INTEGER' type keyword indicates that the variable is not integer-constrained. The value of variables in the 'INTEGER' row gives an ordering to the integer-constrained variables that is used when the <code>VARSELECT=</code> option equals PRIOR.<br><b>NOTE:</b> Every integer-constrained variable must have an upper bound defined in a row with type 'UPPERBD'. See the section " <a href="#">Controlling the Branch-and-Bound Search</a> " on page 219 for further discussion. |
| BINARY              | identifies variables that are constrained to be either 0 or 1. This is equivalent to specifying that the variable is an integer variable and has a lower bound of 0 and an upper bound of 1. A missing value in a row with 'BINARY' type keyword indicates that the variable is not constrained to be 0 or 1. The value of variables in the 'BINARY' row gives an ordering to the integer-constrained variables that is used when the <code>VARSELECT=</code> option equals PRIOR. See the section " <a href="#">Controlling the Branch-and-Bound Search</a> " on page 219 for further discussion.  |

|          |  |
|----------|--|
| BASIC    | identifies variables that form an initial basic feasible solution. A missing value in a row with ‘BASIC’ type indicates that the variable is not basic.  |
| PRICESEN | identifies a vector that is used to evaluate the sensitivity of the optimal solution to changes in the objective function. See the section “ <a href="#">Price Sensitivity Analysis</a> ” on page 224 and the section “ <a href="#">Price Parametric Programming</a> ” on page 227 for further discussion.                                   |
| FREE     | identifies a nonbinding constraint. Any number of FREE constraints can appear in a problem data set.   |
| RHS      | identifies a right-hand-side column in the sparse input format. This replaces the <a href="#">RHS</a> statement. It is useful when converting the MPS format into the sparse format of PROC LP. See the section “ <a href="#">Converting Standard MPS Format to Sparse Format</a> ” on page 209 for more information.                        |
| RHSEN    | identifies a right-hand-side sensitivity analysis vector in the sparse input format. This replaces the <a href="#">RHSEN</a> statement. It is useful when converting the MPS format into the sparse format of PROC LP. See the section “ <a href="#">Converting Standard MPS Format to Sparse Format</a> ” on page 209 for more information. |
| RANGE    | identifies a range vector in the sparse input format. This replaces the <a href="#">RANGE</a> statement. It is useful when converting the MPS format into the sparse format of PROC LP. See the section “ <a href="#">Converting Standard MPS Format to Sparse Format</a> ” on page 209 for more information.                                |

---

## VAR Statement

**VAR** *variables* ;

For the dense input format, the VAR statement identifies variables in the problem data set that are to be interpreted as structural variables in the linear program. Only numeric variables can be specified. If no VAR statement is specified, the LP procedure uses all numeric variables not included in an [RHS](#) or [RHSEN](#) statement as structural variables.

---

## Details: LP Procedure

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### Missing Values

The LP procedure treats missing values as missing in all rows except those that identify either upper or lower bounds on structural variables. If the row is an upper-bound row, then the type identifier is ‘UPPERBD’ and the LP procedure treats missing values as  $+\infty$ . If the row is a lower-bound row, then the type identifier is ‘LOWERBD’ and the LP procedure treats missing values as 0, except for the variables that are identified as ‘UNRSTRT’.



---

## Dense Data Input Format

In the dense format, a model is expressed in a similar way as it is formulated. Each SAS variable corresponds to a model's column and each SAS observation corresponds to a model's row. A SAS variable in the input data set is one of the following:

- a **type** variable
- an **id** variable
- a **structural** variable
- a **right-hand-side** variable
- a **right-hand-side sensitivity analysis** variable
- a **range** variable

The type variable tells PROC LP how to interpret the observation as a part of the mathematical programming problem. It identifies and classifies objectives, constraints, and the rows that contain information of variables like types, bounds, and so on. PROC LP recognizes the following keywords as values for the type variable: MIN, MAX, EQ, LE, GE, SOSEQ, SOSLE, UNRSTRT, LOWERBD, UPPERBD, FIXED, INTEGER, BINARY, BASIC, PRICESEN, and FREE. The values of the id variable are the names of the rows in the model. The other variables identify and classify the columns with numerical values.

The TYPE, ID (or ROW), and RHS statements can be omitted if the input data set contains variables `_TYPE_`, `_ID_` (or `_ROW_`), and `_RHS_`; otherwise, they must be used. The VAR statement is optional. When it is not specified, PROC LP uses as structural variables all numeric variables not explicitly or implicitly included in statement lists. The RHSEN and RANGE statements are optional statements for sensitivity and range analyses. They can be omitted if the input data set contains the `_RHSEN_` and `_RANGE_` variables.

---

## Sparse Data Input Format

The sparse format to PROC LP is designed to enable you to specify only the nonzero coefficients in the description of linear programs, integer programs, and mixed-integer programs. The SAS data set that describes the sparse model must contain at least four SAS variables:

- a **type** variable
- a **column** variable
- a **row** variable
- a **coefficient** variable

Each observation in the data set associates a type with a row or column, and defines a coefficient or numerical value in the model. The value of the type variable is a keyword that tells PROC LP how to interpret the observation. In addition to the keywords in the dense format, PROC LP also recognizes the keywords RHS,

RHSSEN, and RANGE as values of the type variable. Table 6.5 shows the keywords that are recognized by PROC LP and in which variables can appear in the problem data set.

The values of the row and column variables are the names of the rows and columns in the model. The values of the coefficient variables define basic coefficients and lower and upper bounds, and identify model variables with types BASIC, FIXED, BINARY, and INTEGER. All character values in the sparse data input format are case insensitive.

The SAS data set can contain multiple pairs of rows and coefficient variables. In this way, more information about the model can be specified in each observation in the data set. See Example 6.2 for details.

**Table 6.5** Variable Keywords Used in the Problem Data Set

| TYPE (_TYPE_) | COL (_COL_) |
|---------------|-------------|
| MIN           |             |
| MAX           |             |
| EQ            |             |
| LE            |             |
| GE            |             |
| SOSEQ         |             |
| SOSLE         |             |
| UNRSTRT       |             |
| LOWERBD       |             |
| UPPERBD       |             |
| FIXED         |             |
| INTEGER       |             |
| BINARY        |             |
| BASIC         |             |
| PRICESEN      |             |
| FREE          |             |
| RHS           | _RHS_       |
| RHSSEN        | _RHSSEN_    |
| RANGE         | _RANGE_     |
| *XXXXXXX      |             |

Follow these rules for sparse data input:

- The order of the observations is unimportant.
- Each unique column name appearing in the COL variable defines a unique column in the model.
- Each unique row name appearing in the ROW variable defines a unique row in the model.
- The type of the row is identified when an observation in which the row name appears (in a ROW variable) has type MIN, MAX, LE, GE, EQ, SOSLE, SOSEQ, LOWERBD, UPPERBD, UNRSTRT, FIXED, BINARY, INTEGER, BASIC, FREE, or PRICESEN.
- The type of each row must be identified at least once. If a row is given a type more than once, the multiple definitions must be identical.

- When there are multiple rows named in an observation (that is, when there are multiple **ROW** variables), the **TYPE** variable applies to each row named in the observation.
- The type of a column is identified when an observation in which the column name but no row name appears has the type LOWERBD, UPPERBD, UNRSTRT, FIXED, BINARY, INTEGER, BASIC, RHS, RHSEN, or RANGE. A column type can also be identified in an observation in which both column and row names appear and the row name has one of the preceding types.
- Each column is assumed to be a structural column in the model unless the column is identified as a right-hand-side vector, a right-hand-side change vector, or a range vector. A column can be identified as one of these types using either the keywords RHS, RHSEN, or RANGE in the **TYPE** variable, the special column names **\_RHS\_**, **\_RHSEN\_**, or **\_RANGE\_**, or the **RHS**, **RHSEN**, or **RANGE** statements following the PROC LP statement.
- A **TYPE** variable beginning with the character \* causes the observation to be interpreted as a comment.

When the column names appear in the Variable Summary in the PROC LP output, they are listed in alphabetical order. The row names appear in the order in which they appear in the problem data set.

---

## Converting Any PROC LP Format to an MPS-Format SAS Data Set

The **MPSOUT=** option enables you to convert an input data set for the LP procedure into an MPS-format SAS data set. The converted data set is readable by the OPTLP and OPTMILP procedures.

The conversion can handle both linear and mixed integer linear programs. The **\_TYPE\_** values for sensitivity analysis (PRICESEN), parametric programming (RHSEN), and input basis (BASIS) are dropped. When multiple objective rows are present, only the first row is marked as the objective row. The remaining rows are marked as free rows. When multiple right-hand side (RHS) columns are present, only the first RHS column is processed. Constraints with a **\_TYPE\_** value of SOSEQ or SOSLE are ignored. The **MPSOUT=** option does not output branching priorities specified for the **VARSELECT=PRIOR** option to a **BRANCH** section in the MPS-format SAS data set.

For information about how the contents of the MPS-format SAS data set are interpreted, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*). For examples that demonstrate the use of the **MPSOUT=** option and migration to the OPTMODEL procedure, see the section “Examples: LP Procedure” on page 238.

---

## Converting Standard MPS Format to Sparse Format

The MPS input format was introduced by IBM as a way of specifying data for linear and integer programs. Before you can solve a linear program specified in the MPS input format by using the LP procedure, the data must be converted to the sparse format of the LP procedure. If you want to solve a linear program specified in the sparse LP format by using the OPTLP procedure, you must convert the data into an MPS-format SAS data set. This section describes how to perform both conversions.

SASMPSXS is a SAS macro function that converts the standard MPS format to the sparse format of the LP procedure. The following is an example of the MPS format:

```

NAME          EXAMPLE
* THIS IS DATA FOR THE PRODUCT MIX PROBLEM.
ROWS
N  PROFIT
L  STAMP
L  ASSEMB
L  FINISH
N  CHNROW
N  PRICE
COLUMNS
    DESK      STAMP      3.00000    ASSEMB      10.00000
    DESK      FINISH     10.00000    PROFIT      95.00000
    DESK      PRICE     175.00000
    CHAIR      STAMP      1.50000    ASSEMB       6.00000
    CHAIR      FINISH      8.00000    PROFIT     41.00000
    CHAIR      PRICE     95.00000
    CABINET    STAMP      2.00000    ASSEMB       8.00000
    CABINET    FINISH      8.00000    PROFIT     84.00000
    CABINET    PRICE    145.00000
    BOOKCSE    STAMP      2.00000    ASSEMB       7.00000
    BOOKCSE    FINISH      7.00000    PROFIT     76.00000
    BOOKCSE    PRICE    130.00000    CHNROW       1.00000
RHS
    TIME      STAMP      800.00000    ASSEMB     1200.0000
    TIME      FINISH      800.00000
RANGES
    T1        ASSEMB      900.00000
BOUNDS
    UP        CHAIR       75.00000
    LO        BOOKCSE     50.00000
ENDATA

```

In this example, the company tries to find an optimal product mix of four items: a DESK, a CHAIR, a CABINET, and a BOOKCASE. Each item is processed in a stamping department (STAMP), an assembly department (ASSEMB), and a finishing department (FINISH). The time each item requires in each department is given in the input data. Because of resource limitations, each department has an upper limit on the time available for processing. Furthermore, because of labor constraints, the assembly department must work at least 300 hours. Finally, marketing tells you not to make more than 75 chairs, to make at least 50 bookcases, and to find the range over which the selling price of a bookcase can vary without changing the optimal product mix.

The SASMPXS macro function uses `MPSFILE='FILENAME'` as an argument to read an MPS input file. It then converts the file and saves the conversion to a default SAS data set, `PROB`. The `FILENAME` should include the path.

Running the following statements on the preceding example

```

%sasmpsxs(mpsfile='filename');

proc print data=prob;
run;

```

produces the sparse input form of the LP procedure:

| OBS | _TYPE_   | _COL_   | _ROW1_ | _COEF1_ | _ROW2_ | _COEF2_ |
|-----|----------|---------|--------|---------|--------|---------|
| 1   | *OW      |         |        | .       |        | .       |
| 2   | FREE     |         | PROFIT | .       |        | .       |
| 3   | LE       |         | STAMP  | .       |        | .       |
| 4   | LE       |         | ASSEMB | .       |        | .       |
| 5   | LE       |         | FINISH | .       |        | .       |
| 6   | FREE     |         | CHNROW | .       |        | .       |
| 7   | FREE     |         | PRICE  | .       |        | .       |
| 8   | *OL      | MNS     |        | .       |        | .       |
| 9   |          | DESK    | STAMP  | 3.0     | ASSEMB | 10      |
| 10  |          | DESK    | FINISH | 10.0    | PROFIT | 95      |
| 11  |          | DESK    | PRICE  | 175.0   |        | .       |
| 12  |          | CHAIR   | STAMP  | 1.5     | ASSEMB | 6       |
| 13  |          | CHAIR   | FINISH | 8.0     | PROFIT | 41      |
| 14  |          | CHAIR   | PRICE  | 95.0    |        | .       |
| 15  |          | CABINET | STAMP  | 2.0     | ASSEMB | 8       |
| 16  |          | CABINET | FINISH | 8.0     | PROFIT | 84      |
| 17  |          | CABINET | PRICE  | 145.0   |        | .       |
| 18  |          | BOOKCSE | STAMP  | 2       | ASSEMB | 7       |
| 19  |          | BOOKCSE | FINISH | 7       | PROFIT | 76      |
| 20  |          | BOOKCSE | PRICE  | 130     | CHNROW | 1       |
| 21  | *HS      |         |        | .       |        | .       |
| 22  | RHS      | TIME    | STAMP  | 800     | ASSEMB | 1200    |
| 23  | RHS      | TIME    | FINISH | 800     |        | .       |
| 24  | *AN      | ES      |        | .       |        | .       |
| 25  | RANGE    | T1      | ASSEMB | 900     |        | .       |
| 26  | *OU      | DS      |        | .       |        | .       |
| 27  | UPPERBDD | CHAIR   | UP     | 75      |        | .       |
| 28  | LOWERBDD | BOOKCSE | LO     | 50      |        | .       |

SASMPSXS recognizes four MPS row types: E, L, G, and N. It converts them into types EQ, LE, GE, and FREE. Since objective rows, price change rows and free rows all share the same type N in the MPS format, you need a DATA step to assign proper types to the objective rows and price change rows.

```
data;
  set prob;
  if _type_='free' and _row1_='profit' then _type_='max';
  if _type_='free' and _row1_='chnrow' then _type_='pricesen';
run;

proc lp sparsedata;
run;
```

In the MPS format, the variable types include LO, UP, FX, FR, MI, and BV. The SASMPSXS macro converts them into types LOWERBD, UPPERBD, FIXED, UNRESTRICTED, -INFINITY, and BINARY, respectively. Occasionally, you may need to define your own variable types, in which case, you must add corresponding type handling entries in the SASMPSXS.SAS program and use the SAS %INCLUDE macro to include the file at the beginning of your program. The SASMPSXS macro function can be found in the SAS sample library. Information on the MPS format can be obtained from Murtagh (1981).

SASMPXS can take no arguments, or it can take one or two arguments. If no arguments are present, SASMPXS assumes that the MPS input file has been saved to a SAS data set named RAW. The macro then takes information from that data set and converts it into the sparse form of the LP procedure. The RAW data set should have the following six variables:

```
data RAW;
  infile ...;
  input field1 $ 2-3   field2 $ 5-12
        field3 $ 15-22 field4   25-36
        field5 $ 40-47 field6   50-61;
  ...
run;
```

If the preceding MPS input data set has a name other than RAW, you can use MPSDATA=SAS-data-set as an argument in the SASMPXS macro function. If you want the converted sparse form data set to have a name other than PROB, you can use LPDATA=SAS-data-set as an argument. The order of the arguments in the SASMPXS macro function is not important.

---

## The Reduced Costs, Dual Activities, and Current Tableau

The evaluation of reduced costs and the dual activities is independent of problem structure. For a basic solution, let  $B$  be the matrix composed of the basic columns of  $A$  and let  $N$  be the matrix composed of the nonbasic columns of  $A$ . The reduced cost associated with the  $i$ th variable is

$$(c^T - c_B^T B^{-1} A)_i$$

and the dual activity of the  $j$ th row is

$$(c_B^T B^{-1})_j$$

The Current Tableau is a section displayed when you specify either the TABLEUPRINT option in the PROC LP statement or the TABLEAU option in the PRINT statement. The output contains a row for each basic variable and a column for each nonbasic variable. In addition, there is a row for the reduced costs and a column for the product

$$B^{-1}b$$

This column is labeled INV(B)\*R. The body of the tableau contains the matrix

$$B^{-1}N$$

---

## Macro Variable \_ORLP\_

The LP procedure defines a macro variable named \_ORLP\_. This variable contains a character string that indicates the status of the procedure. It is set whenever the user gets control, at breakpoints, and at procedure termination. The form of the \_ORLP\_ character string is STATUS= PHASE= OBJECTIVE= P\_FEAS= D\_FEAS= INT\_ITER= INT\_FEAS= ACTIVE= INT\_BEST= PHASE1\_ITER= PHASE2\_ITER= PHASE3\_ITER=. The terms are interpreted as follows:

|              |   |
|--------------|---|
| STATUS=      | the status of the current solution                              |
| PHASE=       | the phase the procedure is in (1, 2, or 3)                      |
| OBJECTIVE=   | the current objective value                                     |
| P_FEAS=      | whether the current solution is primal feasible                 |
| D_FEAS=      | whether the current solution is dual feasible                   |
| INT_ITER=    | the number of integer iterations performed                      |
| INT_FEAS=    | the number of integer feasible solutions found                  |
| ACTIVE=      | the number of active nodes in the current branch-and-bound tree |
| INT_BEST=    | the best integer objective value found                          |
| PHASE1_ITER= | the number of iterations performed in phase 1                   |
| PHASE2_ITER= | the number of iterations performed in phase 2                   |
| PHASE3_ITER= | the number of iterations performed in phase 3                   |

Table 6.7 shows the possible values for the nonnumeric terms in the string.

**Table 6.7** Possible Values for Nonnumeric Terms

| STATUS=        | P_FEAS= | D_FEAS= |
|----------------|---------|---------|
| SUCCESSFUL     | YES     | YES     |
| UNBOUNDED      | NO      | NO      |
| INFEASIBLE     |         |         |
| MAX_TIME       |         |         |
| MAX_ITER       |         |         |
| PIVOT          |         |         |
| BREAK          |         |         |
| INT_FEASIBLE   |         |         |
| INT_INFEASIBLE |         |         |
| INT_MAX_ITER   |         |         |
| PAUSE          |         |         |
| FEASIBLEPAUSE  |         |         |
| IPAUSE         |         |         |
| PROXIMITYPAUSE |         |         |
| ACTIVE         |         |         |
| RELAXED        |         |         |
| FATHOMED       |         |         |
| IPIVOT         |         |         |
| UNSTABLE       |         |         |
| SINGULAR       |         |         |
| MEMORY_ERROR   |         |         |
| IO_ERROR       |         |         |
| SYNTAX_ERROR   |         |         |
| SEMANTIC_ERROR |         |         |
| BADDATA_ERROR  |         |         |
| UNKNOWN_ERROR  |         |         |

This information can be used when PROC LP is one step in a larger program that needs to identify how the LP procedure terminated. Because `_ORLP_` is a standard SAS macro variable, it can be used in the ways that all macro variables can be used (see the *SAS Guide to Macro Processing*).

---

## Pricing

PROC LP performs multiple pricing when determining which variable will enter the basis at each pivot (Greenberg 1978). This heuristic can shorten execution time in many problems. The specifics of the multiple pricing algorithm depend on the value of the `PRICETYPE=` option. However, in general, when some form of multiple pricing is used, during the first iteration PROC LP places the `PRICE=` nonbasic columns yielding the greatest marginal improvement to the objective function in a candidate list. This list identifies a subproblem of the original. On subsequent iterations, only the reduced costs for the nonbasic variables in the candidate list are calculated. This accounts for the potential time savings. When either the candidate list is empty or the subproblem is optimal, a new candidate list must be identified and the process repeats. Because identification of the subproblem requires pricing the complete problem, an iteration in which this occurs is called a *major iteration*. A *minor iteration* is an iteration in which only the subproblem is to be priced.



The value of the **PRICETYPE=** option determines the type of multiple pricing that is to be used. The types of multiple pricing include partial suboptimization (**PRICETYPE=PARTIAL**), complete suboptimization (**PRICETYPE=COMPLETE**), and complete suboptimization with dynamically varying the value of the **PRICE=** option (**PRICETYPE=DYNAMIC**).

When partial suboptimization is used, in each minor iteration the nonbasic column in the subproblem yielding the greatest marginal improvement to the objective is brought into the basis and removed from the candidate list. The candidate list now has one less entry. At each subsequent iteration, another column from the subproblem is brought into the basis and removed from the candidate list. When there are either no remaining candidates or the remaining candidates do not improve the objective, the subproblem is abandoned and a major iteration is performed. If the objective cannot be improved on a major iteration, the current solution is optimal and PROC LP terminates.

Complete suboptimization is identical to partial suboptimization with one exception. When a nonbasic column from the subproblem is brought into the basis, it is replaced in the candidate list by the basic column that is leaving the basis. As a result, the candidate list does not diminish at each iteration.

When **PRICETYPE=DYNAMIC**, complete suboptimization is performed, but the value of the **PRICE=** option changes so that the ratio of minor to major iterations is within two units of the **PRICE=** option.

These heuristics can shorten execution time for small values of the **PRICE=** option. Care should be exercised in choosing a value from the **PRICE=** option because too large a value can use more time than if pricing were not used.

---

## Scaling

Based on the **SCALE=** option specified, the procedure scales the coefficients of both the constraints and objective rows before iterating. This technique can improve the numerical stability of an ill-conditioned problem. If you want to modify the default matrix scaling used, which is **SCALE=BOTH**, use the **SCALE=COLUMN**, **SCALE=ROW**, or **SCALE=NONE** option in the PROC LP statement. If **SCALE=BOTH**, the matrix coefficients are scaled so that the largest element in absolute value in each row or column equals 1. They are scaled by columns first and then by rows. If **SCALE=COLUMN (ROW)**, the matrix coefficients are scaled so that the largest element in absolute value in each column (row) equals 1. If **SCALE=NONE**, no scaling is performed.

---

## Preprocessing

With the preprocessing option, you can identify redundant and infeasible constraints, improve lower and upper bounds of variables, fix variable values and improve coefficients and RHS values before solving a problem. Preprocessing can be applied to LP, IP and MIP problems. For an LP problem, it may significantly reduce the problem size. For an IP or MIP problem, it can often reduce the gap between the optimal solution and the solution of the relaxed problem, which could lead to a smaller search tree in the branch-and-bound algorithm. As a result, the CPU time may be reduced on many problems. Although there is no guarantee that preprocessing will always yield a faster solution, it does provide a highly effective approach to solving large and difficult problems.

Preprocessing is especially useful when the original problem causes numerical difficulties to PROC LP. Since preprocessing could identify redundant constraints and tighten lower and upper bounds of variables, the reformulated problem may eliminate the numerical difficulties in practice.

When a constraint is identified as redundant, its type is marked as ‘FREE’ in the Constraint Summary. If a variable is fixed, its type is marked as ‘FIXED’ in the Variables Summary. If a constraint is identified as infeasible, PROC LP stops immediately and displays the constraint name in the SAS log file. This capability sometimes gives valuable insight into the model or the formulation and helps establish if the model is reasonable and the formulation is correct.

For a large and dense problem, preprocessing may take a longer time for each iteration. To limit the number of preprocessings, use the `PMAXIT=` option. To stop any further preprocessings during the preprocessing stage, press the CTRL-BREAK key. PROC LP will enter phase 1 at the end of the current iteration.

---

## Integer Programming

Formulations of mathematical programs often require that some of the decision variables take only integer values. Consider the formulation

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax \{ \geq, =, \leq \} b \\ & \ell \leq x \leq u \\ & x_i \text{ is integer, } i \in \mathcal{S} \end{array}$$

The set of indices  $\mathcal{S}$  identifies those variables that must take only integer values. When  $\mathcal{S}$  does not contain all of the integers between 1 and  $n$ , inclusive, this problem is called a mixed-integer program (MIP). Otherwise, it is known as an integer program. Let  $x^{opt}(\text{MIP})$  denote an optimal solution to (MIP). An integer variable with bounds between 0 and 1 is also called a binary variable.

## Specifying the Problem

An integer or mixed-integer problem can be solved with PROC LP. To solve this problem, you must identify the integer variables. You can do this with a row in the input data set that has the keyword ‘INTEGER’ for the type variable. Any variable that has a nonmissing and nonzero value for this row is interpreted as an integer variable. It is important to note that integer variables must have upper bounds explicitly defined using the ‘UPPERBD’ keyword. The values in the ‘INTEGER’ row not only identify those variables that must be integers, but they also give an ordering to the integer variables that can be used in the solution technique.

You can follow the same steps to identify binary variables. For the binary variables, there is no need to supply any upper bounds.

Following the rules of sparse data input format, you can also identify individual integer or binary variables.

## The Branch-and-Bound Technique

The branch-and-bound approach is used to solve integer and mixed-integer problems. The following discussion outlines the approach and explains how to use several options to control the procedure.

The branch-and-bound technique solves an integer program by solving a sequence of linear programs. The sequence can be represented by a tree, with each node in the tree being identified with a linear program that is derived from the problems on the path leading to the root of the tree. The root of the tree is identified with a linear program that is identical to (MIP), except that  $\mathcal{S}$  is empty. This relaxed version of (MIP), called (LP(0)), can be written as

$$\begin{aligned} x^{opt}(0) = & \min c^T x \\ \text{subject to } & Ax \{ \geq, =, \leq \} b \\ & \ell \leq x \leq u \end{aligned}$$

The branch-and-bound approach generates linear programs along the nodes of the tree using the following scheme. Consider  $x^{opt}(0)$ , the optimal solution to (LP(0)). If  $x^{opt}(0)_i$  is integer for all  $i \in \mathcal{S}$ , then  $x^{opt}(0)$  is optimal in (MIP). Suppose for some  $i \in \mathcal{S}$ ,  $x^{opt}(0)_i$  is nonintegral. In that case, define two new problems (LP(1)) and (LP(2)), descendants of the parent problem (LP(0)). The problem (LP(1)) is identical to (LP(0)) except for the additional constraint

$$x_i \leq \lfloor x^{opt}(0)_i \rfloor$$

and the problem (LP(2)) is identical to (LP(0)) except for the additional constraint

$$x_i \geq \lceil x^{opt}(0)_i \rceil$$

The notation  $\lceil y \rceil$  means the smallest integer greater than or equal to  $y$ , and the notation  $\lfloor y \rfloor$  means the largest integer less than or equal to  $y$ . Note that the two new problems do not have  $x^{opt}(0)$  as a feasible solution, but because the solution to (MIP) must satisfy one of the preceding constraints,  $x_i^{opt}(\text{MIP})$  must satisfy one of the new constraints. The two problems thus defined are called active nodes in the branch-and-bound tree, and the variable  $x_i$  is called the branching variable.

Next, the algorithm chooses one of the problems associated with an active node and attempts to solve it using the dual simplex algorithm. The problem may be infeasible, in which case the problem is dropped. If it can be solved, and it in turn does not have an integer solution (that is, a solution for which  $x_i$  is integer for all  $i \in \mathcal{S}$ ), then it defines two new problems. These new problems each contain all of the constraints of the parent problems plus the appropriate additional one.

Branching continues in this manner until either there are no active nodes or an integer solution is found. When an integer solution is found, its objective value provides a bound for the objective of (MIP). In particular, if  $z$  is the objective value of the current best integer solution, then any active problems whose parent problem has objective value  $\geq z$  can be discarded (assuming that the problem is a minimization). This can be done because all problems that descend from this parent will also have objective value  $\geq z$ . This technique is known as *fathoming*. When there are no active nodes remaining to be solved, the current integer solution is optimal in (MIP). If no integer solution has been found, then (MIP) is (integer) infeasible.

It is important to realize that integer programs are NP-complete. Roughly speaking, this means that the effort required to solve them grows exponentially with the size of the problem. For example, a problem with 10 binary variables can, in the worst case, generate  $2^{10} = 1024$  nodes in the branch-and-bound tree. A problem with 20 binary variables can, in the worst case, generate  $2^{20} = 1,048,576$  nodes in the branch-and-bound tree. Although the algorithm is unlikely to have to generate every single possible node, the need to explore even a small fraction of the potential number of nodes for a large problem can be resource intensive.

## The Integer Iteration Log

To help monitor the growth of the branch-and-bound tree, the LP procedure reports on the status of each problem that is solved. The report, displayed in the Integer Iteration Log, can be used to reconstruct the branch-and-bound tree. Each row in the report describes the results of the attempted solution of the linear program at a node in the tree. In the following discussion, a problem on a given line in the log is called the current problem. The following columns are displayed in the report:

|           |  |
|-----------|--|
| Iter      | identifies the number of the branch-and-bound iteration.   |
| Problem   | identifies how the current problem fits in the branch-and-bound tree.  |
| Condition | reports the result of the attempted solution of the current problem. Values for Condition are: <ul style="list-style-type: none"> <li>• ACTIVE: The current problem was solved successfully.</li> <li>• INFEASIBLE: The current problem is infeasible.</li> <li>• FATHOMED: The current problem cannot lead to an improved integer solution and therefore it is dropped.</li> <li>• SINGULAR: A singular basis was encountered in attempting to solve the current problem. Solution of this relaxed problem is suspended and will be attempted later if necessary.</li> <li>• SUBOPTIMAL: The current problem has an integer feasible solution.</li> </ul> |
| Objective | reports the objective value of the current problem.  |
| Branched  | names the variable that is branched in subtrees defined by the descendants of this problem.  |
| Value     | gives the current value of the variable named in the column labeled Branched.  |
| Sinfeas   | gives the sum of the integer infeasibilities in the optimal solution to the current problem.   |
| Active    | reports the total number of nodes currently active in the branch-and-bound tree.   |
| Proximity | reports the gap between the best integer solution and the current lower (upper for maximizations) bound of all active nodes.   |

To reconstruct the branch-and-bound tree from this report, consider the interpretation of iteration  $j$ . If Iter= $j$  and Problem= $k$ , then the problem solved on iteration  $j$  is identical to the problem solved on iteration  $|k|$  with an additional constraint. If  $k > 0$ , then the constraint is an upper bound on the variable named in the Branched column on iteration  $|k|$ . If  $k < 0$ , then the constraint is a lower bound on that variable. The value

of the bound can be obtained from the value of Value in iteration  $|k|$  as described in the previous section.

Example 6.8 in the section “Examples: LP Procedure” on page 238 shows an Integer Iteration Log in its output.

### Controlling the Branch-and-Bound Search

There are several options you can use to control branching. This is accomplished by controlling the program’s choice of the branching variable and of the next active node. In the discussion that follows, let

$$f_i(k) = x^{opt}(k)_i - \lfloor x^{opt}(k)_i \rfloor$$

where  $x^{opt}(k)$  is the optimal solution to the problem solved in iteration  $k$ .

The **CANSELECT=** option directs the choice of the next active node. Valid keywords for this option include LIFO, FIFO, OBJ, PROJECT, PSEUDOC, and ERROR. The following list describes the action that each of these causes when the procedure must choose for solution a problem from the list of active nodes.

|         |  |
|---------|--|
| LIFO    | chooses the last problem added to the tree of active nodes. This search has the effect of a depth-first search of the branch-and-bound tree.   |
| FIFO    | chooses the first node added to the tree of active nodes. This search has the effect of a breadth-first search of the branch-and-bound tree.   |
| OBJ     | chooses the problem whose parent has the smallest (largest if the problem is a maximization) objective value.  |
| PROJECT | chooses the problem with the largest (smallest if the problem is a maximization) projected objective value. The projected objective value is evaluated using the sum of integer infeasibilities, $s(k)$ , associated with an active node (LP( $k$ )), defined by |

$$s(k) = \sum_{i \in S} \min\{f_i(k), 1 - f_i(k)\}$$

An empirical measure of the rate of increase (decrease) in the objective value is defined as

$$\lambda = (z^* - z(0))/s(0)$$

where

- $z(k)$  is the optimal objective value for (LP( $k$ ))
- $z^*$  is the objective value of the current best integer solution

The projected objective value for problems (LP( $k + 1$ )) and (LP( $k + 2$ )) is defined as

$$z(k) + \lambda s(k)$$

**PSEUDOC** chooses the problem with the largest (least if the problem is a maximization) projected pseudocost) The projected pseudocost is evaluated using the weighted sum of infeasibilities  $s_w(k)$  associated with an active problem (LP( $k$ )), defined by

$$s_w(k) = \sum_{i \in S} \min\{d_i(k)f_i(k), u_i(k)(1 - f_i(k))\}$$

The weights  $u_i$  and  $d_i$  are initially equal to the absolute value of the  $i$ th objective coefficient and are updated at each integer iteration. They are modified by examining the empirical marginal change in the objective as additional constraints are placed on the variables in  $S$  along the path from (LP(0)) to a node associated with an integer feasible solution. In particular, if the definition of problems (LP( $k + 1$ )) and (LP( $k + 2$ )) from parent (LP( $k$ )) involve the addition of constraints  $x_i \leq \lfloor x^{opt}(k)_i \rfloor$  and  $x_i \geq \lceil x^{opt}(k)_i \rceil$ , respectively, and one of them is on a path to an integer feasible solution, then only one of the following is true:

$$d_i(k) = (z(k + 1) - z(k))/f_i(k)$$

$$u_i(k) = (z(k + 2) - z(k))/(1 - f_i(k))$$

Note the similarity between  $s_w(k)$  and  $s(k)$ . The weighted quantity  $s_w(k)$  accounts to some extent for the influence of the objective function. The projected pseudocost for problems (LP( $k + 1$ )) and (LP( $k + 2$ )) is defined as

$$z_w(k) \equiv z(k) + s_w(k)$$

**ERROR** chooses the problem with the largest error. The error associated with problems (LP( $k + 1$ )) and (LP( $k + 2$ )) is defined as

$$(z^* - z_w(k))/(z^* - z(k))$$

The **BACKTRACK=** option controls the search for the next problem. This option can take the same values as the **CANSELECT=** option. In addition to the case outlined under the **DELTAIT=** option, backtracking is required as follows based on the **CANSELECT=** option in effect:

- If **CANSELECT=LIFO** and there is no active node in the portion of the active tree currently under exploration with a bound better than the value of **WOBJECTIVE=**, then the procedure must backtrack.
- If **CANSELECT=FIFO, PROJECT, PSEUDOC, or ERROR** and the bound corresponding to the node under consideration is not better than the value of **WOBJECTIVE=**, then the procedure must backtrack.

The default value is **OBJ**.

The **VARSELECT=** option directs the choice of branching variable. Valid keywords for this option include **CLOSE, FAR, PRIOR, PSEUDOC, PRICE, and PENALTY**. The following list describes the action that each of these causes when  $x^{opt}(k)$ , an optimal solution of problem (LP( $k$ )), is used to define active problems (LP( $k + 1$ )) and (LP( $k + 2$ )).

|         |  |
|---------|--|
| CLOSE   | chooses as branching variable the variable $x_i$ such that $i$ minimizes<br>$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \text{IEPSILON} \leq f_i(k) \leq 1 - \text{IEPSILON}\}$  |
| FAR     | chooses as branching variable the variable $x_i$ such that $i$ maximizes<br>$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \text{IEPSILON} \leq f_i(k) \leq 1 - \text{IEPSILON}\}$  |
| PRIOR   | chooses as branching variable $x_i$ such that $i \in \mathcal{S}$ , $x^{opt}(k)_i$ is nonintegral, and variable $x_i$ has the minimum value in the INTEGER row in the input data set. This choice for the <b>VARSELECT=</b> option is recommended when you have enough insight into the model to identify those integer variables that have the most significant effect on the objective value.  |
| PENALTY | chooses as branching variable $x_i$ such that $i \in \mathcal{S}$ and a bound on the increase in the objective of (LP( $k$ )) (penalty) resulting from adding the constraint<br>$x_i \leq \lfloor x^{opt}(k)_i \rfloor \quad \text{or} \quad x_i \geq \lceil x^{opt}(k)_i \rceil$<br>is maximized. The bound is calculated without pivoting using techniques of sensitivity analysis (Garfinkel and Nemhauser 1972). Because the cost of calculating the maximum penalty can be large if $\mathcal{S}$ is large, you may want to limit the number of variables in $\mathcal{S}$ for which the penalty is calculated. The penalty is calculated for <b>PENALTYDEPTH=</b> variables in $\mathcal{S}$ . |
| PRICE   | chooses as branching variable $x_i$ such that $i \in \mathcal{S}$ , $x^{opt}(k)_i$ is nonintegral, and variable $x_i$ has the minimum price coefficient (maximum for maximization).  |
| PSEUDOC | chooses as branching variable the variable $x_i$ such that $i$ maximizes<br>$\{\min\{d_i f_i(k), u_i(1 - f_i(k))\} \mid i \in \mathcal{S} \text{ and } \text{IEPSILON} \leq f_i(k) \leq 1 - \text{IEPSILON}\}$<br>The weights $u_i$ and $d_i$ are initially equal to the absolute value of the $i$ th objective coefficient and are updated whenever an integer feasible solution is encountered. See the discussion on the <b>CANSELECT=</b> option for details on the method of updating the weights.  |

## Customizing Search Heuristics

Often a good heuristic for searching the branch-and-bound tree of a problem can be found. You are tempted to continue using this heuristic when the problem data changes but the problem structure remains constant. The ability to reset procedure options interactively enables you to experiment with search techniques in an attempt to identify approaches that perform well. Then you can easily reapply these techniques to subsequent problems.

For example, the PIP branch-and-bound strategy (Crowder, Johnson, and Padberg 1983) describes one such heuristic. The following program uses a similar strategy. Here, the OBJ rule (choose the active node with least parent objective function in the case of a minimization problem) is used for selecting the next active node to be solved until an integer feasible solution is found. Once such a solution is found, the search procedure is changed to the LIFO rule: choose the problem most recently placed in the list of active nodes.

```
proc lp canselect=obj ifeasiblepause=1;
run;
reset canselect=lifo ifeasiblepause=9999999;
run;
```

### Further Discussion on AUTO and CONTROL= options

Consider a minimization problem. At each integer iteration, PROC LP will select a node to solve from a pool of active nodes. The best bound strategy ( **CANSELECT=OBJ**) will pick the node with the smallest projected objective value. This strategy improves the lower bound of the integer program and usually takes fewer integer iterations. One disadvantage is that PROC LP must recalculate the inverse of the basis matrix at almost every integer iteration; such recalculation is relatively expensive. Another disadvantage is that this strategy does not pay attention to improving the upper bound of the integer program. Thus the number of active nodes tends to grow rapidly if PROC LP cannot quickly find an optimal integer solution.

On the other hand, the LIFO strategy is very efficient and does not need to calculate the inverse of the basis matrix unless the previous node is fathomed. It is a depth-first strategy so it tends to find an integer feasible solution quickly. However, this strategy will pick nodes locally and usually will take longer integer iterations than the best bound strategy.

There is another strategy that is often overlooked. Here it is called the **best upper bound** strategy. With this strategy, each time you select an active node, instead of picking the node with the smallest projected objective value, you select the one with the largest projected objective value. This strategy is as efficient as the LIFO strategy. Moreover, it selects active nodes globally. This strategy tries to improve the upper bound of the integer program by searching for new integer feasible solutions. It also fathoms active nodes quickly and keeps the total number of active nodes below the current level. A disadvantage is that this strategy may evaluate more nodes that do not have any potential in finding an optimal integer solution.

The best bound strategy has the advantage of improving the lower bound. The LIFO strategy has the advantages of efficiency and finding a local integer feasible solution. The best upper bound strategy has the advantages of keeping the size of active nodes under control and at the same time trying to identify any potential integer feasible solution globally.

Although the best bound strategy is generally preferred, in some instances other strategies may be more effective. For example, if you have found an integer optimal solution but you do not know it, you still have to enumerate all possible active nodes. Then the three strategies will basically take the same number of integer iterations after an optimal solution is found but not yet identified. Since the LIFO and best upper bound strategies are very efficient per integer iteration, both will outperform the best bound strategy.

Since no one strategy suits all situations, a hybrid strategy has been developed to increase applicability. The **CONTROL=** option combines the above three strategies naturally and provides a simple control parameter in [0, 1] dealing with different integer programming problems and different solution situations. The **AUTO** option automatically sets and adjusts the **CONTROL=** parameter so that you do not need to know any problem structure or decide a node selection strategy in advance.

Since the LIFO strategy is less costly, you should use it as much as possible in the combinations. The following process is called a **diving process**. Starting from an active node, apply the LIFO strategy as much as you can until the current node becomes feasible or is fathomed, or exceeds a preset limit. During this process, there is no inverse matrix calculation involved except for the first node. When the diving process is over, apply one of the three strategies to select the next starting node. One set of combinations is called a cycle.



The control parameter  $r$  controls the frequency of the three strategies being applied and the depth of the diving process in a cycle. It starts with a pure best bound strategy at  $r = 0$ , and then gradually increases the frequency of the diving processes and their depths as  $r$  increases. At  $r = 0.5$ , one cycle contains a best bound strategy plus a full diving process. After  $r = 0.5$ , the number of the diving processes will gradually increase in a cycle. In addition, the best upper bound strategy will join the cycle. As  $r$  continues to increase, the frequency of the best upper bound strategy will increase. At  $r = 1$ , it becomes a pure best upper bound strategy.

The **AUTO** option will automatically adjust the value of the **CONTROL=** option. At the start, it sets **CONTROL=0.7**, which emphasizes finding an upper bound. After an integer feasible solution is found, it sets **CONTROL=0.5**, which emphasizes efficiency and lower bound improvement. When the number of active nodes grows over the default or user defined limit  $m$ , the number indicates that a better upper bound is needed. The **AUTO** option will start to increase the value of **CONTROL=** from 0.5. If the size of the active nodes continues to grow, so will the value of the **CONTROL=** option. When the size of active nodes reaches to the default or user-defined limit  $n$ , **CONTROL=** will be set to 1. At this moment, the growth of active nodes is stopped. When the size of active nodes reduces, **AUTO** will decrease the value of **CONTROL=** option.

You can use other strategies to improve the lower bound by setting **CANSELECT=** to other options.

## Saving and Restoring the List of Active Nodes

The list of active nodes can be saved in a SAS data set for use at a subsequent invocation of PROC LP. The **ACTIVEOUT=** option in the PROC LP statement names the data set into which the current list of active nodes is saved when the procedure terminates due to an error termination condition. Examples of such conditions are time limit exceeded, integer iterations exceeded, and phase 3 iterations exceeded. The **ACTIVEIN=** option in the PROC LP statement names a data set that can be used to initialize the list of active nodes. To achieve the greatest benefit when restarting PROC LP, use the **PRIMALOUT=** and **PRIMALIN=** options in conjunction with the **ACTIVEOUT=** and **ACTIVEIN=** options. See [Example 6.10](#) in the section “[Examples: LP Procedure](#)” on page 238 for an illustration.

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## Sensitivity Analysis

Sensitivity analysis is a technique for examining the effects of changes in model parameters on the optimal solution. The analysis enables you to examine the size of a perturbation to the right-hand-side or objective vector by an arbitrary change vector for which the basis of the current optimal solution remains optimal.

**NOTE:** When sensitivity analysis is performed on integer-constrained problems, the integer variables are fixed at the value they obtained in the integer optimal solution. Therefore, care must be used when interpreting the results of such analyses. Care must also be taken when preprocessing is enabled, because preprocessing usually alters the original formulation.

## Right-Hand-Side Sensitivity Analysis

Consider the problem ( $lpr(\phi)$ ):

$$\begin{aligned} x^{opt}(\phi) = & \min c^T x \\ \text{subject to} & \quad Ax \{ \geq, =, \leq \} b + \phi r \\ & \quad \ell \leq x \leq u \end{aligned}$$

where  $r$  is a right-hand-side change vector.

Let  $x^{opt}(\phi)$  denote an optimal basic feasible solution to  $(lpr(\phi))$ . PROC LP can be used to examine the effects of changes in  $\phi$  on the solution  $x^{opt}(0)$  of problem  $(lpr(0))$ . For the basic solution  $x^{opt}(0)$ , let  $B$  be the matrix composed of the basic columns of  $A$  and let  $N$  be the matrix composed of the nonbasic columns of  $A$ . For the basis matrix  $B$ , the basic components of  $x^{opt}(0)$ , written as  $x^{opt}(0)_B$ , can be expressed as

$$x^{opt}(0)_B = B^{-1}(b - Nx^{opt}(0)_N)$$

Furthermore, because  $x^{opt}(0)$  is feasible,

$$\ell_B \leq B^{-1}(b - Nx^{opt}(0)_N) \leq u_B$$

where  $\ell_B$  is a column vector of the lower bounds on the structural basic variables, and  $u_B$  is a column vector of the upper bounds on the structural basic variables. For each right-hand-side change vector  $r$  identified in the RHSSSEN statement, PROC LP finds an interval  $[\phi_{min}, \phi_{max}]$  such that

$$\ell_B \leq B^{-1}(b + \phi r - Nx^{opt}(0)_N) \leq u_B$$

for  $\phi \in [\phi_{min}, \phi_{max}]$ . Furthermore, because changes in the right-hand side do not affect the reduced costs, for  $\phi \in [\phi_{min}, \phi_{max}]$ ,

$$x^{opt}(\phi)^T = ((B^{-1}(b + \phi r - Nx^{opt}(0)_N))^T, x^{opt}(0)_N^T)$$

is optimal in  $(lpr(\phi))$ .

For  $\phi = \phi_{min}$  and  $\phi = \phi_{max}$ , PROC LP reports the following:

- the names of the leaving variables
- the value of the optimal objective in the modified problems
- the RHS values in the modified problems
- the solution status, reduced costs and activities in the modified problems

The leaving variable identifies the basic variable  $x_i$  that first reaches either the lower bound  $\ell_i$  or the upper bound  $u_i$  as  $\phi$  reaches  $\phi_{min}$  or  $\phi_{max}$ . This is the basic variable that would leave the basis to maintain primal feasibility. Multiple RHSSSEN variables can appear in a problem data set.

## Price Sensitivity Analysis

Consider the problem  $(lpp(\phi))$ :

$$\begin{aligned} x^{opt}(\phi) = & \min(c + \phi r)^T x \\ \text{subject to} & Ax \{ \geq, =, \leq \} b \\ & \ell \leq x \leq u \end{aligned}$$

where  $r$  is a price change vector.

Let  $x^{opt}(\phi)$  denote an optimal basic feasible solution to  $(lpp(\phi))$ . PROC LP can be used to examine the effects of changes in  $\phi$  on the solution  $x^{opt}(0)$  of problem  $(lpp(0))$ . For the basic solution  $x^{opt}(0)$ , let  $B$  be

the matrix composed of the basic columns of  $A$  and let  $N$  be the matrix composed of the nonbasic columns of  $A$ . For basis matrix  $B$ , the reduced cost associated with the  $i$ th variable can be written as

$$rc_i(\phi) = ((c + \phi r)_N^T - (c + \phi r)_B^T B^{-1} N)_i$$

where  $(c + \phi r)_N$  and  $(c + \phi r)_B$  is a partition of the vector of price coefficients into nonbasic and basic components. Because  $x^{opt}(0)$  is optimal in  $(lpp(0))$ , the reduced costs satisfy

$$rc_i(\phi) \geq 0$$

if the nonbasic variable in column  $i$  is at its lower bound, and

$$rc_i(\phi) \leq 0$$

if the nonbasic variable in column  $i$  is at its upper bound.

For each price coefficient change vector  $r$  identified with the keyword PRICESEN in the **TYPE** variable, PROC LP finds an interval  $[\phi_{min}, \phi_{max}]$  such that for  $\phi \in [\phi_{min}, \phi_{max}]$ ,

$$rc_i(\phi) \geq 0$$

if the nonbasic variable in column  $i$  is at its lower bound, and

$$rc_i(\phi) \leq 0$$

if the nonbasic variable in column  $i$  is at its upper bound. Because changes in the price coefficients do not affect feasibility, for  $\phi \in [\phi_{min}, \phi_{max}]$ ,  $x^{opt}(\phi)$  is optimal in  $(lpp(\phi))$ . For  $\phi = \phi_{min}$  and  $\phi = \phi_{max}$ , PROC LP reports the following:

- the names of entering variables
- the value of the optimal objective in the modified problems
- the price coefficients in the modified problems
- the solution status, reduced costs, and activities in the modified problems

The entering variable identifies the variable whose reduced cost first goes to zero as  $\phi$  reaches  $\phi_{min}$  or  $\phi_{max}$ . This is the nonbasic variable that would enter the basis to maintain optimality (dual feasibility). Multiple PRICESEN variables may appear in a problem data set.

---

## Range Analysis

Range analysis is sensitivity analysis for specific change vectors. As with the sensitivity analysis case, care must be used in interpreting the results of range analysis when the problem has integers or the preprocessing option is enabled.

## Right-Hand-Side Range Analysis

The effects on the optimal solution of changes in each right-hand-side value can be studied using the **RANGERHS** option in the **PROC LP** or **RESET** statement. This option results in sensitivity analysis for the  $m$  right-hand-side change vectors specified by the columns of the  $m \times m$  identity matrix.

## Price Range Analysis

The effects on the optimal solution of changes in each price coefficient can be studied using the **RANGEPRICE** option in the **PROC LP** or **RESET** statement. This option results in sensitivity analysis for the  $n$  price change vectors specified by the rows of the  $n \times n$  identity matrix.

---

## Parametric Programming

Sensitivity analysis and range analysis examine how the optimal solution behaves with respect to perturbations of model parameter values. These approaches assume that the basis at optimality is not allowed to change. When greater flexibility is desired and a change of basis is acceptable, parametric programming can be used.

As with the sensitivity analysis case, care must be used in interpreting the results of parametric programming when the problem has integers or the preprocessing option is enabled.

## Right-Hand-Side Parametric Programming

As discussed in the section “**Right-Hand-Side Sensitivity Analysis**” on page 223, for each right-hand-side change vector  $r$ , **PROC LP** finds an interval  $[\phi_{min}, \phi_{max}]$  such that for  $\phi \in [\phi_{min}, \phi_{max}]$ ,

$$x^{opt}(\phi)^T = ((B^{-1}(b + \phi r - Nx^{opt}(0)_N))^T, x^{opt}(0)_N^T)$$

is optimal in  $(lpr(\phi))$  for the fixed basis  $B$ . Leaving variables that inhibit further changes in  $\phi$  without a change in the basis  $B$  are associated with the quantities  $\phi_{min}$  and  $\phi_{max}$ . By specifying **RHSPHI**= $\Phi$  in either the **PROC LP** statement or the **RESET** statement, you can examine the solution  $x^{opt}(\phi)$  as  $\phi$  increases or decreases from 0 to  $\Phi$ .

When **RHSPHI**= $\Phi$  is specified, the procedure first finds the interval  $[\phi_{min}, \phi_{max}]$  as described previously. Then, if  $\Phi \in [\phi_{min}, \phi_{max}]$ , no further investigation is needed. However, if  $\Phi > \phi_{max}$  or  $\Phi < \phi_{min}$ , then the procedure attempts to solve the new problem  $(lpr(\Phi))$ . To accomplish this, it pivots the leaving variable out of the basis while maintaining dual feasibility. If this new solution is primal feasible in  $(lpr(\Phi))$ , no further investigation is needed; otherwise, the procedure identifies the new leaving variable and pivots it out of the basis, again maintaining dual feasibility. Dual pivoting continues in this manner until a solution that is primal feasible in  $(lpr(\Phi))$  is identified. Because dual feasibility is maintained at each pivot, the  $(lpr(\Phi))$  primal feasible solution is optimal.

At each pivot, the procedure reports on the variables that enter and leave the basis, the current range of  $\phi$ , and the objective value. When  $x^{opt}(\Phi)$  is found, it is displayed. If you want the solution  $x^{opt}(\phi)$  at each pivot, then specify the **PARAPRINT** option in either the **PROC LP** or the **RESET** statement.

## Price Parametric Programming

As discussed in the section “[Price Sensitivity Analysis](#)” on page 224, for each price change vector  $r$ , PROC LP finds an interval  $[\phi_{min}, \phi_{max}]$  such that for each  $\phi \in [\phi_{min}, \phi_{max}]$ ,

$$rc_i(\phi) = ((c + \phi r)_N^T - (c + \phi r)_B^T B^{-1} N)_i$$

satisfies the conditions for optimality in  $(lpp(\phi))$  for the fixed basis  $B$ . Entering variables that inhibit further changes in  $\phi$  without a change in the basis  $B$  are associated with the quantities  $\phi_{min}$  and  $\phi_{max}$ . By specifying **PRICEPHI**= $\Phi$  in either the PROC LP statement or the **RESET** statement, you can examine the solution  $x^{opt}(\phi)$  as  $\phi$  increases or decreases from 0 to  $\Phi$ .

When **PRICEPHI**= $\Phi$  is specified, the procedure first finds the interval  $[\phi_{min}, \phi_{max}]$ , as described previously. Then, if  $\Phi \in [\phi_{min}, \phi_{max}]$ , no further investigation is needed. However, if  $\Phi > \phi_{max}$  or  $\Phi < \phi_{min}$ , the procedure attempts to solve the new problem  $(lpp(\Phi))$ . To accomplish this, it pivots the entering variable into the basis while maintaining primal feasibility. If this new solution is dual feasible in  $(lpp(\Phi))$ , no further investigation is needed; otherwise, the procedure identifies the new entering variable and pivots it into the basis, again maintaining primal feasibility. Pivoting continues in this manner until a solution that is dual feasible in  $(lpp(\Phi))$  is identified. Because primal feasibility is maintained at each pivot, the  $(lpp(\Phi))$  dual feasible solution is optimal.

At each pivot, the procedure reports on the variables that enter and leave the basis, the current range of  $\phi$ , and the objective value. When  $x^{opt}(\Phi)$  is found, it is displayed. If you want the solution  $x^{opt}(\phi)$  at each pivot, then specify the **PARAPRINT** option in either the **PROC LP** or the **RESET** statement.

---

## Interactive Facilities

The interactive features of the LP procedure enable you to examine intermediate results, perform sensitivity analysis, parametric programming, and range analysis, and control the solution process.

### Controlling Interactive Features

You can gain control of the LP procedure for interactive processing by setting a breakpoint or pressing the CTRL-BREAK key combination, or when certain error conditions are encountered:

- when a feasible solution is found
- at each pivot of the simplex algorithm
- when an integer feasible solution is found
- at each integer pivot of the branch-and-bound algorithm
- after the data are read but before iteration begins
- after at least one integer feasible solution has been found which is within desirable proximity of optimality
- after the problem has been solved but before results are displayed

When the LP procedure pauses, you can enter any of the interactive statements **RESET**, **PIVOT**, **IPIVOT**, **PRINT**, **SHOW**, **QUIT**, and **RUN**.

Breakpoints are set using the **FEASIBLEPAUSE**, **PAUSE=**, **IFEASIBLEPAUSE=**, **IPAUSE=**, **PROXIMITY-PAUSE=**, **READPAUSE**, and **ENDPAUSE** options. The LP procedure displays a message on the SAS log when it gives you control because of encountering one of these breakpoints.

During phase 1, 2, or 3, the CTRL-BREAK key pauses the LP procedure and releases the control at the beginning of the next iteration.

The error conditions, which usually cause the LP procedure to pause, include time limit exceeded, phase 1 iterations exceeded, phase 2 iterations exceeded, phase 3 iterations exceeded, and integer iterations exceeded. You can use the **RESET** statement to reset the option that caused the error condition.

The **PIVOT** and **IPIVOT** statements result in control being returned to you after a single simplex algorithm pivot and an integer pivot. The **PRINT** and **SHOW** statements display current solution information and return control to you. On the other hand, the **QUIT** statement requests that you leave the LP procedure immediately. If you want to quit but save output data sets, then type **QUIT/SAVE**. The **RUN** statement requests the LP procedure to continue its execution immediately.

## Displaying Intermediate Results

Once you have control of the procedure, you can examine the current values of the options and the status of the problem being solved using the **SHOW** statement. All displaying done by the **SHOW** statement goes to the SAS log.

Details about the current status of the solution are obtained using the **PRINT** statement. The various display options enable you to examine parts of the variable and constraint summaries, display the current tableau, perform sensitivity analysis on the current solution, and perform range analysis.

## Interactive Facilities in Batch Mode

All of the interactive statements can be used when processing in batch mode. This is particularly convenient when the interactive facilities are used to combine different search strategies in solving integer problems.

## Sensitivity Analysis

Two features that enhance the ability to perform sensitivity analysis need further explanation. When you specify **/SENSITIVITY** in a **PRINT COLUMN(colnames)** statement, the LP procedure defines a new change row to use in sensitivity analysis and parametric programming. This new change row has a +1 entry for each variable listed in the **PRINT** statement. This enables you to define new change rows interactively.

When you specify **/SENSITIVITY** in a **PRINT ROW(rownames)** statement, the LP procedure defines a new change column to use in sensitivity analysis and parametric programming. This new change column has a +1 entry for each right-hand-side coefficient listed in the **PRINT** statement. This enables you to define new change columns interactively.

In addition, you can interactively change the **RHSPHI=** and **PRICEPHI=** options using the **RESET** statement. This enables you to perform parametric programming interactively.

## Memory Management

There are no restrictions on the problem size in the LP procedure. The number of constraints and variables in a problem that PROC LP can solve depends on the host platform, the available memory, and the available disk space for utility data sets.

Memory usage is affected by a great many factors including the density of the technological coefficient matrix, the model structure, and the density of the decomposed basis matrix. The algorithm requires that the decomposed basis fit completely in memory. Any additional memory is used for nonbasic columns. The partition between the decomposed basis and the nonbasic columns is dynamic so that as the inverse grows, which typically happens as iterations proceed, more memory is available to it and less is available for the nonbasic columns.

The LP procedure determines the initial size of the decomposed basis matrix. If the area used is too small, PROC LP must spend time compressing this matrix, which degrades performance. If PROC LP must compress the decomposed basis matrix on the average more than 15 times per iteration, then the size of the memory devoted to the basis is increased. If the work area cannot be made large enough to invert the basis, an error return occurs. On the other hand, if PROC LP compresses the decomposed basis matrix on the average once every other iteration, then memory devoted to the decomposed basis is decreased, freeing memory for the nonbasic columns.

For many models, memory constraints are not a problem because both the decomposed basis and all the nonbasic columns will have no problem fitting. However, when the models become large relative to the available memory, the algorithm tries to adjust memory distribution in order to solve the problem. In the worst cases, only one nonbasic column fits in memory with the decomposed basis matrix.

Problems involving memory use can occur when solving mixed-integer problems. Data associated with each node in the branch-and-bound tree must be kept in memory. As the tree grows, competition for memory by the decomposed basis, the nonbasic columns, and the branch-and-bound tree may become critical. If the situation becomes critical, the procedure automatically switches to branching strategies that use less memory. However, it is possible to reach a point where no further processing is possible. In this case, PROC LP terminates on a memory error.

## Output Data Sets

The LP procedure can optionally produce five output data sets. These are the **ACTIVEOUT=**, **PRIMALOUT=**, **DUALOUT=**, **TABLEAUOUT=**, and **MPSOUT=** data sets. Each contains two variables that identify the particular problem in the input data set. These variables are

|                 |  |
|-----------------|--|
| <b>_OBJ_ID_</b> | identifies the objective function ID.    |
| <b>_RHS_ID_</b> | identifies the right-hand-side variable. |

Additionally, each data set contains other variables, which are discussed below.



## ACTIVEOUT= Data Set

The **ACTIVEOUT=** data set contains a representation of the current active branch-and-bound tree. You can use this data set to initialize the branch-and-bound tree to continue iterations on an incompletely solved problem. Each active node in the tree generates two observations in this data set. The first is a 'LOWERBD' observation that is used to reconstruct the lower-bound constraints on the currently described active node. The second is an 'UPPERBD' observation that is used to reconstruct the upper-bound constraints on the currently described active node. In addition to these, an observation that describes the current best integer solution is included. The data set contains the following variables:

|                 |   |
|-----------------|---|
| <b>_STATUS_</b> | contains the keywords LOWERBD, UPPERBD, and INTBEST for identifying the type of observation.                                    |
| <b>_PROB_</b>   | contains the problem number for the current observation.  |
| <b>_OBJECT_</b> | contains the objective value of the parent problem that generated the current observation's problem.                            |
| <b>_SINFEA_</b> | contains the sum of the integer infeasibilities of the current observation's problem.   |
| <b>_PROJEC_</b> | contains the data needed for <b>CANSELECT=PROJECT</b> when the branch-and-bound tree is read using the <b>ACTIVEIN=</b> option. |
| <b>_PSEUDO_</b> | contains the data needed for <b>CANSELECT=PSEUDOC</b> when the branch-and-bound tree is read using the <b>ACTIVEIN=</b> option. |

**INTEGER VARIABLES** Integer-constrained structural variables are also included in the **ACTIVEOUT=** data set. For each observation, these variables contain values for defining the active node in the branch-and-bound tree.

## PRIMALOUT= Data Set

The **PRIMALOUT=** data set contains the current primal solution. If the problem has integer-constrained variables, the **PRIMALOUT=** data set contains the current best integer feasible solution. If none have been found, the **PRIMALOUT=** data set contains the relaxed solution. In addition to **\_OBJ\_ID\_** and **\_RHS\_ID\_**, the data set contains the following variables:

|                 |  |
|-----------------|--|
| <b>_VAR_</b>    | identifies the variable name.  |
| <b>_TYPE_</b>   | identifies the type of the variable as specified in the input data set. Artificial variables are labeled as type 'ARTIFCL'.  |
| <b>_STATUS_</b> | identifies whether the variable is basic, nonbasic, or at an upper bound in the current solution.  |
| <b>_LBOUND_</b> | contains the input lower bound on the variable unless the variable is integer-constrained and an integer solution is given. In this case, <b>_LBOUND_</b> contains the lower bound on the variable needed to realize the integer solution on subsequent calls to PROC LP when using the <b>PRIMALIN=</b> option. |
| <b>_VALUE_</b>  | identifies the value of the variable in the current solution or the current best integer feasible solution.  |
| <b>_UBOUND_</b> | contains the input upper bound on the variable unless the variable is integer-constrained and an integer solution is given. In this case, <b>_UBOUND_</b> contains the upper bound on  |



the variable needed to realize the integer solution on subsequent calls to PROC LP when using the **PRIMALIN=** option.

|                 |  |
|-----------------|--|
| <b>_PRICE_</b>  | contains the input price coefficient of the variable.  |
| <b>_R_COST_</b> | identifies the value of the reduced cost in the current solution. <a href="#">Example 6.3</a> in the section “ <a href="#">Examples: LP Procedure</a> ” on page 238 shows a typical <b>PRIMALOUT=</b> data set. Note that it is necessary to include the information on objective function and right-hand side in order to distinguish problems in multiple problem data sets. |

### DUALOUT= Data Set

The **DUALOUT=** data set contains the dual solution for the current solution. If the problem has integer-constrained variables, the **DUALOUT=** data set contains the dual for the current best integer solution, if any. Otherwise it contains the dual for the relaxed solution. In addition to **\_OBJ\_ID\_** and **\_RHS\_ID\_**, it contains the following variables:

|                 |   |
|-----------------|---|
| <b>_ROW_ID_</b> | identifies the row or constraint name.  |
| <b>_TYPE_</b>   | identifies the type of the row as specified in the input data set.  |
| <b>_RHS_</b>    | gives the value of the right-hand side on input.  |
| <b>_L_RHS_</b>  | gives the lower bound for the row evaluated from the input right-hand-side value, the <b>TYPE</b> of the row, and the value of the <b>RANGE</b> variable for the row. |
| <b>_VALUE_</b>  | gives the value of the row, at optimality, excluding logical variables.   |
| <b>_U_RHS_</b>  | gives the upper bound for the row evaluated from the input right-hand-side value, the <b>TYPE</b> of the row, and the value of the <b>RANGE</b> variable for the row. |
| <b>_DUAL_</b>   | gives the value of the dual variable associated with the row.   |

### TABLEAUOUT= Data Set

The **TABLEAUOUT=** data set contains the current tableau. Each observation, except for the first, corresponds to a basic variable in the solution. The observation labeled **R\_COSTS** contains the reduced costs  $c_N^T - c_B^T B^{-1} N$ . In addition to **\_OBJ\_ID\_** and **\_RHS\_ID\_**, it contains the following variables:

|                             |  |
|-----------------------------|--|
| <b>_BASIC_</b>              | gives the names of the basic variables in the solution.                  |
| <b>INVB_R</b>               | gives the values of $B^{-1}r$ , where $r$ is the right-hand-side vector. |
| <b>STRUCTURAL VARIABLES</b> | give the values in the tableau, namely $B^{-1}A$ .                       |

### MPSOUT= Data Set

The **MPSOUT=** data set contains problem data converted from a PROC LP format into an MPS-format SAS data set. The six fields, **FIELD1** to **FIELD6**, in the **MPSOUT=** data set correspond to the six columns in MPS standard. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*).

---

## Input Data Sets

In addition to the **DATA=** input data set, PROC LP recognizes the **ACTIVEIN=** and the **PRIMALIN=** data sets.

### ACTIVEIN= Data Set

The **ACTIVEIN=** data set contains a representation of the current active tree. The format is identical to that of the **ACTIVEOUT=** data set.

### PRIMALIN= Data Set

The format of the **PRIMALIN=** data set is identical to the **PRIMALOUT=** data set. PROC LP uses the **PRIMALIN=** data set to identify variables at their upper bounds in the current solution and variables that are basic in the current solution.

You can add observations to the end of the problem data set if they define cost (right-hand-side) sensitivity change vectors and have **PRICESEN** (**RHSEN**) types. This enables you to solve a problem, save the solution in a SAS data set, and perform sensitivity analysis later. You can also use the **PRIMALIN=** data set to restart problems that have not been completely solved or to which new variables have been added.

---

## Displayed Output

The output from the LP procedure is discussed in the following six sections:

- Problem Summary
- Solution Summary including a Variable Summary and a Constraint Summary
- Infeasible Information Summary
- RHS Sensitivity Analysis Summary (the RHS Range Analysis Summary is not discussed)
- Price Sensitivity Analysis Summary (the Price Range Analysis Summary is not discussed)
- Iteration Log

For integer-constrained problems, the procedure also displays an **Integer Iteration Log**. The description of this Log can be found in the section “**Integer Programming**” on page 216. When you request that the tableau be displayed, the procedure displays the Current Tableau. The description of this can be found in the section “**The Reduced Costs, Dual Activities, and Current Tableau**” on page 212.

A problem data set can contain a set of constraints with several right-hand sides and several objective functions. PROC LP considers each combination of right-hand side and objective function as defining a new linear programming problem and solves each, performing all specified sensitivity analysis on each problem. For each problem defined, PROC LP displays a new sequence of output sections. **Example 6.1** in the section “**Examples: LP Procedure**” on page 238 discusses each of these elements.

The LP procedure produces the following displayed output by default.

## The Problem Summary

The problem summary includes the

- type of optimization and the name of the objective row (as identified by the **ID** or **ROW** variable)
- name of the SAS variable that contains the right-hand-side constants
- name of the SAS variable that contains the type keywords
- density of the coefficient matrix (the ratio of the number of nonzero elements to the number of total elements) after the slack and surplus variables have been appended
- number of each type of variable in the mathematical program
- number of each type of constraint in the mathematical program

## The Solution Summary

The solution summary includes the

- termination status of the procedure
- objective value of the current solution
- number of phase 1 iterations that were completed
- number of phase 2 iterations that were completed
- number of phase 3 iterations that were completed
- number of integer iterations that were completed
- number of integer feasible solutions that were found
- number of initial basic feasible variables identified
- time used in solving the problem excluding reading the data and displaying the solution
- number of inversions of the basis matrix
- current value of several of the options

## The Variable Summary

The variable summary includes the

- column number associated with each structural or logical variable in the problem
- name of each structural or logical variable in the problem. (PROC LP gives the logical variables the name of the constraint **ID**. If no **ID** variable is specified, the procedure names the logical variable `_OBS $n$ _`, where  $n$  is the observation that describes the constraint.)

- variable's status in the current solution. The status can be BASIC, DEGEN, ALTER, blank, LOWBD, or UPPBD, depending upon whether the variable is a basic variable, a degenerate variable (that is, a basic variable whose activity is at its input lower bound), a nonbasic variable that can be brought into the basis to define an alternate optimal solution, a nonbasic variable at its default lower bound 0, a nonbasic variable at its lower bound, or a nonbasic variable at its upper bound.
- type of variable (whether it is logical or structural, and, if structural, its bound type, or other value restriction). See [Example 6.1](#) for a list of possible types in the variable summary.
- value of the objective coefficient associated with each variable
- activity of the variable in the current solution
- variable's reduced cost in the current solution

### The Constraint Summary

The constraint summary includes the

- constraint row number and its [ID](#)
- kind of constraint (whether it is an OBJECTIVE, LE, EQ, GE, RANGELE, RANGEEQ, RANGEGE, or FREE row)
- number of the slack or surplus variable associated with the constraint row
- value of the right-hand-side constant associated with the constraint row
- current activity of the row (excluding logical variables)
- current activity of the dual variable (shadow price) associated with the constraint row

### The Infeasible Information Summary

The infeasible information summary includes the

- name of the infeasible row or variable
- current activity for the row or variable
- type of the row or variable
- value of right-hand-side constant
- name of each nonzero and nonmissing variable in the row
- activity and upper and lower bounds for the variable

## The RHS Sensitivity Analysis Summary

The RHS sensitivity analysis summary includes the

- value of  $\phi_{min}$
- leaving variable when  $\phi = \phi_{min}$
- objective value when  $\phi = \phi_{min}$
- value of  $\phi_{max}$
- leaving variable when  $\phi = \phi_{max}$
- objective value when  $\phi = \phi_{max}$
- column number and name of each logical and structural variable
- variable's status when  $\phi \in [\phi_{min}, \phi_{max}]$
- variable's reduced cost when  $\phi \in [\phi_{min}, \phi_{max}]$
- value of right-hand-side constant when  $\phi = \phi_{min}$
- activity of the variable when  $\phi = \phi_{min}$
- value of right-hand-side constant when  $\phi = \phi_{max}$
- activity of the variable when  $\phi = \phi_{max}$

## The Price Sensitivity Analysis Summary

The price sensitivity analysis summary includes the

- value of  $\phi_{min}$
- entering variable when  $\phi = \phi_{min}$
- objective value when  $\phi = \phi_{min}$
- value of  $\phi_{max}$
- entering variable when  $\phi = \phi_{max}$
- objective value when  $\phi = \phi_{max}$
- column number and name of each logical and structural variable
- variable's status when  $\phi \in [\phi_{min}, \phi_{max}]$
- activity of the variable when  $\phi \in [\phi_{min}, \phi_{max}]$
- price of the variable when  $\phi = \phi_{min}$
- variable's reduced cost when  $\phi = \phi_{min}$
- price of the variable when  $\phi = \phi_{max}$
- variable's reduced cost when  $\phi = \phi_{max}$

## The Iteration Log

The iteration log includes the

- phase number
- iteration number in each phase
- name of the leaving variable
- name of the entering variable
- variable's reduced cost
- objective value

## ODS Table and Variable Names

PROC LP assigns a name to each table it creates. You can use these names to select output tables when using the Output Delivery System (ODS).

**Table 6.9** ODS Tables Produced in PROC LP

| Table Name              | Description                                       | Statement/Option                                     |
|-------------------------|---|--|
| ProblemSummary          | Problem summary                                   | Default  |
| SolutionSummary         | Solution summary                                  | Default  |
| VariableSummary         | Variable summary                                  | Default  |
| ConstraintSummary       | Constraint summary                                | Default  |
| IterationLog            | Iteration log                                     | FLOW   |
| IntegerIterationLog     | Integer iteration log                             | Default  |
| PriceSensitivitySummary | Price sensitivity analysis summary                | Default, PRINT PRICESEN, or PRINT COLUMN/SENSITIVITY |
| PriceActivities         | Price activities at $\phi_{min}$ and $\phi_{max}$ | Default, PRINT PRICESEN, or PRINT COLUMN/SENSITIVITY |
| PriceActivity           | Price activity at $\phi_{min}$ or $\phi_{max}$    | PRICEPHI= and PARAPRINT                              |
| PriceParametricLog      | Price parametric programming log                  | PRICEPHI=  |
| PriceRangeSummary       | Price range analysis                              | RANGEPRI or PRINT RANGEPRI                           |
| RhsSensitivitySummary   | RHS sensitivity analysis summary                  | Default, PRINT RHSEN, or PRINT ROW/SENSITIVITY       |
| RhsActivities           | RHS activities at $\phi_{min}$ and $\phi_{max}$   | Default, PRINT RHSEN, or PRINT ROW/SENSITIVITY       |
| RhsActivity             | RHS activity at $\phi_{min}$ or $\phi_{max}$      | RHSPHI= and PARAPRINT                                |
| RhsParametricLog        | RHS parametric programming log                    | RHSPHI=  |
| RhsRangeSummary         | RHS range analysis                                | RANGERHS or PRINT RANGERHS                           |
| InfeasibilitySummary    | Infeasible row or variable summary                | Default  |

**Table 6.9** (continued)

| Table Name            | Description                            | Statement/Option              |
|-----------------------|--|-------------------------------|
| InfeasibilityActivity | Variable activity in an infeasible row | Default                       |
| CurrentTableau        | Current tableau                        | TABLEAUPRINT or PRINT TABLEAU |
| Matrix                | Technological matrix                   | PRINT MATRIX                  |
| MatrixPicture         | Technological matrix picture           | PRINT MATRIX/PICTURE          |
| MatrixPictureLegend   | Technological matrix picture legend    | PRINT MATRIX/PICTURE          |

The following table lists the variable names of the preceding tables used in the ODS template of the LP procedure.

**Table 6.10** Variable Names for the ODS Tables Produced in PROC LP

| Table Name            | Variables   |
|-----------------------|---|
| VariableSummary       | VarName, Status, Type, Price, Activity, ReducedCost                                     |
| ConstraintSummary     | Row, RowName, Type, SSCol, Rhs, Activity, Dual  |
| IterationLog          | Phase, Iteration, EnterVar, EnterCol, LeaveVar, LeaveCol, ReducedCost, ObjValue         |
| IntegerIterationLog   | Iteration, Problem, Condition, Objective, Branch, Value, SumOfInfeas, Active, Proximity |
| PriceActivities       | Col, VarName, Status, Activity, MinPrice, MinReducedCost, MaxPrice, MaxReducedCost      |
| PriceActivity         | Col, VarName, Status, Activity, Price, ReducedCost                                      |
| PriceParametricLog    | LeaveVar, LeaveCol, EnterVar, EnterCol, ObjValue, CurrentPhi                            |
| PriceRangeSummary     | Col, VarName, MinPrice, MinEnterVar, MinObj, MaxPrice, MaxEnterVar, MaxObj              |
| RhsActivities         | Col, VarName, Status, ReducedCost, MinRhs, MinActivity, MaxRhs, MaxActivity             |
| RhsActivity           | Col, VarName, Status, ReducedCost, Rhs, Activity,                                       |
| RhsParametricLog      | LeaveVar, LeaveCol, EnterVar, EnterCol, ObjValue, CurrentPhi                            |
| RhsRangeSummary       | RowName, MinRhs, MinLeaveVar, MinObj, MaxRhs, MaxLeaveVar, MaxObj                       |
| InfeasibilityActivity | VarName, Coefficient, Activity, Lower, Upper  |

## Memory Limit

The system option MEMSIZE sets a limit on the amount of memory used by the SAS System. If you do not specify a value for this option, then the SAS System sets a default memory limit. Your operating environment determines the actual size of the default memory limit, which is sufficient for many applications. However, to solve most realistic optimization problems, the LP procedure might require more memory. Increasing the memory limit can reduce the chance of an out-of-memory condition.

**NOTE:** The MEMSIZE system option is not available in some operating environments. See the documentation for your operating environment for more information.

You can specify `-MEMSIZE 0` to indicate all available memory should be used, but this setting should be used with caution. In most operating environments, it is better to specify an adequate amount of memory than to specify `-MEMSIZE 0`. For example, if you are running PROC OPTLP to solve LP problems with only a few hundred thousand variables and constraints, `-MEMSIZE 500M` might be sufficient to allow the procedure to run without an out-of-memory condition. When problems have millions of variables, `-MEMSIZE 1000M` or higher might be needed. These are “rules of thumb”—problems with atypical structure, density, or other characteristics can increase the optimizer’s memory requirements.

The MEMSIZE option can be specified at system invocation, on the SAS command line, or in a configuration file. The syntax is described in the *SAS Companion* book for your operating system.

To report a procedure’s memory consumption, you can use the FULLSTIMER option. The syntax is described in the *SAS Companion* book for your operating system.

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## Examples: LP Procedure

The following examples illustrate some of the capabilities of PROC LP. These examples, together with the other SAS/OR examples, can be found in the SAS sample library. A description of the features of PROC LP as shown in the examples are

- [Example 6.1](#) shows dense input format.
- [Example 6.2](#) shows sparse input format.
- [Example 6.3](#) uses the [RANGEPRICE](#) option to show you the range over which each objective coefficient can vary without changing the variables in the basis.
- [Example 6.4](#) shows more sensitivity analysis and restarting a problem.
- [Example 6.5](#) shows parametric programming.
- [Example 6.6](#) shows special ordered sets.
- [Example 6.7](#) shows goal programming.
- [Example 6.8](#) shows integer programming.
- [Example 6.9](#) shows an infeasible problem.
- [Example 6.10](#) shows restarting integer programs.
- [Example 6.11](#) controls the search of the branch-and-bound tree.
- [Example 6.12](#) shows matrix generation and report writing for an assignment problem.
- [Example 6.13](#) shows matrix generation and report writing for a scheduling problem.
- [Example 6.14](#) shows a multicommodity transshipment problem.
- [Example 6.15](#) shows migration to PROC OPTLP via the `MPSOUT=` option.
- [Example 6.16](#) shows migration to PROC OPTMODEL.
- [Example 6.17](#) shows migration to PROC OPTMODEL.



## Example 6.1: An Oil Blending Problem

The blending problem presented in the introduction is a good example for demonstrating some of the features of the LP procedure. Recall that a step in refining crude oil into finished oil products involves a distillation process that splits crude into various streams. Suppose that there are three types of crude available: Arabian light, Arabian heavy, and Brega. These are distilled into light naphtha, intermediate naphtha, and heating oil. Using one of two recipes, these in turn are blended into jet fuel.

Assume that you can sell as much fuel as is produced. What production strategy maximizes the profit from jet fuel sales? The following SAS code demonstrates a way of answering this question using linear programming. The SAS data set is a representation of the formulation for this model given in the introductory section.

```
data;
  input _row_ $17.
        a_light a_heavy brega naphthal naphthai heatingo jet_1
        jet_2 _type_ $ _rhs_;
  datalines;
profit          -175 -165 -205    0  0  0  300  300  max      .
naphtha_1_conv   .035 .030 .045  -1  0  0   0   0   eq      0
naphtha_i_conv   .100 .075 .135   0 -1  0   0   0   eq      0
heating_o_conv   .390 .300 .430   0  0 -1   0   0   eq      0
recipe_1         0    0    0    0 .3 .7  -1   0   eq      0
recipe_2         0    0    0    .2 0 .8   0  -1   eq      0
available        110  165  80    .  .  .   .   . upperbd .
;
```

The `_ROW_` variable contains the names of the rows in the model; the variables `A_LIGHT` to `JET_2` are the names of the structural variables in the model; the `_TYPE_` variable contains the keywords that tell the LP procedure how to interpret each row in the model; and the `_RHS_` variable gives the value of the right-hand-side constants.

The structural variables are interpreted as the quantity of each type of constituent or finished product. For example, the value of `A_HEAVY` in the solution is the amount of Arabian heavy crude to buy while the value of `JET_1` in the solution is the amount of recipe 1 jet fuel that is produced. As discussed previously, the values given in the model data set are the technological coefficients whose interpretation depends on the model. In this example, the coefficient -175 in the `PROFIT` row for the variable `A_LIGHT` gives a cost coefficient (because the row with `_ROW_=PROFIT` has `_TYPE_=MAX`) for the structural variable `A_LIGHT`. This means that for each unit of Arabian heavy crude purchased, a cost of 175 units is incurred.

The coefficients 0.035, 0.100, and 0.390 for the `A_LIGHT` variable give the percentages of each unit of Arabian light crude that is distilled into the light naphtha, intermediate naphtha, and heating oil components. The 110 value in the row `_ROW_=AVAILABLE` gives the quantity of Arabian light that is available.

PROC LP produces the following [Problem Summary](#) output. Included in the summary is an identification of the objective, defined by the first observation of the problem data set; the right-hand-side variable, defined by the variable `_RHS_`; and the type identifier, defined by the variable `_TYPE_`. See [Output 6.1.1](#).

**Output 6.1.1** Problem Summary for the Oil Blending Problem

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.00      |
| Variables           | Number     |
| Non-negative        | 5          |
| Upper Bounded       | 3          |
| Total               | 8          |
| Constraints         | Number     |
| EQ                  | 5          |
| Objective           | 1          |
| Total               | 6          |

The next section of output ([Output 6.1.2](#)) contains the [Solution Summary](#), which indicates whether or not an optimal solution was found. In this example, the procedure terminates successfully (with an optimal solution), with 1544 as the value of the objective function. Also included in this section of output is the number of phase 1 and phase 2 iterations, the number of variables used in the initial basic feasible solution, and the time used to solve the problem. For several options specified in the PROC LP statement, the current option values are also displayed.

**Output 6.1.2** Solution Summary for the Oil Blending Problem

| The LP Procedure                 |              |
|----------------------------------|--------------|
| Solution Summary                 |              |
| Terminated Successfully          |              |
| Objective Value                  | 1544         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 4            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 5            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 3            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

The next section of output ([Output 6.1.3](#)) contains the **Variable Summary**. A line is displayed for each variable in the mathematical program with the variable name, the status of the variable in the solution, the type of variable, the variable's price coefficient, the activity of the variable in the solution, and the reduced cost for the variable. The status of a variable can be

|       |   |
|-------|---|
| BASIC | if the variable is a basic variable in the solution.                            |
| DEGEN | if the variable is a basic variable whose activity is at its input lower bound. |
| ALTER | if the variable is nonbasic and is basic in an alternate optimal solution.      |
| LOWBD | if the variable is nonbasic and is at its lower bound.                          |
| UPPBD | if the variable is nonbasic and is at its upper bound.                          |

The **TYPE** column shows how PROC LP interprets the variable in the problem data set. Types include the following:

|         |  |
|---------|--|
| NON-NEG | if the variable is a nonnegative variable with lower bound 0 and upper bound $+\infty$ .         |
| LOWERBD | if the variable has a lower bound specified in a LOWERBD observation and upper bound $+\infty$ . |

|         |  |
|---------|--|
| UPPERBD | if the variable has an upper bound that is less than $+\infty$ and lower bound 0. This upper bound is specified in an UPPERBD observation.   |
| UPLOWBD | if the variable has a lower bound specified in a LOWERBD observation and an upper bound specified in an UPPERBD observation.   |
| INTEGER | if the variable is constrained to take integer values. If this is the case, then it must also be upper and lower bounded.  |
| BINARY  | if the variable is constrained to take value 0 or 1.   |
| UNRSTR  | if the variable is an unrestricted variable having bounds of $-\infty$ and $+\infty$ .   |
| SLACK   | if the variable is a slack variable that PROC LP has appended to a LE constraint. For variables of this type, the variable name is the same as the name of the constraint (given in the <b>ROW</b> variable) for which this variable is the slack. A nonzero slack variable indicates that the constraint is not tight. The slack is the amount by which the right-hand side of the constraint exceeds the left-hand side.         |
| SURPLUS | if the variable is a surplus variable that PROC LP has appended to a GE constraint. For variables of this type, the variable name is the same as the name of the constraint (given in the <b>ROW</b> variable) for which this variable is the surplus. A nonzero surplus variable indicates that the constraint is not tight. The surplus is the amount by which the left-hand side of the constraint exceeds the right-hand side. |

The **Variable Summary** gives the value of the structural variables at optimality. In this example, it tells you how to produce the jet fuel to maximize your profit. You should buy 110 units of A\_LIGHT and 80 units of BREGA. These are used to make 7.45 units of NAPHTHAL, 21.8 units of NAPHTHAL, and 77.3 units of HEATINGO. These in turn are used to make 60.65 units of JET\_1 using recipe 1 and 63.33 units of JET\_2 using recipe 2.

**Output 6.1.3** Variable Summary for the Oil Blending Problem

| The LP Procedure |               |        |         |       |          |              |
|------------------|---------------|--------|---------|-------|----------|--------------|
| Variable Summary |               |        |         |       |          |              |
| Col              | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
| 1                | a_light       | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 2                | a_heavy       |        | UPPERBD | -165  | 0        | -21.45       |
| 3                | brega         | UPPBD  | UPPERBD | -205  | 80       | 3.35         |
| 4                | naphthal      | BASIC  | NON-NEG | 0     | 7.45     | 0            |
| 5                | naphthai      | BASIC  | NON-NEG | 0     | 21.8     | 0            |
| 6                | heatingo      | BASIC  | NON-NEG | 0     | 77.3     | 0            |
| 7                | jet_1         | BASIC  | NON-NEG | 300   | 60.65    | 0            |
| 8                | jet_2         | BASIC  | NON-NEG | 300   | 63.33    | 0            |

The reduced cost associated with each nonbasic variable is the marginal value of that variable if it is brought into the basis. In other words, the objective function value would (assuming no constraints were violated) increase by the reduced cost of a nonbasic variable if that variable's value increased by one. Similarly, the objective function value would (assuming no constraints were violated) decrease by the reduced cost of a nonbasic variable if that variable's value were decreased by one. Basic variables always have a zero reduced cost. At optimality, for a maximization problem, nonbasic variables that are not at an upper bound have nonpositive reduced costs (for example, A\_HEAVY has a reduced cost of -21.45). The objective would decrease if they were to increase beyond their optimal values. Nonbasic variables at upper bounds have nonnegative reduced costs, showing that increasing the upper bound (if the reduced cost is not zero) does not decrease the objective. For a nonbasic variable at its upper bound, the reduced cost is the marginal value of increasing its upper bound, often called its shadow price.

For minimization problems, the definition of reduced costs remains the same but the conditions for optimality change. For example, at optimality the reduced costs of all non-upper-bounded variables are nonnegative, and the reduced costs of upper-bounded variables at their upper bound are nonpositive.

The next section of output ([Output 6.1.4](#)) contains the [Constraint Summary](#). For each constraint row, free row, and objective row, a line is displayed in the Constraint Summary. Included on the line are the constraint name, the row type, the slack or surplus variable associated with the row, the right-hand-side constant associated with the row, the activity of the row (not including the activity of the slack and surplus variables), and the dual activity (shadow prices).

A dual variable is associated with each constraint row. At optimality, the value of this variable, the dual activity, tells you the marginal value of the right-hand-side constant. For each unit increase in the right-hand-side constant, the objective changes by this amount. This quantity is also known as the shadow price. For example, the marginal value for the right-hand-side constant of constraint HEATING\_O\_CONV is -450.

**Output 6.1.4** Constraint Summary for the Oil Blending Problem

| The LP Procedure   |                 |           |         |     |          |               |
|--------------------|-----------------|-----------|---------|-----|----------|---------------|
| Constraint Summary |                 |           |         |     |          |               |
| Row                | Constraint Name | Type      | S/S Col | Rhs | Activity | Dual Activity |
| 1                  | profit          | OBJECTIVE | .       | 0   | 1544     | .             |
| 2                  | naphtha_l_conv  | EQ        | .       | 0   | 0        | -60           |
| 3                  | naphtha_i_conv  | EQ        | .       | 0   | 0        | -90           |
| 4                  | heating_o_conv  | EQ        | .       | 0   | 0        | -450          |
| 5                  | recipe_1        | EQ        | .       | 0   | 0        | -300          |
| 6                  | recipe_2        | EQ        | .       | 0   | 0        | -300          |

## Example 6.2: A Sparse View of the Oil Blending Problem

Typically, mathematical programming models are very sparse. This means that only a small percentage of the coefficients are nonzero. The sparse problem input is ideal for these models. The oil blending problem in the section “[An Introductory Example](#)” on page 177 has a sparse form. This example shows the same problem in a sparse form with the data given in a different order. In addition to representing the problem in a concise form, the sparse format

- allows long column names
- enables easy matrix generation (see [Example 6.12](#), [Example 6.13](#), and [Example 6.14](#))
- is compatible with [MPS](#) sparse format

The model in the sparse format is solved by invoking PROC LP with the [SPARSEDATA](#) option as follows.

```
data oil;
    format _type_ $8. _col_ $14. _row_ $16. ;
    input _type_ $ _col_ $ _row_ $ _coef_ ;
datalines;
max      .          profit          .
.        arabian_light profit      -175
.        arabian_heavy profit      -165
.        brega       profit      -205
.        jet_1       profit       300
.        jet_2       profit       300
eq       .          napha_l_conv    .
.        arabian_light napha_l_conv .035
.        arabian_heavy napha_l_conv .030
.        brega       napha_l_conv  .045
.        naphtha_light napha_l_conv -1
eq       .          napha_i_conv    .
.        arabian_light napha_i_conv .100
.        arabian_heavy napha_i_conv .075
```

```

.      brega      napha_i_conv      .135
.      naphtha_inter napha_i_conv      -1
eq      .      heating_oil_conv      .
.      arabian_light heating_oil_conv      .390
.      arabian_heavy heating_oil_conv      .300
.      brega      heating_oil_conv      .430
.      heating_oil heating_oil_conv      -1
eq      .      recipe_1      .
.      naphtha_inter recipe_1      .3
.      heating_oil recipe_1      .7
eq      .      recipe_2      .
.      jet_1      recipe_1      -1
.      naphtha_light recipe_2      .2
.      heating_oil recipe_2      .8
.      jet_2      recipe_2      -1
.      _rhs_      profit      0
upperbd .      available      .
.      arabian_light available      110
.      arabian_heavy available      165
.      brega      available      80
;

proc lp SPARSEDATA;
run;

```

The output from PROC LP follows.

#### Output 6.2.1 Output for the Sparse Oil Blending Problem

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.00      |
| Variables           | Number     |
| Non-negative        | 5          |
| Upper Bounded       | 3          |
| Total               | 8          |
| Constraints         | Number     |
| EQ                  | 5          |
| Objective           | 1          |
| Total               | 6          |

## The LP Procedure

## Solution Summary

Terminated Successfully

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 1544         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 5            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 5            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 3            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## The LP Procedure

## Variable Summary

| Col | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
|-----|---------------|--------|---------|-------|----------|--------------|
| 1   | arabian_heavy |        | UPPERBD | -165  | 0        | -21.45       |
| 2   | arabian_light | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 3   | brega         | UPPBD  | UPPERBD | -205  | 80       | 3.35         |
| 4   | heating_oil   | BASIC  | NON-NEG | 0     | 77.3     | 0            |
| 5   | jet_1         | BASIC  | NON-NEG | 300   | 60.65    | 0            |
| 6   | jet_2         | BASIC  | NON-NEG | 300   | 63.33    | 0            |
| 7   | naphtha_inter | BASIC  | NON-NEG | 0     | 21.8     | 0            |
| 8   | naphtha_light | BASIC  | NON-NEG | 0     | 7.45     | 0            |



| The LP Procedure   |                  |           |         |     |          |               |
|--------------------|------------------|-----------|---------|-----|----------|---------------|
| Constraint Summary |                  |           |         |     |          |               |
| Row                | Constraint Name  | Type      | S/S Col | Rhs | Activity | Dual Activity |
| 1                  | profit           | OBJECTIVE | .       | 0   | 1544     | .             |
| 2                  | napha_1_conv     | EQ        | .       | 0   | 0        | -60           |
| 3                  | napha_i_conv     | EQ        | .       | 0   | 0        | -90           |
| 4                  | heating_oil_conv | EQ        | .       | 0   | 0        | -450          |
| 5                  | recipe_1         | EQ        | .       | 0   | 0        | -300          |
| 6                  | recipe_2         | EQ        | .       | 0   | 0        | -300          |

### Example 6.3: Sensitivity Analysis: Changes in Objective Coefficients

Simple solution of a linear program is often not enough. A manager needs to evaluate how sensitive the solution is to changing assumptions. The LP procedure provides several tools that are useful for “what if,” or sensitivity, analysis. One tool studies the effects of changes in the objective coefficients.

For example, in the oil blending problem, the cost of crude and the selling price of jet fuel can be highly variable. If you want to know the range over which each objective coefficient can vary without changing the variables in the basis, you can use the [RANGEPRI](#) option in the PROC LP statement.

```
proc lp data=oil sparsedata
  rangeprice primalout=solution;
run;
```

In addition to the Problem and Solution summaries, the LP procedure produces a Price Range Summary, shown in [Output 6.3.1](#).

For each structural variable, the upper and lower ranges of the price (objective function coefficient) and the objective value are shown. The blocking variables, those variables that would enter the basis if the objective coefficient were perturbed further, are also given. For example, the output shows that if the cost of ARABIAN\_LIGHT crude were to increase from 175 to 186.6 per unit (remember that you are maximizing profit so the ARABIAN\_LIGHT objective coefficient would decrease from -175 to -186.6), then it would become optimal to use less of this crude for any fractional increase in its cost. Increasing the unit cost to 186.6 would drive its reduced cost to zero. Any additional increase would drive its reduced cost negative and would destroy the optimality conditions; thus, you would want to use less of it in your processing. The output shows that, at the point where the reduced cost is zero, you would only be realizing a profit of  $268 = 1544 - (110 \times 11.6)$  and that ARABIAN\_LIGHT enters the basis, that is, leaves its upper bound. On the other hand, if the cost of ARABIAN\_HEAVY were to decrease to 143.55, you would want to stop using the formulation of 110 units of ARABIAN\_LIGHT and 80 units of BREGA and switch to a production scheme that included ARABIAN\_HEAVY, in which case the profit would increase from the 1544 level.

**Output 6.3.1** Price Range Summary for the Oil Blending Problem

| The LP Procedure                 |              |
|----------------------------------|--------------|
| Problem Summary                  |              |
| Objective Function               | Max profit   |
| Rhs Variable                     | _rhs_        |
| Type Variable                    | _type_       |
| Problem Density (%)              | 45.00        |
| Variables                        | Number       |
| Non-negative                     | 5            |
| Upper Bounded                    | 3            |
| Total                            | 8            |
| Constraints                      | Number       |
| EQ                               | 5            |
| Objective                        | 1            |
| Total                            | 6            |
| Solution Summary                 |              |
| Terminated Successfully          |              |
| Objective Value                  | 1544         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 5            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 5            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 3            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

Output 6.3.1 continued

Variable Summary

| Col | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
|-----|---------------|--------|---------|-------|----------|--------------|
| 1   | arabian_heavy |        | UPPERBD | -165  | 0        | -21.45       |
| 2   | arabian_light | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 3   | brega         | UPPBD  | UPPERBD | -205  | 80       | 3.35         |
| 4   | heating_oil   | BASIC  | NON-NEG | 0     | 77.3     | 0            |
| 5   | jet_1         | BASIC  | NON-NEG | 300   | 60.65    | 0            |
| 6   | jet_2         | BASIC  | NON-NEG | 300   | 63.33    | 0            |
| 7   | naphtha_inter | BASIC  | NON-NEG | 0     | 21.8     | 0            |
| 8   | naphtha_light | BASIC  | NON-NEG | 0     | 7.45     | 0            |

Constraint Summary

| Row | Constraint Name  | Type      | S/S Col | Rhs | Activity | Dual Activity |
|-----|------------------|-----------|---------|-----|----------|---------------|
| 1   | profit           | OBJECTIVE | .       | 0   | 1544     | .             |
| 2   | napha_l_conv     | EQ        | .       | 0   | 0        | -60           |
| 3   | napha_i_conv     | EQ        | .       | 0   | 0        | -90           |
| 4   | heating_oil_conv | EQ        | .       | 0   | 0        | -450          |
| 5   | recipe_1         | EQ        | .       | 0   | 0        | -300          |
| 6   | recipe_2         | EQ        | .       | 0   | 0        | -300          |

Price Range Analysis

| -----Minimum Phi----- |               |                           |
|-----------------------|---------------|---------------------------|
| Col                   | Variable Name | Price Entering Objective  |
| 1                     | arabian_heavy | -INFINITY . 1544          |
| 2                     | arabian_light | -186.6 arabian_light 268  |
| 3                     | brega         | -208.35 brega 1276        |
| 4                     | heating_oil   | -7.790698 brega 941.77907 |
| 5                     | jet_1         | 290.19034 brega 949.04392 |
| 6                     | jet_2         | 290.50992 brega 942.99292 |
| 7                     | naphtha_inter | -24.81481 brega 1003.037  |
| 8                     | naphtha_light | -74.44444 brega 989.38889 |

Price Range Analysis

| -----Maximum Phi----- |                         |           |
|-----------------------|-------------------------|-----------|
| Col                   | Price Entering          | Objective |
| 1                     | -143.55 arabian_heavy   | 1544      |
| 2                     | INFINITY .              | INFINITY  |
| 3                     | INFINITY .              | INFINITY  |
| 4                     | 71.5 arabian_heavy      | 7070.95   |
| 5                     | 392.25806 arabian_heavy | 7139.4516 |
| 6                     | 387.19512 arabian_heavy | 7066.0671 |
| 7                     | 286 arabian_heavy       | 7778.8    |
| 8                     | 715 arabian_heavy       | 6870.75   |

Note that in the PROC LP statement, the **PRIMALOUT= SOLUTION** option was given. This caused the procedure to save the optimal solution in a SAS data set named SOLUTION. This data set can be used to perform further analysis on the problem without having to restart the solution process. [Example 6.4](#) shows how this is done. A display of the data follows in [Output 6.3.2](#).

**Output 6.3.2** The PRIMALOUT= Data Set for the Oil Blending Problem

| Obs | _OBJ_ID_ | _RHS_ID_ | _VAR_            | _TYPE_  | _STATUS_ |
|-----|----------|----------|------------------|---------|----------|
| 1   | profit   | _rhs_    | arabian_heavy    | UPPERBD |          |
| 2   | profit   | _rhs_    | arabian_light    | UPPERBD | UPPER    |
| 3   | profit   | _rhs_    | brega            | UPPERBD | UPPER    |
| 4   | profit   | _rhs_    | heating_oil      | NON-NEG | BASIC    |
| 5   | profit   | _rhs_    | jet_1            | NON-NEG | BASIC    |
| 6   | profit   | _rhs_    | jet_2            | NON-NEG | BASIC    |
| 7   | profit   | _rhs_    | naphtha_inter    | NON-NEG | BASIC    |
| 8   | profit   | _rhs_    | naphtha_light    | NON-NEG | BASIC    |
| 9   | profit   | _rhs_    | PHASE_1_OBJECTIV | OBJECT  | DEGEN    |
| 10  | profit   | _rhs_    | profit           | OBJECT  | BASIC    |

| Obs | _LBOUND_ | _VALUE_ | _UBOUND_   | _PRICE_ | _R_COST_ |
|-----|----------|---------|------------|---------|----------|
| 1   | 0        | 0.00    | 165        | -165    | -21.45   |
| 2   | 0        | 110.00  | 110        | -175    | 11.60    |
| 3   | 0        | 80.00   | 80         | -205    | 3.35     |
| 4   | 0        | 77.30   | 1.7977E308 | 0       | 0.00     |
| 5   | 0        | 60.65   | 1.7977E308 | 300     | 0.00     |
| 6   | 0        | 63.33   | 1.7977E308 | 300     | 0.00     |
| 7   | 0        | 21.80   | 1.7977E308 | 0       | 0.00     |
| 8   | 0        | 7.45    | 1.7977E308 | 0       | 0.00     |
| 9   | 0        | 0.00    | 0          | 0       | 0.00     |
| 10  | 0        | 1544.00 | 1.7977E308 | 0       | 0.00     |

## Example 6.4: Additional Sensitivity Analysis

The objective coefficient ranging analysis, discussed in the last example, is useful for assessing the effects of changing costs and returns on the optimal solution if each objective function coefficient is modified in isolation. However, this is often not the case.

Suppose you anticipate that the cost of crude will be increasing and you want to examine how that will affect your optimal production plans. Furthermore, you estimate that if the price of ARABIAN\_LIGHT goes up by 1 unit, then the price of ARABIAN\_HEAVY will rise by 1.2 units and the price of BREGA will increase by 1.5 units. However, you plan on passing some of your increased overhead on to your jet fuel customers, and you decide to increase the price of jet fuel 1 unit for each unit of increased cost of ARABIAN\_LIGHT.

An examination of the solution sensitivity to changes in the cost of crude is a two-step process. First, add the information on the proportional rates of change in the crude costs and the jet fuel price to the problem data set. Then, invoke the LP procedure. The following program accomplishes this. First, it adds a new row, named CHANGE, to the model. It gives this row a type of PRICESEN. That tells PROC LP to perform objective function coefficient sensitivity analysis using the given rates of change. The program then invokes PROC LP to perform the analysis. Notice that the **PRIMALIN= SOLUTION** option is used in the PROC LP

statement. This tells the LP procedure to use the saved solution. Although it is not necessary to do this, it will eliminate the need for PROC LP to re-solve the problem and can save computing time.

```
data sen;
  format _type_ $8. _col_ $14. _row_ $6.;
  input _type_ $ _col_ $ _row_ $ _coef_;
  datalines;
pricesen .          change    .
.        arabian_light change    1
.        arabian_heavy change  1.2
.        brega        change  1.5
.        jet_1         change  -1
.        jet_2         change  -1
;

data;
  set oil sen;
run;

proc lp sparsedata primalin=solution;
run;
```

Output 6.4.1 shows the range over which the current basic solution remains optimal so that the current production plan need not change. The objective coefficients are modified by adding  $\phi$  times the change vector given in the SEN data set, where  $\phi$  ranges from a minimum of -4.15891 to a maximum of 29.72973. At the minimum value of  $\phi$ , the profit decreases to 1103.073. This value of  $\phi$  corresponds to an increase in the cost of ARABIAN\_HEAVY to 169.99 (namely,  $-175 + \phi \times 1.2$ ), ARABIAN\_LIGHT to 179.16 ( $= -175 + \phi \times 1$ ), and BREGA to 211.24 ( $= -205 + \phi \times 1.5$ ), and corresponds to an increase in the price of JET\_1 and JET\_2 to 304.16 ( $= 300 + \phi \times (-1)$ ). These values can be found in the Price column under the section labeled Minimum Phi.

**Output 6.4.1** The Price Sensitivity Analysis Summary for the Oil Blending Problem

| The LP Procedure                 |              |
|----------------------------------|--------------|
| Problem Summary                  |              |
| Objective Function               | Max profit   |
| Rhs Variable                     | _rhs_        |
| Type Variable                    | _type_       |
| Problem Density (%)              | 45.00        |
| Variables                        | Number       |
| Non-negative                     | 5            |
| Upper Bounded                    | 3            |
| Total                            | 8            |
| Constraints                      | Number       |
| EQ                               | 5            |
| Objective                        | 1            |
| Total                            | 6            |
| Solution Summary                 |              |
| Terminated Successfully          |              |
| Objective Value                  | 1544         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 0            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 7            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 2            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## Output 6.4.1 continued

## Variable Summary

| Col | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
|-----|---------------|--------|---------|-------|----------|--------------|
| 1   | arabian_heavy |        | UPPERBD | -165  | 0        | -21.45       |
| 2   | arabian_light | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 3   | brega         | UPPBD  | UPPERBD | -205  | 80       | 3.35         |
| 4   | heating_oil   | BASIC  | NON-NEG | 0     | 77.3     | 0            |
| 5   | jet_1         | BASIC  | NON-NEG | 300   | 60.65    | 0            |
| 6   | jet_2         | BASIC  | NON-NEG | 300   | 63.33    | 0            |
| 7   | naphtha_inter | BASIC  | NON-NEG | 0     | 21.8     | 0            |
| 8   | naphtha_light | BASIC  | NON-NEG | 0     | 7.45     | 0            |

## Constraint Summary

| Row | Constraint Name  | Type      | S/S Col | Rhs | Activity | Dual Activity |
|-----|------------------|-----------|---------|-----|----------|---------------|
| 1   | profit           | OBJECTIVE | .       | 0   | 1544     | .             |
| 2   | napha_l_conv     | EQ        | .       | 0   | 0        | -60           |
| 3   | napha_i_conv     | EQ        | .       | 0   | 0        | -90           |
| 4   | heating_oil_conv | EQ        | .       | 0   | 0        | -450          |
| 5   | recipe_1         | EQ        | .       | 0   | 0        | -300          |
| 6   | recipe_2         | EQ        | .       | 0   | 0        | -300          |

## The LP Procedure

Price Sensitivity Analysis Summary  
Sensitivity Vector change

Minimum Phi                    -4.158907511  
 Entering Variable                brega  
 Optimal Objective                1103.0726257

Maximum Phi                    29.72972973  
 Entering Variable                arabian\_heavy  
 Optimal Objective                4695.9459459

|     |               | ----Minimum Phi---- |          | ----Maximum Phi---- |              |
|-----|---------------|---------------------|----------|---------------------|--------------|
| Col | Variable Name | Status              | Activity | Reduced Price       | Reduced Cost |
| 1   | arabian_heavy |                     | 0        | -169.9907           | -24.45065    |
| 2   | arabian_light | UPPBD               | 110      | -179.1589           | 10.027933    |
| 3   | brega         | UPPBD               | 80       | -211.2384           | 0            |
| 4   | heating_oil   | BASIC               | 77.3     | 0                   | 0            |
| 5   | jet_1         | BASIC               | 60.65    | 304.15891           | 0            |
| 6   | jet_2         | BASIC               | 63.33    | 304.15891           | 0            |
| 7   | naphtha_inter | BASIC               | 21.8     | 0                   | 0            |
| 8   | naphtha_light | BASIC               | 7.45     | 0                   | 0            |

The [Price Sensitivity Analysis Summary](#) also shows the effects of lowering the cost of crude and lowering the price of jet fuel. In particular, at the maximum  $\phi$  of 29.72973, the current optimal production plan yields a profit of 4695.95. Any increase or decrease in  $\phi$  beyond the limits given results in a change in the production plan. More precisely, the columns that constitute the basis change.

### Example 6.5: Price Parametric Programming for the Oil Blending Problem

This example continues to examine the effects of a change in the cost of crude and the selling price of jet fuel. Suppose that you know the cost of ARABIAN\_LIGHT crude is likely to increase 30 units, with the effects on oil and fuel prices as described in [Example 6.4](#). The analysis in the last example only accounted for an increase of a little over 4 units (because the minimum  $\phi$  was -4.15891). Because an increase in the cost of ARABIAN\_LIGHT beyond 4.15891 units requires a change in the optimal basis, it may also require a change in the optimal production strategy. This type of analysis, where you want to find how the solution changes with changes in the objective function coefficients or right-hand-side vector, is called parametric programming.

You can answer this question by using the `PRICEPHI=` option in the PROC LP statement. The following program instructs PROC LP to continually increase the cost of the crudes and the return from jet fuel using the ratios given previously, until the cost of ARABIAN\_LIGHT increases at least 30 units.

```
proc lp sparsedata primalin=solution pricephi=-30;
run;
```

The `PRICEPHI=` option in the PROC LP statement tells PROC LP to perform parametric programming on any price change vectors specified in the problem data set. The value of the `PRICEPHI=` option tells PROC LP how far to change the value of  $\phi$  and in what direction. A specification of `PRICEPHI=-30` tells PROC LP to continue pivoting until the problem has objective function equal to (original objective function value)  $- 30 \times$  (change vector).

[Output 6.5.1](#) shows the result of this analysis. The first page is the [Price Sensitivity Analysis Summary](#), as discussed in [Example 6.4](#). The next page is an accounting for the change in basis as a result of decreasing  $\phi$  beyond -4.1589. It shows that BREGA left the basis at an upper bound and entered the basis at a lower bound. The interpretation of these basis changes can be difficult (Hadley 1962; Dantzig 1963).

The last page of output shows the optimal solution at the displayed value of  $\phi$ , namely -30.6878. At an increase of 30.6878 units in the cost of ARABIAN\_LIGHT and the related changes to the other crudes and the jet fuel, it is optimal to modify the production of jet fuel as shown in the activity column. Although this plan is optimal, it results in a profit of 0. This may suggest that the ratio of a unit increase in the price of jet fuel per unit increase in the cost of ARABIAN\_LIGHT is lower than desirable.



**Output 6.5.1** Price Parametric Programming for the Oil Blending Problem

## The LP Procedure

## Problem Summary

|                     |            |
|---------------------|------------|
| Objective Function  | Max profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.00      |

|               |        |
|---------------|--------|
| Variables     | Number |
| Non-negative  | 5      |
| Upper Bounded | 3      |
| Total         | 8      |

|             |        |
|-------------|--------|
| Constraints | Number |
| EQ          | 5      |
| Objective   | 1      |
| Total       | 6      |

## Solution Summary

## Terminated Successfully

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 1544         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 0            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 7            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 2            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## Output 6.5.1 continued

## Variable Summary

| Col | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
|-----|---------------|--------|---------|-------|----------|--------------|
| 1   | arabian_heavy |        | UPPERBD | -165  | 0        | -21.45       |
| 2   | arabian_light | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 3   | brega         | UPPBD  | UPPERBD | -205  | 80       | 3.35         |
| 4   | heating_oil   | BASIC  | NON-NEG | 0     | 77.3     | 0            |
| 5   | jet_1         | BASIC  | NON-NEG | 300   | 60.65    | 0            |
| 6   | jet_2         | BASIC  | NON-NEG | 300   | 63.33    | 0            |
| 7   | naphtha_inter | BASIC  | NON-NEG | 0     | 21.8     | 0            |
| 8   | naphtha_light | BASIC  | NON-NEG | 0     | 7.45     | 0            |

## Constraint Summary

| Row | Constraint Name  | Type      | S/S Col | Rhs | Activity | Dual Activity |
|-----|------------------|-----------|---------|-----|----------|---------------|
| 1   | profit           | OBJECTIVE | .       | 0   | 1544     | .             |
| 2   | napha_l_conv     | EQ        | .       | 0   | 0        | -60           |
| 3   | napha_i_conv     | EQ        | .       | 0   | 0        | -90           |
| 4   | heating_oil_conv | EQ        | .       | 0   | 0        | -450          |
| 5   | recipe_1         | EQ        | .       | 0   | 0        | -300          |
| 6   | recipe_2         | EQ        | .       | 0   | 0        | -300          |

## The LP Procedure

Price Sensitivity Analysis Summary  
Sensitivity Vector change

Minimum Phi                    -4.158907511  
 Entering Variable                brega  
 Optimal Objective                1103.0726257

Maximum Phi                    29.72972973  
 Entering Variable                arabian\_heavy  
 Optimal Objective                4695.9459459

|     |               | ----Minimum Phi---- |          | ----Maximum Phi---- |              |
|-----|---------------|---------------------|----------|---------------------|--------------|
| Col | Variable Name | Status              | Activity | Reduced Price       | Reduced Cost |
| 1   | arabian_heavy |                     | 0        | -169.9907           | -24.45065    |
| 2   | arabian_light | UPPBD               | 110      | -179.1589           | 10.027933    |
| 3   | brega         | UPPBD               | 80       | -211.2384           | 0            |
| 4   | heating_oil   | BASIC               | 77.3     | 0                   | 0            |
| 5   | jet_1         | BASIC               | 60.65    | 304.15891           | 0            |
| 6   | jet_2         | BASIC               | 63.33    | 304.15891           | 0            |
| 7   | naphtha_inter | BASIC               | 21.8     | 0                   | 0            |
| 8   | naphtha_light | BASIC               | 7.45     | 0                   | 0            |

**Output 6.5.1** continued

| The LP Procedure                 |                   |           |             |  |
|----------------------------------|-------------------|-----------|-------------|--|
| Price Parametric Programming Log |                   |           |             |  |
| Sensitivity Vector change        |                   |           |             |  |
| Leaving Variable                 | Entering Variable | Objective | Current Phi |  |
| brega                            | brega             | 1103.0726 | -4.158908   |  |

| The LP Procedure                   |  |               |  |  |
|------------------------------------|--|---------------|--|--|
| Price Sensitivity Analysis Summary |  |               |  |  |
| Sensitivity Vector change          |  |               |  |  |
| Minimum Phi                        |  | -30.68783069  |  |  |
| Entering Variable                  |  | arabian_light |  |  |
| Optimal Objective                  |  | 0             |  |  |

| -----Minimum Phi----- |               |        |          |           |              |
|-----------------------|---------------|--------|----------|-----------|--------------|
| Col                   | Variable Name | Status | Activity | Price     | Reduced Cost |
| 1                     | arabian_heavy |        | 0        | -201.8254 | -43.59127    |
| 2                     | arabian_light | ALTER  | 110      | -205.6878 | 0            |
| 3                     | brega         |        | 0        | -251.0317 | -21.36905    |
| 4                     | heating_oil   | BASIC  | 42.9     | 0         | 0            |
| 5                     | jet_1         | BASIC  | 33.33    | 330.68783 | 0            |
| 6                     | jet_2         | BASIC  | 35.09    | 330.68783 | 0            |
| 7                     | naphtha_inter | BASIC  | 11       | 0         | 0            |
| 8                     | naphtha_light | BASIC  | 3.85     | 0         | 0            |

What is the optimal return if  $\phi$  is exactly -30? Because the change in the objective is linear as a function of  $\phi$ , you can calculate the objective for any value of  $\phi$  between those given by linear interpolation. For example, for any  $\phi$  between -4.1589 and -30.6878, the optimal objective value is

$$\phi \times (1103.0726 - 0) / (-4.1589 - 30.6878) + b$$

where

$$b = 30.6878 \times (1103.0726 - 0) / (-4.1589 - 30.6878)$$

For  $\phi = -30$ , this is 28.5988.

## Example 6.6: Special Ordered Sets and the Oil Blending Problem

Often managers want to evaluate the cost of making a choice among alternatives. In particular, they want to make the most profitable choice. Suppose that only one oil crude can be used in the production process. This

identifies a set of variables of which only one can be above its lower bound. This additional restriction could be included in the model by adding a binary integer variable for each of the three crudes. Constraints would be needed that would drive the appropriate binary variable to 1 whenever the corresponding crude is used in the production process. Then a constraint limiting the total of these variables to only one would be added. A similar formulation for a fixed charge problem is shown in [Example 6.8](#).

The SOSLE type implicitly does this. The following DATA step adds a row to the model that identifies which variables are in the set. The SOSLE type tells the LP procedure that only one of the variables in this set can be above its lower bound. If you use the SOSEQ type, it tells PROC LP that exactly one of the variables in the set must be above its lower bound. Only integer variables can be in an SOSEQ set.

```
data special;
  format _type_ $6. _col_ $14. _row_ $8. ;
  input _type_ $ _col_ $ _row_ $ _coef_;
  datalines;
SOSLE .          special .
.      arabian_light special 1
.      arabian_heavy special 1
.      brega       special 1
;

data;
  set oil special;
run;

proc lp sparsedata;
run;
```

[Output 6.6.1](#) includes an Integer Iteration Log. This log shows the progress that PROC LP is making in solving the problem. This is discussed in some detail in [Example 6.8](#).

**Output 6.6.1** The Oil Blending Problem with a Special Ordered Set

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.00      |
| Variables           | Number     |
| Non-negative        | 5          |
| Upper Bounded       | 3          |
| Total               | 8          |
| Constraints         | Number     |
| EQ                  | 5          |
| Objective           | 1          |
| Total               | 6          |

## Output 6.6.1 continued

| Integer Iteration Log |         |            |           |               |         |                  |
|-----------------------|---------|------------|-----------|---------------|---------|------------------|
| Iter                  | Problem | Condition  | Objective | Branched      | Sinfeas | Active Proximity |
| 1                     | 0       | ACTIVE     | 1544      | arabian_light | 0       | 2 .              |
| 2                     | -1      | SUBOPTIMAL | 1276      | .             | .       | 1 268            |
| 3                     | 1       | FATHOMED   | 268       | .             | .       | 0 .              |

| Solution Summary                 |              |
|----------------------------------|--------------|
| Integer Optimal Solution         |              |
| Objective Value                  | 1276         |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 5            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 3            |
| Integer Solutions                | 1            |
| Initial Basic Feasible Variables | 5            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 5            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

| Variable Summary |               |        |         |       |          |              |
|------------------|---------------|--------|---------|-------|----------|--------------|
| Col              | Variable Name | Status | Type    | Price | Activity | Reduced Cost |
| 1                | arabian_heavy |        | UPPERBD | -165  | 0        | -21.45       |
| 2                | arabian_light | UPPBD  | UPPERBD | -175  | 110      | 11.6         |
| 3                | brega         |        | UPPERBD | -205  | 0        | 3.35         |
| 4                | heating_oil   | BASIC  | NON-NEG | 0     | 42.9     | 0            |
| 5                | jet_1         | BASIC  | NON-NEG | 300   | 33.33    | 0            |
| 6                | jet_2         | BASIC  | NON-NEG | 300   | 35.09    | 0            |
| 7                | naphtha_inter | BASIC  | NON-NEG | 0     | 11       | 0            |
| 8                | naphtha_light | BASIC  | NON-NEG | 0     | 3.85     | 0            |

Output 6.6.1 continued

| Constraint Summary |                  |           |         |     |          |               |
|--------------------|------------------|-----------|---------|-----|----------|---------------|
| Row                | Constraint Name  | Type      | S/S Col | Rhs | Activity | Dual Activity |
| 1                  | profit           | OBJECTIVE | .       | 0   | 1276     | .             |
| 2                  | napha_1_conv     | EQ        | .       | 0   | 0        | -60           |
| 3                  | napha_i_conv     | EQ        | .       | 0   | 0        | -90           |
| 4                  | heating_oil_conv | EQ        | .       | 0   | 0        | -450          |
| 5                  | recipe_1         | EQ        | .       | 0   | 0        | -300          |
| 6                  | recipe_2         | EQ        | .       | 0   | 0        | -300          |

The solution shows that only the ARABIAN\_LIGHT crude is purchased. The requirement that only one crude be used in the production is met, and the profit is 1276. This tells you that the value of purchasing crude from an additional source, namely BREGA, is worth  $1544 - 1276 = 268$ .

### Example 6.7: Goal-Programming a Product Mix Problem

This example shows how to use PROC LP to solve a linear goal-programming problem. PROC LP has the ability to solve a series of linear programs, each with a new objective function. These objective functions are ordered by priority. The first step is to solve a linear program with the highest priority objective function constrained only by the formal constraints in the model. Then, the problem with the next highest priority objective function is solved, constrained by the formal constraints in the model and by the value that the highest priority objective function realized. That is, the second problem optimizes the second highest priority objective function among the alternate optimal solutions to the first optimization problem. The process continues until a linear program is solved for each of the objectives.

This technique is useful for differentiating among alternate optimal solutions to a linear program. It also fits into the formal paradigm presented in goal programming. In goal programming, the objective functions typically take on the role of driving a linear function of the structural variables to meet a target level as closely as possible. The details of this can be found in many books on the subject, including Ignizio (1976).

Consider the following problem taken from Ignizio (1976). A small paint company manufactures two types of paint, latex and enamel. In production, the company uses 10 hours of labor to produce 100 gallons of latex and 15 hours of labor to produce 100 gallons of enamel. Without hiring outside help or requiring overtime, the company has 40 hours of labor available each week. Furthermore, each paint generates a profit at the rate of \$1.00 per gallon. The company has the following objectives listed in decreasing priority:

- avoid the use of overtime
- achieve a weekly profit of \$1000
- produce at least 700 gallons of enamel paint each week

The program to solve this problem follows.

```

data object;
  input _row_ $ latex enamel n1 n2 n3 p1 p2 p3 _type_ $ _rhs_;
  datalines;
overtime . . . . . 1 . . min 1
profit . . . 1 . . . . min 2
enamel . . . . 1 . . . min 3
overtime 10 15 1 . . -1 . . eq 40
profit 100 100 . 1 . . -1 . eq 1000
enamel . 1 . . 1 . . -1 eq 7
;

proc lp data=object goalprogram;
run;

```

The data set called OBJECT contains the model. Its first three observations are the objective rows, and the next three observations are the constraints. The values in the right-hand-side variable `_RHS_` in the objective rows give the priority of the objectives. The objective in the first observation with `_ROW_='OVERTIME'` has the highest priority, the objective named PROFIT has the next highest, and the objective named ENAMEL has the lowest. Note that the value of the right-hand-side variable determines the priority, not the order, in the data set.

Because this example is set in the formal goal-programming scheme, the model has structural variables representing negative (`n1`, `n2`, and `n3`) and positive (`p1`, `p2`, and `p3`) deviations from target levels. For example, `n1+p1` is the deviation from the objective of avoiding the use of overtime and underusing the normal work time, namely using exactly 40 work hours. The other objectives are handled similarly.

Notice that the PROC LP statement includes the **GOALPROGRAM** option. Without this option, the procedure would solve three separate problems: one for each of the three objective functions. In that case, however, the procedure would not constrain the second and third programs using the results of the preceding programs; also, the values 1, 2, and 3 for `_RHS_` in the objective rows would have no effect.

Output 6.7.1 shows the solution of the goal program, apparently as three linear program outputs. However, examination of the constraint summaries in the second and third problems shows that the constraints labeled by the objectives OVERTIME and PROFIT have type **FIXEDOBJ**. This indicates that these objective rows have become constraints in the subsequent problems.

**Output 6.7.1** Goal Programming

## The LP Procedure

## Problem Summary

|                     |              |
|---------------------|--------------|
| Objective Function  | Min overtime |
| Rhs Variable        | _rhs_        |
| Type Variable       | _type_       |
| Problem Density (%) | 45.83        |

|           |        |
|-----------|--------|
| Variables | Number |
|-----------|--------|

|              |   |
|--------------|---|
| Non-negative | 8 |
|--------------|---|

|       |   |
|-------|---|
| Total | 8 |
|-------|---|

|             |        |
|-------------|--------|
| Constraints | Number |
|-------------|--------|

|    |   |
|----|---|
| EQ | 3 |
|----|---|

|           |   |
|-----------|---|
| Objective | 3 |
|-----------|---|

|       |   |
|-------|---|
| Total | 6 |
|-------|---|

## Solution Summary

## Terminated Successfully

|                 |   |
|-----------------|---|
| Objective Value | 0 |
|-----------------|---|

|                    |   |
|--------------------|---|
| Phase 1 Iterations | 2 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Phase 2 Iterations | 0 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Phase 3 Iterations | 0 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Integer Iterations | 0 |
|--------------------|---|

|                   |   |
|-------------------|---|
| Integer Solutions | 0 |
|-------------------|---|

|                                  |   |
|----------------------------------|---|
| Initial Basic Feasible Variables | 7 |
|----------------------------------|---|

|                     |   |
|---------------------|---|
| Time Used (seconds) | 0 |
|---------------------|---|

|                      |   |
|----------------------|---|
| Number of Inversions | 2 |
|----------------------|---|

|         |      |
|---------|------|
| Epsilon | 1E-8 |
|---------|------|

|          |              |
|----------|--------------|
| Infinity | 1.797693E308 |
|----------|--------------|

|                            |     |
|----------------------------|-----|
| Maximum Phase 1 Iterations | 100 |
|----------------------------|-----|

|                            |     |
|----------------------------|-----|
| Maximum Phase 2 Iterations | 100 |
|----------------------------|-----|

|                            |          |
|----------------------------|----------|
| Maximum Phase 3 Iterations | 99999999 |
|----------------------------|----------|

|                            |     |
|----------------------------|-----|
| Maximum Integer Iterations | 100 |
|----------------------------|-----|

|                      |     |
|----------------------|-----|
| Time Limit (seconds) | 120 |
|----------------------|-----|



Output 6.7.1 continued

Variable Summary

| Variable |        |        |         |       |          | Reduced |
|----------|--------|--------|---------|-------|----------|---------|
| Col      | Name   | Status | Type    | Price | Activity | Cost    |
| 1        | latex  | ALTER  | NON-NEG | 0     | 0        | 0       |
| 2        | enamel | ALTER  | NON-NEG | 0     | 0        | 0       |
| 3        | n1     | BASIC  | NON-NEG | 0     | 40       | 0       |
| 4        | n2     | BASIC  | NON-NEG | 0     | 1000     | 0       |
| 5        | n3     | BASIC  | NON-NEG | 0     | 7        | 0       |
| 6        | p1     |        | NON-NEG | 1     | 0        | 1       |
| 7        | p2     | ALTER  | NON-NEG | 0     | 0        | 0       |
| 8        | p3     | ALTER  | NON-NEG | 0     | 0        | 0       |

Constraint Summary

| Constraint |          | S/S       |     |      |          | Dual     |
|------------|----------|-----------|-----|------|----------|----------|
| Row        | Name     | Type      | Col | Rhs  | Activity | Activity |
| 1          | overtime | OBJECTIVE | .   | 0    | 0        | .        |
| 2          | profit   | FREE_OBJ  | .   | 0    | 1000     | .        |
| 3          | enamel   | FREE_OBJ  | .   | 0    | 7        | .        |
| 4          | overtime | EQ        | .   | 40   | 40       | 0        |
| 5          | profit   | EQ        | .   | 1000 | 1000     | 0        |
| 6          | enamel   | EQ        | .   | 7    | 7        | 0        |

Problem Summary

|                     |            |
|---------------------|------------|
| Objective Function  | Min profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.83      |
| Variables           |            |
| Number              |            |
| Non-negative        | 8          |
| Total               | 8          |
| Constraints         |            |
| Number              |            |
| EQ                  | 3          |
| Objective           | 3          |
| Total               | 6          |

## Output 6.7.1 continued

## Solution Summary

Terminated Successfully

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 600          |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 3            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 7            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 5            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## Variable Summary

| Variable |        |         |       |          |  | Reduced |
|----------|--------|---------|-------|----------|--|---------|
| Col Name | Status | Type    | Price | Activity |  | Cost    |
| 1 latex  | BASIC  | NON-NEG | 0     | 4        |  | 0       |
| 2 enamel |        | NON-NEG | 0     | 0        |  | 50      |
| 3 n1     |        | NON-NEG | 0     | 0        |  | 10      |
| 4 n2     | BASIC  | NON-NEG | 1     | 600      |  | 0       |
| 5 n3     | BASIC  | NON-NEG | 0     | 7        |  | 0       |
| 6 p1     | DEGEN  | NON-NEG | 0     | 0        |  | 0       |
| 7 p2     |        | NON-NEG | 0     | 0        |  | 1       |
| 8 p3     | ALTER  | NON-NEG | 0     | 0        |  | 0       |

## Constraint Summary

| Constraint |           | S/S |      |          |  | Dual     |
|------------|-----------|-----|------|----------|--|----------|
| Row Name   | Type      | Col | Rhs  | Activity |  | Activity |
| 1 overtime | FIXEDOBJ  | .   | 0    | 0        |  | .        |
| 2 profit   | OBJECTIVE | .   | 0    | 600      |  | .        |
| 3 enamel   | FREE_OBJ  | .   | 0    | 7        |  | .        |
| 4 overtime | EQ        | .   | 40   | 40       |  | -10      |
| 5 profit   | EQ        | .   | 1000 | 1000     |  | 1        |
| 6 enamel   | EQ        | .   | 7    | 7        |  | 0        |

**Output 6.7.1** *continued***Problem Summary**

|                     |            |
|---------------------|------------|
| Objective Function  | Min enamel |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 45.83      |

|           |        |
|-----------|--------|
| Variables | Number |
|-----------|--------|

|              |   |
|--------------|---|
| Non-negative | 8 |
|--------------|---|

|       |   |
|-------|---|
| Total | 8 |
|-------|---|

|             |        |
|-------------|--------|
| Constraints | Number |
|-------------|--------|

|    |   |
|----|---|
| EQ | 3 |
|----|---|

|           |   |
|-----------|---|
| Objective | 3 |
|-----------|---|

|       |   |
|-------|---|
| Total | 6 |
|-------|---|

**Solution Summary****Terminated Successfully**

|                 |   |
|-----------------|---|
| Objective Value | 7 |
|-----------------|---|

|                    |   |
|--------------------|---|
| Phase 1 Iterations | 0 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Phase 2 Iterations | 1 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Phase 3 Iterations | 0 |
|--------------------|---|

|                    |   |
|--------------------|---|
| Integer Iterations | 0 |
|--------------------|---|

|                   |   |
|-------------------|---|
| Integer Solutions | 0 |
|-------------------|---|

|                                  |   |
|----------------------------------|---|
| Initial Basic Feasible Variables | 7 |
|----------------------------------|---|

|                     |   |
|---------------------|---|
| Time Used (seconds) | 0 |
|---------------------|---|

|                      |   |
|----------------------|---|
| Number of Inversions | 8 |
|----------------------|---|

|         |      |
|---------|------|
| Epsilon | 1E-8 |
|---------|------|

|          |              |
|----------|--------------|
| Infinity | 1.797693E308 |
|----------|--------------|

|                            |     |
|----------------------------|-----|
| Maximum Phase 1 Iterations | 100 |
|----------------------------|-----|

|                            |     |
|----------------------------|-----|
| Maximum Phase 2 Iterations | 100 |
|----------------------------|-----|

|                            |          |
|----------------------------|----------|
| Maximum Phase 3 Iterations | 99999999 |
|----------------------------|----------|

|                            |     |
|----------------------------|-----|
| Maximum Integer Iterations | 100 |
|----------------------------|-----|

|                      |     |
|----------------------|-----|
| Time Limit (seconds) | 120 |
|----------------------|-----|

Output 6.7.1 continued

| Variable Summary |          |        |         |       |          |              |
|------------------|----------|--------|---------|-------|----------|--------------|
|                  | Variable |        |         |       |          |              |
| Col              | Name     | Status | Type    | Price | Activity | Reduced Cost |
| 1                | latex    | BASIC  | NON-NEG | 0     | 4        | 0            |
| 2                | enamel   | DEGEN  | NON-NEG | 0     | 0        | 0            |
| 3                | n1       |        | NON-NEG | 0     | 0        | 0.2          |
| 4                | n2       | BASIC  | NON-NEG | 0     | 600      | 0            |
| 5                | n3       | BASIC  | NON-NEG | 1     | 7        | 0            |
| 6                | p1       | DEGEN  | NON-NEG | 0     | 0        | 0            |
| 7                | p2       |        | NON-NEG | 0     | 0        | 0.02         |
| 8                | p3       |        | NON-NEG | 0     | 0        | 1            |

| Constraint Summary |            |           |         |      |          |               |
|--------------------|------------|-----------|---------|------|----------|---------------|
|                    | Constraint |           |         |      |          |               |
| Row                | Name       | Type      | S/S Col | Rhs  | Activity | Dual Activity |
| 1                  | overtime   | FIXEDOBJ  | .       | 0    | 0        | .             |
| 2                  | profit     | FIXEDOBJ  | .       | 0    | 600      | .             |
| 3                  | enamel     | OBJECTIVE | .       | 0    | 7        | .             |
| 4                  | overtime   | EQ        | .       | 40   | 40       | -0.2          |
| 5                  | profit     | EQ        | .       | 1000 | 1000     | 0.02          |
| 6                  | enamel     | EQ        | .       | 7    | 7        | 1             |

The solution to the last linear program shows a value of 4 for the variable LATEX and a value of 0 for the variable ENAMEL. This tells you that the solution to the linear goal program is to produce 400 gallons of latex and no enamel paint.

The values of the objective functions in the three linear programs tell you whether you can achieve the three objectives. The activities of the constraints labeled OVERTIME, PROFIT, and ENAMEL tell you values of the three linear program objectives. Because the first linear programming objective OVERTIME is 0, the highest priority objective, which is to avoid using additional labor, is accomplished. However, because the second and third objectives are nonzero, the second and third priority objectives are not satisfied completely. The PROFIT objective is 600. Because the PROFIT objective is to minimize the negative deviation from the profit constraint, this means that a profit of only  $400 = 1000 - 600$  is realized. Similarly, the ENAMEL objective is 7, indicating that there is a negative deviation from the ENAMEL target of 7 units.

## Example 6.8: A Simple Integer Program

Recall the linear programming problem presented in Chapter 3, “Introduction to Optimization” (*SAS/OR User’s Guide: Mathematical Programming*). In that problem, a firm produces two products, chocolates and gumdrops, that are processed by four processes: cooking, color/flavor, condiments, and packaging. The objective is to determine the product mix that maximizes the profit to the firm while not exceeding manufacturing capacities. The problem is extended to demonstrate a use of integer-constrained variables.

Suppose that you must manufacture only one of the two products. In addition, there is a setup cost of 100 if you make the chocolates and 75 if you make the gumdrops. To identify which product will maximize profit, you define two zero-one integer variables, ICHOCO and IGUMDR, and you also define two new constraints, CHOCOLATE and GUM. The constraint labeled CHOCOLATE forces ICHOCO to equal one when chocolates are manufactured. Similarly, the constraint labeled GUM forces IGUMDR to equal 1 when gumdrops are manufactured. Also, you should include a constraint labeled ONLY\_ONE that requires the sum of ICHOCO and IGUMDR to equal 1. (Note that this could be accomplished more simply by including ICHOCO and IGUMDR in a SOSEQ set.) Since ICHOCO and IGUMDR are integer variables, this constraint eliminates the possibility of both products being manufactured. Notice the coefficients -10000, which are used to force ICHOCO or IGUMDR to 1 whenever CHOCO and GUMDR are nonzero. This technique, which is often used in integer programming, can cause severe numerical problems. If this driving coefficient is too large, then arithmetic overflows and underflow may result. If the driving coefficient is too small, then the integer variable may not be driven to 1 as desired by the modeler.

The objective coefficients of the integer variables ICHOCO and IGUMDR are the negatives of the setup costs for the two products. The following is the data set that describes this problem and the call to PROC LP to solve it:

```
data;
  format _row_ $10. ;
  input _row_ $ choco gumdr ichoco igumdr _type_ $ _rhs_;
  datalines;
object      .25      .75      -100      -75 max      .
cooking      15       40       0        0 1e      27000
color        0      56.25      0        0 1e      27000
package     18.75      0        0        0 1e      27000
condiments   12       50       0        0 1e      27000
chocolate    1        0     -10000      0 1e        0
gum          0        1        0     -10000 1e        0
only_one     0        0        1        1 eq        1
binary       .        .        1        2 binary   .
;

proc lp;
run;
```

The solution shows that gumdrops are produced. See [Output 6.8.1](#).

**Output 6.8.1** Summaries and an Integer Programming Iteration Log

| The LP Procedure      |         |            |           |          |       |         |        |           |
|-----------------------|---------|------------|-----------|----------|-------|---------|--------|-----------|
| Problem Summary       |         |            |           |          |       |         |        |           |
| Objective Function    |         | Max object |           |          |       |         |        |           |
| Rhs Variable          |         | _rhs_      |           |          |       |         |        |           |
| Type Variable         |         | _type_     |           |          |       |         |        |           |
| Problem Density (%)   |         | 25.71      |           |          |       |         |        |           |
| Variables             |         | Number     |           |          |       |         |        |           |
| Non-negative          |         | 2          |           |          |       |         |        |           |
| Binary                |         | 2          |           |          |       |         |        |           |
| Slack                 |         | 6          |           |          |       |         |        |           |
| Total                 |         | 10         |           |          |       |         |        |           |
| Constraints           |         | Number     |           |          |       |         |        |           |
| LE                    |         | 6          |           |          |       |         |        |           |
| EQ                    |         | 1          |           |          |       |         |        |           |
| Objective             |         | 1          |           |          |       |         |        |           |
| Total                 |         | 8          |           |          |       |         |        |           |
| Integer Iteration Log |         |            |           |          |       |         |        |           |
| Iter                  | Problem | Condition  | Objective | Branched | Value | Sinfeas | Active | Proximity |
| 1                     | 0       | ACTIVE     | 397.5     | igumdr   | 0.9   | 0.2     | 2      | .         |
| 2                     | 1       | SUBOPTIMAL | 260       | .        | .     | .       | 1      | 70        |
| 3                     | -1      | SUBOPTIMAL | 285       | .        | .     | .       | 0      | .         |

Output 6.8.1 continued

Solution Summary

Integer Optimal Solution

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 285          |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 5            |
| Phase 3 Iterations               | 5            |
| Integer Iterations               | 3            |
| Integer Solutions                | 2            |
| Initial Basic Feasible Variables | 9            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 5            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

Variable Summary

| Variable |            |        |         |       | Reduced  |           |
|----------|------------|--------|---------|-------|----------|-----------|
| Col      | Name       | Status | Type    | Price | Activity | Cost      |
| 1        | choco      | DEGEN  | NON-NEG | 0.25  | 0        | 0         |
| 2        | gumdr      | BASIC  | NON-NEG | 0.75  | 480      | 0         |
| 3        | ichoco     | DEGEN  | BINARY  | -100  | 0        | 0         |
| 4        | igumdr     |        | BINARY  | -75   | 1        | -2475     |
| 5        | cooking    | BASIC  | SLACK   | 0     | 7800     | 0         |
| 6        | color      |        | SLACK   | 0     | 0        | -0.013333 |
| 7        | package    | BASIC  | SLACK   | 0     | 27000    | 0         |
| 8        | condiments | BASIC  | SLACK   | 0     | 3000     | 0         |
| 9        | chocolate  |        | SLACK   | 0     | 0        | -0.25     |
| 10       | gum        | BASIC  | SLACK   | 0     | 9520     | 0         |

Constraint Summary

| Constraint |            |           | S/S | Dual  |          |           |
|------------|------------|-----------|-----|-------|----------|-----------|
| Row        | Name       | Type      | Col | Rhs   | Activity | Activity  |
| 1          | object     | OBJECTIVE | .   | 0     | 285      | .         |
| 2          | cooking    | LE        | 5   | 27000 | 19200    | 0         |
| 3          | color      | LE        | 6   | 27000 | 27000    | 0.0133333 |
| 4          | package    | LE        | 7   | 27000 | 0        | 0         |
| 5          | condiments | LE        | 8   | 27000 | 24000    | 0         |
| 6          | chocolate  | LE        | 9   | 0     | 0        | 0.25      |
| 7          | gum        | LE        | 10  | 0     | -9520    | 0         |
| 8          | only_one   | EQ        | .   | 1     | 1        | 2400      |

The branch-and-bound tree can be reconstructed from the information contained in the integer iteration log. The column labeled *Iter* numbers the integer iterations. The column labeled *Problem* identifies the *Iter* number of the parent problem from which the current problem is defined. For example, *Iter*=2 has *Problem*=-1. This means that problem 2 is a direct descendant of problem 1. Furthermore, because problem 1 branched on *ICHOCO*, you know that problem 2 is identical to problem 1 with an additional constraint on variable *ICHOCO*. The minus sign in the *Problem*=-1 in *Iter*=2 tells you that the new constraint on variable *ICHOCO* is a lower bound. Moreover, because *Value*=0.1 in *Iter*=1, you know that *ICHOCO*=0.1 in *Iter*=1 so that the added constraint in *Iter*=2 is  $ICHOCO \geq [0.1]$ . In this way, the information in the log can be used to reconstruct the branch-and-bound tree. In fact, when you save an **ACTIVEOUT=** data set, it contains information in this format that is used to reconstruct the tree when you restart a problem using the **ACTIVEIN=** data set. See [Example 6.10](#).

Note that if you defined a **SOSEQ** special ordered set containing the variables *CHOCO* and *GUMDR*, the integer variables *ICHOCO* and *IGUMDR* and the three associated constraints would not have been needed.

---

### Example 6.9: An Infeasible Problem

This is an example of the **Infeasible Information Summary** that is displayed when an infeasible problem is encountered. Consider the following problem:

$$\begin{array}{ll}
 \max & x + y + z + w \\
 \text{subject to} & x + 3y + 2z + 4w \leq 5 \\
 & 3x + y + 2z + w \leq 4 \\
 & 5x + 3y + 3z + 3w = 9 \\
 & x, y, z, w \geq 0
 \end{array}$$

Examination of this problem reveals that it is unsolvable. Consequently, PROC LP identifies it as infeasible. The following program attempts to solve it.

```

data infeas;
    format _id_ $6.;
    input _id_ $ x1-x4 _type_ $ _rhs_;
    datalines;
profit    1    1    1    1    max    .
const1    1    3    2    4    le     5
const2    3    1    2    1    le     4
const3    5    3    3    3    eq     9
;

```



The results are shown in [Output 6.9.1](#).

**Output 6.9.1** The Solution of an Infeasible Problem

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max profit |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 77.78      |
| Variables           | Number     |
| Non-negative        | 4          |
| Slack               | 2          |
| Total               | 6          |
| Constraints         | Number     |
| LE                  | 2          |
| EQ                  | 1          |
| Objective           | 1          |
| Total               | 4          |

**ERROR:** Infeasible problem. Note the constraints in the constraint summary that are identified as infeasible. If none of the constraints are flagged then check the implicit bounds on the variables.

## The LP Procedure

## Solution Summary

## Infeasible Problem

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 2.5          |
| Phase 1 Iterations               | 2            |
| Phase 2 Iterations               | 0            |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 5            |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 2            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## The LP Procedure

## Variable Summary

| Variable |        |        |         |       |          | Reduced |
|----------|--------|--------|---------|-------|----------|---------|
| Col      | Name   | Status | Type    | Price | Activity | Cost    |
| 1        | x1     | BASIC  | NON-NEG | 1     | 0.75     | 0       |
| 2        | x2     | BASIC  | NON-NEG | 1     | 1.75     | 0       |
| 3        | x3     |        | NON-NEG | 1     | 0        | 0.5     |
| 4        | x4     |        | NON-NEG | 1     | 0        | 0       |
| *INF*    | const1 | BASIC  | SLACK   | 0     | -1       | 0       |
| 6        | const2 |        | SLACK   | 0     | 0        | 0.5     |

## The LP Procedure

## Constraint Summary

| Constraint |        |           |            |     |          | Dual     |
|------------|--------|-----------|------------|-----|----------|----------|
| Row        | Name   | Type      | S/S<br>Col | Rhs | Activity | Activity |
| 1          | profit | OBJECTIVE | .          | 0   | 2.5      | .        |
| *INF*      | const1 | LE        | 5          | 5   | 6        | 0        |
| 3          | const2 | LE        | 6          | 4   | 4        | -0.5     |
| 4          | const3 | EQ        | .          | 9   | 9        | 0.5      |

| The LP Procedure               |             |          |             |             |
|--------------------------------|-------------|----------|-------------|-------------|
| Infeasible Information Summary |             |          |             |             |
| Infeasible Row                 | const1      |          |             |             |
| Constraint Activity            | 6           |          |             |             |
| Row Type                       | LE          |          |             |             |
| Rhs Data                       | 5           |          |             |             |
| Variable                       | Coefficient | Activity | Lower Bound | Upper Bound |
| x1                             | 1           | 0.75     | 0           | INFINITY    |
| x2                             | 3           | 1.75     | 0           | INFINITY    |
| x3                             | 2           | 0        | 0           | INFINITY    |
| x4                             | 4           | 0        | 0           | INFINITY    |

Note the information given in the Infeasible Information Summary for the infeasible row CONST1. It shows that the inequality row CONST1 with right-hand side 5 was found to be infeasible with activity 6. The summary also shows each variable that has a nonzero coefficient in that row and its activity level at the infeasibility. Examination of these model parameters might give you a clue as to the cause of infeasibility, such as an incorrectly entered coefficient or right-hand-side value.

## Example 6.10: Restarting an Integer Program

The following example is attributed to Haldi (Garfinkel and Nemhauser 1972) and is used in the literature as a test problem. Notice that the `ACTIVEOUT=` and the `PRIMALOUT=` options are used when invoking `PROC LP`. These cause the LP procedure to save the primal solution in the data set named P and the active tree in the data set named A. If the procedure fails to find an optimal integer solution on the initial call, it can be called later using the A and P data sets as starting information.

```
data haldi10;
  input x1-x12 _type_ $ _rhs_;
  datalines;
0 0 0 0 0 0 1 1 1 1 1 1 MAX .
9 7 16 8 24 5 3 7 8 4 6 5 LE 110
12 6 6 2 20 8 4 6 3 1 5 8 LE 95
15 5 12 4 4 5 5 5 6 2 1 5 LE 80
18 4 4 18 28 1 6 4 2 9 7 1 LE 100
-12 0 0 0 0 0 1 0 0 0 0 0 LE 0
0 -15 0 0 0 0 0 1 0 0 0 0 LE 0
0 0 -12 0 0 0 0 0 1 0 0 0 LE 0
0 0 0 -10 0 0 0 0 0 1 0 0 LE 0
0 0 0 0 -11 0 0 0 0 0 1 0 LE 0
0 0 0 0 0 -11 0 0 0 0 0 1 LE 0
1 1 1 1 1 1 1000 1000 1000 1000 1000 1000 UPPERBD .
1 2 3 4 5 6 7 8 9 10 11 12 INTEGER .
;
```

The **ACTIVEOUT=** data set contains a representation of the current active problems in the branch-and-bound tree. The **PRIMALOUT=** data set contains a representation of the solution to the current problem. These two can be used to restore the procedure to an equivalent state to the one it was in when it stopped.

The results from the call to PROC LP is shown in **Output 6.10.1**. Notice that the procedure performed 100 iterations and then terminated on maximum integer iterations. This is because, by default, **IMAXIT=100**. The procedure reports the current best integer solution.

**Output 6.10.1** Output from the HALDI10 Problem

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max _OBS1_ |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 31.82      |
| Variables           | Number     |
| Integer             | 6          |
| Binary              | 6          |
| Slack               | 10         |
| Total               | 22         |
| Constraints         | Number     |
| LE                  | 10         |
| Objective           | 1          |
| Total               | 11         |

## The LP Procedure

## Integer Iteration Log

| Iter | Problem | Condition  | Objective | Branched | Value | Sinfeas | Active | Proximity |
|------|---------|------------|-----------|----------|-------|---------|--------|-----------|
| 1    | 0       | ACTIVE     | 18.709524 | x9       | 1.543 | 1.11905 | 2      | .         |
| 2    | 1       | ACTIVE     | 18.467723 | x12      | 9.371 | 0.88948 | 3      | .         |
| 3    | 2       | ACTIVE     | 18.460133 | x8       | 0.539 | 1.04883 | 4      | .         |
| 4    | -3      | ACTIVE     | 18.453638 | x12      | 8.683 | 1.12993 | 5      | .         |
| 5    | 4       | ACTIVE     | 18.439678 | x10      | 7.448 | 1.20125 | 6      | .         |
| 6    | 5       | ACTIVE     | 18.403728 | x6       | 0.645 | 1.3643  | 7      | .         |
| 7    | -6      | ACTIVE     | 18.048289 | x4       | 0.7   | 1.18395 | 8      | .         |
| 8    | -7      | ACTIVE     | 17.679087 | x8       | 1.833 | 0.52644 | 9      | .         |
| 9    | 8       | ACTIVE     | 17.52     | x10      | 6.667 | 0.70111 | 10     | .         |
| 10   | 9       | ACTIVE     | 17.190085 | x12      | 7.551 | 1.37615 | 11     | .         |
| 11   | -10     | ACTIVE     | 17.02     | x1       | 0.085 | 0.255   | 12     | .         |
| 12   | 11      | ACTIVE     | 16.748    | x11      | 0.748 | 0.47    | 13     | .         |
| 13   | -12     | ACTIVE     | 16.509091 | x9       | 0.509 | 0.69091 | 14     | .         |
| 14   | 13      | ACTIVE     | 16.261333 | x11      | 1.261 | 0.44267 | 15     | .         |
| 15   | 14      | ACTIVE     | 16        | x3       | 0.297 | 0.45455 | 16     | .         |
| 16   | 15      | ACTIVE     | 16        | x5       | 0.091 | 0.15758 | 16     | .         |
| 17   | -16     | INFEASIBLE | -0.4      | .        | .     | .       | 15     | .         |
| 18   | -15     | ACTIVE     | 11.781818 | x10      | 1.782 | 0.37576 | 15     | .         |
| 19   | 18      | ACTIVE     | 11        | x2       | 0.197 | 0.28788 | 16     | .         |
| 20   | 19      | INFEASIBLE | 10        | .        | .     | .       | 15     | .         |
| 21   | -19     | INFEASIBLE | 6.1818182 | .        | .     | .       | 14     | .         |
| 22   | -14     | ACTIVE     | 11.963636 | x5       | 0.182 | 0.28485 | 14     | .         |
| 23   | -22     | INFEASIBLE | -4.4      | .        | .     | .       | 13     | .         |
| 24   | -13     | ACTIVE     | 15.281818 | x10      | 4.282 | 0.52273 | 13     | .         |
| 25   | 24      | ACTIVE     | 15.041333 | x5       | 0.095 | 0.286   | 14     | .         |
| 26   | -25     | INFEASIBLE | -2.9      | .        | .     | .       | 13     | .         |
| 27   | 25      | INFEASIBLE | 14        | .        | .     | .       | 12     | .         |
| 28   | 12      | ACTIVE     | 16        | x3       | 0.083 | 0.15    | 13     | .         |
| 29   | -28     | ACTIVE     | 15.277778 | x9       | 0.278 | 0.34444 | 14     | .         |
| 30   | -29     | ACTIVE     | 13.833333 | x10      | 3.833 | 0.23333 | 14     | .         |
| 31   | 30      | ACTIVE     | 13        | x2       | 0.4   | 0.4     | 15     | .         |
| 32   | 31      | INFEASIBLE | 12        | .        | .     | .       | 14     | .         |
| 33   | -31     | SUBOPTIMAL | 10        | .        | .     | .       | 13     | 8         |
| 34   | 29      | ACTIVE     | 15        | x2       | 0.067 | 0.06667 | 13     | 8         |
| 35   | -34     | SUBOPTIMAL | 12        | .        | .     | .       | 12     | 6         |
| 36   | 28      | ACTIVE     | 15        | x2       | 0.067 | 0.06667 | 12     | 6         |
| 37   | -36     | SUBOPTIMAL | 15        | .        | .     | .       | 11     | 3         |
| 38   | -11     | FATHOMED   | 14.275    | .        | .     | .       | 10     | 3         |
| 39   | 10      | ACTIVE     | 16.804848 | x1       | 0.158 | 0.50313 | 11     | 3         |
| 40   | -39     | FATHOMED   | 14.784    | .        | .     | .       | 10     | 3         |
| 41   | 39      | ACTIVE     | 16.40381  | x11      | 1.404 | 0.68143 | 11     | 3         |
| 42   | -41     | ACTIVE     | 16.367677 | x10      | 5.368 | 0.69949 | 12     | 3         |
| 43   | 42      | ACTIVE     | 16.113203 | x11      | 2.374 | 1.00059 | 12     | 3         |
| 44   | 43      | ACTIVE     | 16        | x5       | 0.182 | 0.33182 | 12     | 3         |

## The LP Procedure

## Integer Iteration Log

| Iter | Problem | Condition  | Objective | Branched | Value | Sinfeas | Active | Proximity |
|------|---------|------------|-----------|----------|-------|---------|--------|-----------|
| 45   | -44     | FATHOMED   | 13.822222 | .        | .     | .       | 11     | 3         |
| 46   | -42     | FATHOMED   | 12.642424 | .        | .     | .       | 10     | 3         |
| 47   | 41      | ACTIVE     | 16        | x5       | 0.229 | 0.37857 | 10     | 3         |
| 48   | 47      | FATHOMED   | 15        | .        | .     | .       | 9      | 3         |
| 49   | -9      | ACTIVE     | 17.453333 | x7       | 0.453 | 0.64111 | 10     | 3         |
| 50   | 49      | ACTIVE     | 17.35619  | x11      | 0.356 | 0.53857 | 11     | 3         |
| 51   | 50      | ACTIVE     | 17        | x5       | 0.121 | 0.27143 | 12     | 3         |
| 52   | 51      | ACTIVE     | 17        | x3       | 0.083 | 0.15    | 13     | 3         |
| 53   | -52     | FATHOMED   | 15.933333 | .        | .     | .       | 12     | 3         |
| 54   | 52      | ACTIVE     | 16        | x2       | 0.067 | 0.06667 | 12     | 3         |
| 55   | -54     | SUBOPTIMAL | 16        | .        | .     | .       | 8      | 2         |
| 56   | -8      | ACTIVE     | 17.655399 | x12      | 7.721 | 0.56127 | 9      | 2         |
| 57   | 56      | ACTIVE     | 17.519375 | x10      | 6.56  | 0.76125 | 10     | 2         |
| 58   | 57      | ACTIVE     | 17.256874 | x2       | 0.265 | 0.67388 | 11     | 2         |
| 59   | 58      | INFEASIBLE | 17.167622 | .        | .     | .       | 10     | 2         |
| 60   | -58     | FATHOMED   | 16.521755 | .        | .     | .       | 9      | 2         |
| 61   | -57     | FATHOMED   | 17.03125  | .        | .     | .       | 8      | 2         |
| 62   | -56     | ACTIVE     | 17.342857 | x9       | 0.343 | 0.50476 | 8      | 2         |
| 63   | 62      | ACTIVE     | 17.2225   | x7       | 0.16  | 0.37333 | 9      | 2         |
| 64   | 63      | ACTIVE     | 17.1875   | x8       | 2.188 | 0.33333 | 9      | 2         |
| 65   | 64      | ACTIVE     | 17.153651 | x11      | 0.154 | 0.30095 | 10     | 2         |
| 66   | -65     | FATHOMED   | 12.381818 | .        | .     | .       | 9      | 2         |
| 67   | 65      | ACTIVE     | 17        | x2       | 0.133 | 0.18571 | 9      | 2         |
| 68   | -67     | FATHOMED   | 13        | .        | .     | .       | 8      | 2         |
| 69   | -63     | FATHOMED   | 14.2      | .        | .     | .       | 7      | 2         |
| 70   | 7       | FATHOMED   | 15.428583 | .        | .     | .       | 6      | 2         |
| 71   | 6       | FATHOMED   | 16.75599  | .        | .     | .       | 5      | 2         |
| 72   | -5      | ACTIVE     | 17.25974  | x6       | 0.727 | 0.82078 | 5      | 2         |
| 73   | -72     | FATHOMED   | 17.142857 | .        | .     | .       | 4      | 2         |
| 74   | -4      | ACTIVE     | 18.078095 | x4       | 0.792 | 0.70511 | 5      | 2         |
| 75   | -74     | ACTIVE     | 17.662338 | x10      | 7.505 | 0.91299 | 5      | 2         |
| 76   | 75      | ACTIVE     | 17.301299 | x9       | 0.301 | 0.57489 | 5      | 2         |
| 77   | 76      | ACTIVE     | 17.210909 | x7       | 0.211 | 0.47697 | 5      | 2         |
| 78   | 77      | FATHOMED   | 17.164773 | .        | .     | .       | 4      | 2         |
| 79   | 74      | FATHOMED   | 12.872727 | .        | .     | .       | 3      | 2         |
| 80   | 3       | ACTIVE     | 18.368316 | x10      | 7.602 | 1.20052 | 4      | 2         |
| 81   | 80      | ACTIVE     | 18.198323 | x7       | 1.506 | 1.85351 | 5      | 2         |
| 82   | 81      | ACTIVE     | 18.069847 | x12      | 8.517 | 1.67277 | 6      | 2         |
| 83   | -82     | ACTIVE     | 17.910909 | x4       | 0.7   | 0.73015 | 7      | 2         |
| 84   | -83     | ACTIVE     | 17.790909 | x7       | 0.791 | 0.54015 | 8      | 2         |
| 85   | -84     | ACTIVE     | 17.701299 | x9       | 0.701 | 0.62229 | 8      | 2         |
| 86   | 85      | ACTIVE     | 17.17619  | x6       | 0.818 | 0.45736 | 8      | 2         |
| 87   | -86     | ACTIVE     | 17.146667 | x11      | 0.147 | 0.24333 | 8      | 2         |
| 88   | 87      | ACTIVE     | 17        | x1       | 0.167 | 0.16667 | 8      | 2         |

| The LP Procedure      |         |            |               |                |         |        |           |
|-----------------------|---------|------------|---------------|----------------|---------|--------|-----------|
| Integer Iteration Log |         |            |               |                |         |        |           |
| Iter                  | Problem | Condition  | Objective     | Branched Value | Sinfeas | Active | Proximity |
| 89                    | 88      | INFEASIBLE | 16 .          | .              | .       | 7      | 2         |
| 90                    | 84      | ACTIVE     | 17.58 x11     | 0.58           | 0.73788 | 8      | 2         |
| 91                    | -90     | FATHOMED   | 17.114286 .   | .              | .       | 7      | 2         |
| 92                    | -81     | ACTIVE     | 18.044048 x12 | 8.542          | 1.71158 | 8      | 2         |
| 93                    | 92      | ACTIVE     | 17.954536 x11 | 0.477          | 1.90457 | 9      | 2         |
| 94                    | 93      | ACTIVE     | 17.875084 x4  | 0.678          | 1.16624 | 10     | 2         |
| 95                    | 94      | FATHOMED   | 13.818182 .   | .              | .       | 9      | 2         |
| 96                    | -94     | ACTIVE     | 17.231221 x6  | 0.727          | 0.76182 | 9      | 2         |
| 97                    | -96     | FATHOMED   | 17.085714 .   | .              | .       | 8      | 2         |
| 98                    | -93     | FATHOMED   | 17.723058 .   | .              | .       | 7      | 2         |
| 99                    | -92     | FATHOMED   | 16.378788 .   | .              | .       | 6      | 2         |
| 100                   | 90      | ACTIVE     | 17 x6         | 0.818          | 0.26515 | 6      | 2         |

**WARNING:** The maximum number of integer iterations has been exceeded. Increase this limit with the 'IMAXIT=' option on the RESET statement.

| The LP Procedure                         |              |
|--|--------------|
| Solution Summary                         |              |
| Terminated on Maximum Integer Iterations |              |
| Integer Feasible Solution                |              |
| Objective Value                          | 16           |
| Phase 1 Iterations                       | 0            |
| Phase 2 Iterations                       | 13           |
| Phase 3 Iterations                       | 160          |
| Integer Iterations                       | 100          |
| Integer Solutions                        | 4            |
| Initial Basic Feasible Variables         | 12           |
| Time Used (seconds)                      | 0            |
| Number of Inversions                     | 38           |
| Epsilon                                  | 1E-8         |
| Infinity                                 | 1.797693E308 |
| Maximum Phase 1 Iterations               | 100          |
| Maximum Phase 2 Iterations               | 100          |
| Maximum Phase 3 Iterations               | 99999999     |
| Maximum Integer Iterations               | 100          |
| Time Limit (seconds)                     | 120          |

| The LP Procedure |         |        |         |       |          |         |
|------------------|---------|--------|---------|-------|----------|---------|
| Variable Summary |         |        |         |       |          |         |
| Variable         |         |        |         |       |          | Reduced |
| Col              | Name    | Status | Type    | Price | Activity | Cost    |
| 1                | x1      | DEGEN  | BINARY  | 0     | 0        | 0       |
| 2                | x2      | ALTER  | BINARY  | 0     | 1        | 0       |
| 3                | x3      |        | BINARY  | 0     | 0        | 12      |
| 4                | x4      | ALTER  | BINARY  | 0     | 1        | 0       |
| 5                | x5      | ALTER  | BINARY  | 0     | 0        | 0       |
| 6                | x6      | ALTER  | BINARY  | 0     | 1        | 0       |
| 7                | x7      |        | INTEGER | 1     | 0        | 1       |
| 8                | x8      |        | INTEGER | 1     | 1        | 1       |
| 9                | x9      | DEGEN  | INTEGER | 1     | 0        | 0       |
| 10               | x10     |        | INTEGER | 1     | 7        | 1       |
| 11               | x11     |        | INTEGER | 1     | 0        | 1       |
| 12               | x12     |        | INTEGER | 1     | 8        | 1       |
| 13               | _OBS2_  | BASIC  | SLACK   | 0     | 15       | 0       |
| 14               | _OBS3_  | BASIC  | SLACK   | 0     | 2        | 0       |
| 15               | _OBS4_  | BASIC  | SLACK   | 0     | 7        | 0       |
| 16               | _OBS5_  | BASIC  | SLACK   | 0     | 2        | 0       |
| 17               | _OBS6_  | ALTER  | SLACK   | 0     | 0        | 0       |
| 18               | _OBS7_  | BASIC  | SLACK   | 0     | 14       | 0       |
| 19               | _OBS8_  |        | SLACK   | 0     | 0        | -1      |
| 20               | _OBS9_  | BASIC  | SLACK   | 0     | 3        | 0       |
| 21               | _OBS10_ | DEGEN  | SLACK   | 0     | 0        | 0       |
| 22               | _OBS11_ | BASIC  | SLACK   | 0     | 3        | 0       |

| The LP Procedure   |         |           |         |     |          |          |
|--------------------|---------|-----------|---------|-----|----------|----------|
| Constraint Summary |         |           |         |     |          |          |
| Constraint         |         |           |         |     |          | Dual     |
| Row                | Name    | Type      | S/S Col | Rhs | Activity | Activity |
| 1                  | _OBS1_  | OBJECTIVE | .       | 0   | 16       | .        |
| 2                  | _OBS2_  | LE        | 13      | 110 | 95       | 0        |
| 3                  | _OBS3_  | LE        | 14      | 95  | 93       | 0        |
| 4                  | _OBS4_  | LE        | 15      | 80  | 73       | 0        |
| 5                  | _OBS5_  | LE        | 16      | 100 | 98       | 0        |
| 6                  | _OBS6_  | LE        | 17      | 0   | 0        | 0        |
| 7                  | _OBS7_  | LE        | 18      | 0   | -14      | 0        |
| 8                  | _OBS8_  | LE        | 19      | 0   | 0        | 1        |
| 9                  | _OBS9_  | LE        | 20      | 0   | -3       | 0        |
| 10                 | _OBS10_ | LE        | 21      | 0   | 0        | 0        |
| 11                 | _OBS11_ | LE        | 22      | 0   | -3       | 0        |

To continue with the solution of this problem, invoke PROC LP with the **ACTIVEIN=** and **PRIMALIN=** options and reset the **IMAXIT=** option. This restores the branch-and-bound tree and simplifies calculating a



basic feasible solution from which to start processing.

```
proc lp data=haldi10 activein=a primalin=p imaxit=250;
run;
```

The procedure picks up iterating from a equivalent state to where it left off. The problem will still not be solved when `IMAXIT=250` occurs.

## Example 6.11: Alternative Search of the Branch-and-Bound Tree

In this example, the HALDI10 problem from [Example 6.10](#) is solved. However, here the default strategy for searching the branch-and-bound tree is modified. By default, the search strategy has `VARSELECT=FAR`. This means that when searching for an integer variable on which to branch, the procedure uses the one that has a value farthest from an integer value. An alternative strategy has `VARSELECT=PENALTY`. This strategy causes PROC LP to look at the cost, in terms of the objective function, of branching on an integer variable. The procedure looks at `PENALTYDEPTH=` integer variables before choosing the one with the largest cost. This is a much more expensive strategy (in terms of execution time) than the `VARSELECT=FAR` strategy, but it can be beneficial if fewer integer iterations must be done to find an optimal solution.

```
proc lp data=haldi10 varselect=penalty;
run;
```

Compare the number of integer iterations needed to solve the problem using this heuristic with the default strategy used in [Example 6.10](#). In this example, the difference is profound; in general, solution times can vary significantly with the search technique. See [Output 6.11.1](#).

### Output 6.11.1 Summaries and an Integer Programming Iteration Log: Using VARSELECT=PENALTY

| The LP Procedure    |            |
|---------------------|------------|
| Problem Summary     |            |
| Objective Function  | Max _OBS1_ |
| Rhs Variable        | _rhs_      |
| Type Variable       | _type_     |
| Problem Density (%) | 31.82      |
| Variables           | Number     |
| Integer             | 6          |
| Binary              | 6          |
| Slack               | 10         |
| Total               | 22         |
| Constraints         | Number     |
| LE                  | 10         |
| Objective           | 1          |
| Total               | 11         |

## Output 6.11.1 continued

| Integer Iteration Log |         |            |           |          |       |         |                  |
|-----------------------|---------|------------|-----------|----------|-------|---------|------------------|
| Iter                  | Problem | Condition  | Objective | Branched | Value | Sinfeas | Active Proximity |
| 1                     | 0       | ACTIVE     | 18.709524 | x4       | 0.8   | 1.11905 | 2 .              |
| 2                     | 1       | ACTIVE     | 16.585187 | x1       | 0.447 | 2.33824 | 3 .              |
| 3                     | 2       | ACTIVE     | 14.86157  | x5       | 0.221 | 2.09584 | 4 .              |
| 4                     | 3       | ACTIVE     | 14.807195 | x2       | 0.897 | 1.31729 | 5 .              |
| 5                     | -4      | ACTIVE     | 14.753205 | x8       | 14.58 | 0.61538 | 6 .              |
| 6                     | 5       | ACTIVE     | 14.730078 | x6       | 0.043 | 0.79446 | 7 .              |
| 7                     | -6      | ACTIVE     | 13.755102 | x3       | 0.051 | 0.58163 | 8 .              |
| 8                     | -7      | ACTIVE     | 11.6      | x8       | 11.6  | 0.4     | 9 .              |
| 9                     | 8       | ACTIVE     | 11.6      | x12      | 0.6   | 0.4     | 10 .             |
| 10                    | -9      | ACTIVE     | 11.6      | x8       | 10.6  | 0.4     | 11 .             |
| 11                    | 10      | ACTIVE     | 11.6      | x12      | 1.6   | 0.4     | 12 .             |
| 12                    | 11      | ACTIVE     | 11.5      | x9       | 0.5   | 0.5     | 13 .             |
| 13                    | -12     | ACTIVE     | 11.4      | x8       | 9.4   | 0.4     | 14 .             |
| 14                    | 13      | ACTIVE     | 11.333333 | x9       | 1.333 | 0.33333 | 15 .             |
| 15                    | -14     | ACTIVE     | 11.2      | x8       | 8.2   | 0.2     | 16 .             |
| 16                    | 15      | ACTIVE     | 11.166667 | x9       | 2.167 | 0.16667 | 17 .             |
| 17                    | -16     | SUBOPTIMAL | 11        | .        | .     | .       | 7 7              |
| 18                    | 7       | ACTIVE     | 13.5      | x8       | 13.5  | 0.5     | 8 7              |
| 19                    | -18     | INFEASIBLE | 11        | .        | .     | .       | 7 7              |
| 20                    | 18      | ACTIVE     | 13.375    | x12      | 0.375 | 0.375   | 8 7              |
| 21                    | -20     | ACTIVE     | 13.166667 | x8       | 12.17 | 0.16667 | 9 7              |
| 22                    | 21      | ACTIVE     | 13.125    | x12      | 1.125 | 0.125   | 10 7             |
| 23                    | 22      | SUBOPTIMAL | 13        | .        | .     | .       | 4 5              |
| 24                    | 6       | ACTIVE     | 14.535714 | x3       | 0.045 | 0.50893 | 5 5              |
| 25                    | -24     | FATHOMED   | 12.625    | .        | .     | .       | 4 5              |
| 26                    | 24      | SUBOPTIMAL | 14        | .        | .     | .       | 1 4              |
| 27                    | -1      | ACTIVE     | 18.309524 | x3       | 0.129 | 1.31905 | 2 4              |
| 28                    | 27      | ACTIVE     | 17.67723  | x6       | 0.886 | 0.43662 | 3 4              |
| 29                    | 28      | ACTIVE     | 15.485156 | x2       | 0.777 | 1.50833 | 4 4              |
| 30                    | -29     | ACTIVE     | 15.2625   | x1       | 0.121 | 1.38333 | 4 4              |
| 31                    | 30      | ACTIVE     | 15.085106 | x10      | 3.532 | 0.91489 | 4 4              |
| 32                    | 31      | FATHOMED   | 14.857143 | .        | .     | .       | 3 4              |
| 33                    | 29      | FATHOMED   | 11.212121 | .        | .     | .       | 2 4              |
| 34                    | -28     | ACTIVE     | 17.56338  | x10      | 7.93  | 0.43662 | 3 4              |
| 35                    | 34      | ACTIVE     | 17.225962 | x8       | 2.38  | 0.69231 | 4 4              |
| 36                    | 35      | ACTIVE     | 17.221818 | x1       | 0.016 | 0.37111 | 5 4              |
| 37                    | -36     | FATHOMED   | 14.43662  | .        | .     | .       | 4 4              |
| 38                    | 36      | ACTIVE     | 17.172375 | x2       | 0.133 | 0.31948 | 5 4              |
| 39                    | 38      | ACTIVE     | 16.890196 | x5       | 0.086 | 0.19608 | 6 4              |
| 40                    | 39      | ACTIVE     | 16.75     | x12      | 9.75  | 0.25    | 7 4              |
| 41                    | -40     | SUBOPTIMAL | 15        | .        | .     | .       | 6 3              |
| 42                    | 40      | SUBOPTIMAL | 16        | .        | .     | .       | 3 2              |
| 43                    | -35     | FATHOMED   | 17.138028 | .        | .     | .       | 2 2              |
| 44                    | -34     | SUBOPTIMAL | 17        | .        | .     | .       | 1 1              |
| 45                    | -27     | FATHOMED   | 16.566667 | .        | .     | .       | 0 .              |

## Output 6.11.1 continued

## Solution Summary

## Integer Optimal Solution

|                                  |              |
|----------------------------------|--------------|
| Objective Value                  | 17           |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 13           |
| Phase 3 Iterations               | 74           |
| Integer Iterations               | 45           |
| Integer Solutions                | 6            |
| Initial Basic Feasible Variables | 12           |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 16           |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 99999999     |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

## Variable Summary

| Variable |         |        |         |       |          | Reduced   |
|----------|---------|--------|---------|-------|----------|-----------|
| Col      | Name    | Status | Type    | Price | Activity | Cost      |
| 1        | x1      | DEGEN  | BINARY  | 0     | 0        | 0         |
| 2        | x2      |        | BINARY  | 0     | 0        | -4        |
| 3        | x3      |        | BINARY  | 0     | 0        | -4        |
| 4        | x4      |        | BINARY  | 0     | 1        | -18       |
| 5        | x5      | DEGEN  | BINARY  | 0     | 0        | 0         |
| 6        | x6      |        | BINARY  | 0     | 1        | -1        |
| 7        | x7      |        | INTEGER | 1     | 0        | -6.5      |
| 8        | x8      |        | INTEGER | 1     | 0        | -3        |
| 9        | x9      |        | INTEGER | 1     | 0        | -1        |
| 10       | x10     |        | INTEGER | 1     | 8        | -8        |
| 11       | x11     |        | INTEGER | 1     | 0        | -8.545455 |
| 12       | x12     | BASIC  | INTEGER | 1     | 9        | 0         |
| 13       | _OBS2_  | BASIC  | SLACK   | 0     | 20       | 0         |
| 14       | _OBS3_  | BASIC  | SLACK   | 0     | 5        | 0         |
| 15       | _OBS4_  | BASIC  | SLACK   | 0     | 10       | 0         |
| 16       | _OBS5_  |        | SLACK   | 0     | 0        | -1        |
| 17       | _OBS6_  |        | SLACK   | 0     | 0        | -1.5      |
| 18       | _OBS7_  | DEGEN  | SLACK   | 0     | 0        | 0         |
| 19       | _OBS8_  | DEGEN  | SLACK   | 0     | 0        | 0         |
| 20       | _OBS9_  | BASIC  | SLACK   | 0     | 2        | 0         |
| 21       | _OBS10_ |        | SLACK   | 0     | 0        | -2.545455 |
| 22       | _OBS11_ | BASIC  | SLACK   | 0     | 2        | 0         |

Output 6.11.1 continued

| Constraint Summary |                 |           |         |     |          |               |
|--------------------|-----------------|-----------|---------|-----|----------|---------------|
| Row                | Constraint Name | Type      | S/S Col | Rhs | Activity | Dual Activity |
| 1                  | _OBS1_          | OBJECTIVE | .       | 0   | 17       | .             |
| 2                  | _OBS2_          | LE        | 13      | 110 | 90       | 0             |
| 3                  | _OBS3_          | LE        | 14      | 95  | 90       | 0             |
| 4                  | _OBS4_          | LE        | 15      | 80  | 70       | 0             |
| 5                  | _OBS5_          | LE        | 16      | 100 | 100      | 1             |
| 6                  | _OBS6_          | LE        | 17      | 0   | 0        | 1.5           |
| 7                  | _OBS7_          | LE        | 18      | 0   | 0        | 0             |
| 8                  | _OBS8_          | LE        | 19      | 0   | 0        | 0             |
| 9                  | _OBS9_          | LE        | 20      | 0   | -2       | 0             |
| 10                 | _OBS10_         | LE        | 21      | 0   | 0        | 2.5454545     |
| 11                 | _OBS11_         | LE        | 22      | 0   | -2       | 0             |

Although the **VARSELECT=PENALTY** strategy works well in this example, there is no guarantee that it will work well with your model. Experimentation with various strategies is necessary to find the one that works well with your model and data, particularly if a model is solved repeatedly with few changes to either the structure or the data.

## Example 6.12: An Assignment Problem

This example departs somewhat from the emphasis of previous ones. Typically, linear programming models are large, have considerable structure, and are solved with some regularity. Some form of automatic model building, or matrix generation as it is commonly called, is a useful aid. The sparse input format provides a great deal of flexibility in model specification so that, in many cases, the DATA step can be used to generate the matrix.

The following assignment problem illustrates some techniques in matrix generation. In this example, you have four machines that can produce any of six grades of cloth, and you have five customers that demand various amounts of each grade of cloth. The return from supplying a customer with a demanded grade depends on the machine on which the cloth was made. In addition, the machine capacity depends both upon the specific machine used and the grade of cloth made.

To formulate this problem, let  $i$  denote customer,  $j$  denote grade, and  $k$  denote machine. Then let  $x_{ijk}$  denote the amount of cloth of grade  $j$  made on machine  $k$  for customer  $i$ ; let  $r_{ijk}$  denote the return from selling one unit of grade  $j$  cloth made on machine  $k$  to customer  $i$ ; let  $d_{ij}$  denote the demand for grade  $j$  cloth by customer  $i$ ; let  $c_{jk}$  denote the number of units of machine  $k$  required to produce one unit of grade  $j$  cloth; and let  $a_k$  denote the number of units of machine  $k$  available. Then, you get

$$\begin{array}{ll}
 \max & \sum_{ijk} r_{ijk} x_{ijk} \\
 \text{subject to} & \sum_k x_{ijk} = d_{ij} \quad \text{for all } i \text{ and } j \\
 & \sum_{ij} c_{jk} x_{ijk} \leq a_k \quad \text{for all } k \\
 & x_{ijk} \geq 0 \quad \text{for all } i, j \text{ and } k
 \end{array}$$

The data are saved in three data sets. The OBJECT data set contains the returns for satisfying demand, the DEMAND data set contains the amounts demanded, and the RESOURCE data set contains the conversion factors for each grade and the total amounts of machine resources available.

```

title 'An Assignment Problem';

data object;
  input machine customer
         grade1 grade2 grade3 grade4 grade5 grade6;
  datalines;
1 1 102 140 105 105 125 148
1 2 115 133 118 118 143 166
1 3 70 108 83 83 88 86
1 4 79 117 87 87 107 105
1 5 77 115 90 90 105 148
2 1 123 150 125 124 154 .
2 2 130 157 132 131 166 .
2 3 103 130 115 114 129 .
2 4 101 128 108 107 137 .
2 5 118 145 130 129 154 .
3 1 83 . . 97 122 147
3 2 119 . . 133 163 180
3 3 67 . . 91 101 101
3 4 85 . . 104 129 129
3 5 90 . . 114 134 179
4 1 108 121 79 . 112 132
4 2 121 132 92 . 130 150
4 3 78 91 59 . 77 72
4 4 100 113 76 . 109 104
4 5 96 109 77 . 105 145
;

data demand;
  input customer
         grade1 grade2 grade3 grade4 grade5 grade6;
  datalines;
1 100 100 150 150 175 250
2 300 125 300 275 310 325
3 400 0 400 500 340 0
4 250 0 750 750 0 0
5 0 600 300 0 210 360
;

data resource;
  input machine
         grade1 grade2 grade3 grade4 grade5 grade6 avail;
  datalines;
1 .250 .275 .300 .350 .310 .295 744
2 .300 .300 .305 .315 .320 . 244
3 .350 . . .320 .315 .300 790
4 .280 .275 .260 . .250 .295 672
;

```

The linear program is built using the DATA step. The model is saved in a SAS data set in the sparse input format for PROC LP. Each section of the following DATA step generates a piece of the linear program. The

first section generates the objective function; the next section generates the demand constraints; and the last section generates the machine resource availability constraints.

```

/* build the linear programming model */

data model;
  array grade{6} grade1-grade6;
  length _type_ $ 8 _row_ $ 8 _col_ $ 8;
  keep _type_ _row_ _col_ _coef_;

  ncust=5;
  nmach=4;
  ngrade=6;

/* generate the objective function */

_type_='MAX';
_row_='OBJ';
do k=1 to nmach;
  do i=1 to ncust;
    link readobj;      /* read the objective coefficient data */
    do j=1 to ngrade;
      if grade{j}^=. then do;
        _col_='X' || put(i,1.) || put(j,1.) || put(k,1.);
        _coef_=grade{j};
        output;
      end;
    end;
  end;
end;

/* generate the demand constraints */

do i=1 to ncust;
  link readdmd;      /* read the demand data */
  do j=1 to ngrade;
    if grade{j}^=. then do;
      _type_='EQ';
      _row_='DEMAND' || put(i,1.) || put(j,1.);
      _col_='_RHS_';
      _coef_=grade{j};
      output;
      _type_=' ';
      do k=1 to nmach;
        _col_='X' || put(i,1.) || put(j,1.) || put(k,1.);
        _coef_=1.0;
        output;
      end;
    end;
  end;
end;
end;

```

```

/* generate the machine constraints */

do k=1 to nmach;
  link readres;          /* read the machine data */
  _type_='LE';
  _row_='MACHINE' || put(k,1.);
  _col_='_RHS_';
  _coef_=avail;
  output;
  _type_=' ';
  do i=1 to ncust;
    do j=1 to ngrade;
      if grade{j}^=. then do;
        _col_='X' || put(i,1.) || put(j,1.) || put(k,1.);
        _coef_=grade{j};
        output;
      end;
    end;
  end;
end;

readobj: set object;
return;
readdmd: set demand;
return;
readres: set resource;
return;
run;

```

With the model built and saved in a data set, it is ready for solution using PROC LP. The following program solves the model and saves the solution in the data set called PRIMAL:

```

/* solve the linear program */

proc lp data=model sparsedata noprint primalout=primal;
run;

```

The following output is produced by PROC LP.

### Output 6.12.1 An Assignment Problem

| An Assignment Problem            |              |
|----------------------------------|--------------|
| The LP Procedure                 |              |
| Problem Summary                  |              |
| Objective Function               | Max OBJ      |
| Rhs Variable                     | _RHS_        |
| Type Variable                    | _type_       |
| Problem Density (%)              | 5.31         |
| Variables                        | Number       |
| Non-negative                     | 120          |
| Slack                            | 4            |
| Total                            | 124          |
| Constraints                      | Number       |
| LE                               | 4            |
| EQ                               | 30           |
| Objective                        | 1            |
| Total                            | 35           |
| Solution Summary                 |              |
| Terminated Successfully          |              |
| Objective Value                  | 871426.03763 |
| Phase 1 Iterations               | 0            |
| Phase 2 Iterations               | 40           |
| Phase 3 Iterations               | 0            |
| Integer Iterations               | 0            |
| Integer Solutions                | 0            |
| Initial Basic Feasible Variables | 36           |
| Time Used (seconds)              | 0            |
| Number of Inversions             | 3            |
| Epsilon                          | 1E-8         |
| Infinity                         | 1.797693E308 |
| Maximum Phase 1 Iterations       | 100          |
| Maximum Phase 2 Iterations       | 100          |
| Maximum Phase 3 Iterations       | 9999999      |
| Maximum Integer Iterations       | 100          |
| Time Limit (seconds)             | 120          |

The solution is prepared for reporting using the DATA step, and a report is written using PROC TABULATE.



```

/* report the solution */

data solution;
  set primal;
  keep customer grade machine amount;
  if substr(_var_,1,1)='X' then do;
    if _value_>0 then do;
      customer = substr(_var_,2,1);
      grade    = substr(_var_,3,1);
      machine  = substr(_var_,4,1);
      amount   = _value_;
      output;
    end;
  end;
run;

proc tabulate data=solution;
  class customer grade machine;
  var amount;
  table (machine*customer), (grade*amount);
run;

```

The report shown in [Output 6.12.2](#) gives the assignment of customer, grade of cloth, and machine that maximizes the return and does not violate the machine resource availability.

## Output 6.12.2 An Assignment Problem

| An Assignment Problem |          |        |        |        |        |
|-----------------------|----------|--------|--------|--------|--------|
|                       |          | grade  |        |        |        |
|                       |          | 1      | 2      | 3      | 4      |
|                       |          | amount | amount | amount | amount |
|                       |          | Sum    | Sum    | Sum    | Sum    |
| machine               | customer |        |        |        |        |
| 1                     | 1        | .      | 100.00 | 150.00 | 150.00 |
|                       | 2        | .      | .      | 300.00 | .      |
|                       | 3        | .      | .      | 256.72 | 210.31 |
|                       | 4        | .      | .      | 750.00 | .      |
|                       | 5        | .      | 92.27  | .      | .      |
| 2                     | 3        | .      | .      | 143.28 | .      |
|                       | 5        | .      | .      | 300.00 | .      |
| 3                     | 2        | .      | .      | .      | 275.00 |
|                       | 3        | .      | .      | .      | 289.69 |
|                       | 4        | .      | .      | .      | 750.00 |
|                       | 5        | .      | .      | .      | .      |
| 4                     | 1        | 100.00 | .      | .      | .      |
|                       | 2        | 300.00 | 125.00 | .      | .      |
|                       | 3        | 400.00 | .      | .      | .      |
|                       | 4        | 250.00 | .      | .      | .      |
|                       | 5        | .      | 507.73 | .      | .      |

(Continued)

**Output 6.12.2** *continued*

| An Assignment Problem |          |        |        |
|-----------------------|----------|--------|--------|
|                       |          | grade  |        |
|                       |          | 5      | 6      |
|                       |          | amount | amount |
|                       |          | Sum    | Sum    |
| machine               | customer |        |        |
| 1                     | 1        | 175.00 | 250.00 |
|                       | 2        | .      | .      |
|                       | 3        | .      | .      |
|                       | 4        | .      | .      |
|                       | 5        | .      | .      |
| 2                     | 3        | 340.00 | .      |
|                       | 5        | .      | .      |
| 3                     | 2        | 310.00 | 325.00 |
|                       | 3        | .      | .      |
|                       | 4        | .      | .      |
|                       | 5        | 210.00 | 360.00 |
| 4                     | 1        | .      | .      |
|                       | 2        | .      | .      |
|                       | 3        | .      | .      |
|                       | 4        | .      | .      |
|                       | 5        | .      | .      |

**Example 6.13: A Scheduling Problem**

Scheduling is an application area where techniques in model generation can be valuable. Problems involving scheduling are often solved with integer programming and are similar to assignment problems. In this example, you have eight one-hour time slots in each of five days. You have to assign four people to these time slots so that each slot is covered on every day. You allow the people to specify preference data for each

slot on each day. In addition, there are constraints that must be satisfied:

- Each person has some slots for which they are unavailable.
- Each person must have either slot 4 or 5 off for lunch.
- Each person can work only two time slots in a row.
- Each person can work only a specified number of hours in the week.

To formulate this problem, let  $i$  denote person,  $j$  denote time slot, and  $k$  denote day. Then, let  $x_{ijk} = 1$  if person  $i$  is assigned to time slot  $j$  on day  $k$ , and 0 otherwise; let  $p_{ijk}$  denote the preference of person  $i$  for slot  $j$  on day  $k$ ; and let  $h_i$  denote the number of hours in a week that person  $i$  will work. Then, you get

$$\begin{array}{ll}
 \max & \sum_{ijk} p_{ijk} x_{ijk} \\
 \text{subject to} & \sum_i x_{ijk} = 1 \quad \text{for all } j \text{ and } k \\
 & x_{i4k} + x_{i5k} \leq 1 \quad \text{for all } i \text{ and } k \\
 & x_{i,\ell,k} + x_{i,\ell+1,k} + x_{i,\ell+2,k} \leq 2 \quad \text{for all } i \text{ and } k, \text{ and } \ell = 1, \dots, 6 \\
 & \sum_{jk} x_{ijk} \leq h_i \quad \text{for all } i \\
 & x_{ijk} = 0 \text{ or } 1 \quad \text{for all } i \text{ and } k \text{ such that } p_{ijk} > 0, \\
 & \quad \text{otherwise } x_{ijk} = 0
 \end{array}$$

To solve this problem, create a data set that has the hours and preference data for each individual, time slot, and day. A 10 represents the most desirable time slot, and a 1 represents the least desirable time slot. In addition, a 0 indicates that the time slot is not available.

```

data raw;
  input name $ hour slot mon tue wed thu fri;
  datalines;
marc 20 1 10 10 10 10 10
marc 20 2 9 9 9 9 9
marc 20 3 8 8 8 8 8
marc 20 4 1 1 1 1 1
marc 20 5 1 1 1 1 1
marc 20 6 1 1 1 1 1
marc 20 7 1 1 1 1 1
marc 20 8 1 1 1 1 1
mike 20 1 10 9 8 7 6
mike 20 2 10 9 8 7 6
mike 20 3 10 9 8 7 6
mike 20 4 10 3 3 3 3
mike 20 5 1 1 1 1 1
mike 20 6 1 2 3 4 5
mike 20 7 1 2 3 4 5
mike 20 8 1 2 3 4 5
bill 20 1 10 10 10 10 10
bill 20 2 9 9 9 9 9
bill 20 3 8 8 8 8 8
bill 20 4 0 0 0 0 0
bill 20 5 1 1 1 1 1
bill 20 6 1 1 1 1 1
bill 20 7 1 1 1 1 1

```

```

bill  20   8    1  1  1  1  1
bob   20   1   10  9  8  7  6
bob   20   2   10  9  8  7  6
bob   20   3   10  9  8  7  6
bob   20   4   10  3  3  3  3
bob   20   5    1  1  1  1  1
bob   20   6    1  2  3  4  5
bob   20   7    1  2  3  4  5
bob   20   8    1  2  3  4  5
;

```

These data are read by the following DATA step, and an integer program is built to solve the problem. The model is saved in the data set named MODEL. First, the objective function is built using the data saved in the RAW data set. Then, the constraints requiring a person to be working in each time slot are built. Next, the constraints allowing each person time for lunch are added. Then, the constraints restricting people to only two consecutive hours are added. Next, the constraints limiting the time that any one person works in a week are added. Finally, the constraints allowing a person to be assigned only to a time slot for which he is available are added. The code to build each of these constraints follows the formulation closely.

```

data model;
  array workweek{5} mon tue wed thu fri;
  array hours{4} hours1 hours2 hours3 hours4;
  retain hours1-hours4;

  set raw end=eof;

  length _row_ $ 8 _col_ $ 8 _type_ $ 8;
  keep _type_ _col_ _row_ _coef_;

  if      name='marc' then i=1;
  else if name='mike' then i=2;
  else if name='bill' then i=3;
  else if name='bob'  then i=4;

  hours{i}=hour;

  /* build the objective function */

  do k=1 to 5;
    _col_='x' || put(i,1.) || put(slot,1.) || put(k,1.);

    _row_='object';
    _coef_=workweek{k} * 1000;
    output;
    _row_='upper';
    if workweek{k}^=0 then _coef_=1;
    output;
    _row_='integer';
    _coef_=1;
    output;
  end;

  /* build the rest of the model */

```

```

if eof then do;
  _coef=.;
  _col=' ';
  _type='upper';
  _row='upper';
  output;
  _type='max';
  _row='object';
  output;
  _type='int';
  _row='integer';
  output;

  /* every hour 1 person working */

  do j=1 to 8;
    do k=1 to 5;
      _row='work' || put(j,1.) || put(k,1.);
      _type='eq';
      _col='_RHS_';
      _coef=1;
      output;
      _coef=1;
      _type=' ';
      do i=1 to 4;
        _col='x' || put(i,1.) || put(j,1.) || put(k,1.);
        output;
      end;
    end;
  end;

  /* each person has a lunch */

  do i=1 to 4;
    do k=1 to 5;
      _row='lunch' || put(i,1.) || put(k,1.);
      _type='le';
      _col='_RHS_';
      _coef=1;
      output;
      _coef=1;
      _type=' ';
      _col='x' || put(i,1.) || '4' || put(k,1.);
      output;
      _col='x' || put(i,1.) || '5' || put(k,1.);
      output;
    end;
  end;

  /* work at most 2 slots in a row */

  do i=1 to 4;
    do k=1 to 5;

```

```

do l=1 to 6;
  _row_='seq' || put(i,1.) || put(k,1.) || put(l,1.);
  _type_='le';
  _col_='_RHS_';
  _coef_=2;
  output;
  _coef_=1;
  _type_=' ';
  do j=0 to 2;
    _col_='x' || put(i,1.) || put(l+j,1.) || put(k,1.);
    output;
  end;
end;
end;

/* work at most n hours in a week */

do i=1 to 4;
  _row_='capacit' || put(i,1.);
  _type_='le';
  _col_='_RHS_';
  _coef_=hours{i};
  output;
  _coef_=1;
  _type_=' ';
  do j=1 to 8;
    do k=1 to 5;
      _col_='x' || put(i,1.) || put(j,1.) || put(k,1.);
      output;
    end;
  end;
end;
end;
run;

```

The model saved in the data set named MODEL is in the sparse format. The constraint that requires one person to work in time slot 1 on day 2 is named WORK12; it is  $\sum_i x_{i12} = 1$ .

The following model is saved in the MODEL data set (which has 1387 observations).

| <u>_TYPE_</u> | <u>_COL_</u> | <u>_ROW_</u> | <u>_COEF_</u> |
|---------------|--------------|--------------|---------------|
| eq            | _RHS_        | work12       | 1             |
|               | x112         | work12       | 1             |
|               | x212         | work12       | 1             |
|               | x312         | work12       | 1             |
|               | x412         | work12       | 1             |

The model is solved using the LP procedure. The option **PRIMALOUT=SOLUTION** causes PROC LP to save the primal solution in the data set named SOLUTION.

```

/* solve the linear program */

proc lp sparsedata noprint primalout=solution
    time=1000 maxit1=1000 maxit2=1000;
run;

```

The following DATA step takes the solution data set SOLUTION and generates a report data set named REPORT. It translates the variable names  $x_{ijk}$  so that a more meaningful report can be written. Then, the PROC TABULATE procedure is used to display a schedule showing how the eight time slots are covered for the week.

```

/* report the solution */
title 'Reported Solution';

data report;
    set solution;
    keep name slot mon tue wed thu fri;
    if substr(_var_,1,1)='x' then do;
        if _value_>0 then do;
            n=substr(_var_,2,1);
            slot=substr(_var_,3,1);
            d=substr(_var_,4,1);
            if      n='1' then name='marc';
            else if n='2' then name='mike';
            else if n='3' then name='bill';
            else          name='bob';
            if      d='1' then mon=1;
            else if d='2' then tue=1;
            else if d='3' then wed=1;
            else if d='4' then thu=1;
            else          fri=1;
            output;
        end;
    end;
run;

proc format;
    value xfmt 1='   xxx   ';
run;

proc tabulate data=report;
    class name slot;
    var mon--fri;
    table (slot * name), (mon tue wed thu fri)*sum=' '*f=xfmt.
        /misstext=' ';
run;

```

Output 6.13.1 from PROC TABULATE summarizes the schedule. Notice that the constraint requiring that a person be assigned to each possible time slot on each day is satisfied.



**Output 6.13.1** A Scheduling Problem

| Reported Solution |      |     |     |     |     |     |
|-------------------|------|-----|-----|-----|-----|-----|
|                   |      | mon | tue | wed | thu | fri |
| slot              | name |     |     |     |     |     |
| 1                 | bill | xxx | xxx | xxx | xxx | xxx |
| 2                 | bob  | xxx |     |     |     |     |
|                   | marc |     | xxx | xxx | xxx | xxx |
| 3                 | marc |     |     | xxx | xxx | xxx |
|                   | mike | xxx | xxx |     |     |     |
| 4                 | mike | xxx | xxx | xxx | xxx | xxx |
| 5                 | bob  | xxx | xxx | xxx | xxx | xxx |
| 6                 | bob  |     | xxx |     |     | xxx |
|                   | marc | xxx |     |     |     |     |
|                   | mike |     |     | xxx | xxx |     |
| 7                 | bill | xxx |     |     |     |     |
|                   | bob  |     |     | xxx | xxx |     |
|                   | mike |     | xxx |     |     | xxx |
| 8                 | bill | xxx |     |     |     |     |
|                   | mike |     | xxx | xxx | xxx | xxx |

Recall that PROC LP puts a character string in the macro variable `_ORLP_` that describes the characteristics of the solution on termination. This string can be parsed using macro functions and the information obtained can be used in report writing. The variable can be written to the log with the command

```
%put &_orlp_;
```

which produces Figure 6.1.

**Figure 6.1** `_ORLP_` Macro Variable

```
STATUS=SUCCESSFUL PHASE=3 OBJECTIVE=211000 P_FEAS=YES D_FEAS=YES
INT_ITER=0 INT_FEAS=1 ACTIVE=0 INT_BEST=211000 PHASE1_ITER=34
PHASE2_ITER=51 PHASE3_ITER=0
```

From this you learn, for example, that at termination the solution is integer optimal and has an objective value of 211000.

### Example 6.14: A Multicommodity Transshipment Problem with Fixed Charges

The following example illustrates a DATA step program for generating a linear program to solve a multicommodity network flow model that has fixed charges. Consider a network consisting of the following nodes: farm-a, farm-b, farm-c, Chicago, St. Louis, and New York. You can ship four commodities from each farm to Chicago or St. Louis and from Chicago or St. Louis to New York. The following table shows the unit shipping cost for each of the four commodities across each of the arcs. The table also shows the supply (positive numbers) at each of the from nodes and the demand (negative numbers) at each of the to nodes. The fixed charge is a fixed cost for shipping any nonzero amount across an arc. For example, if any amount of any of the four commodities is sent from farm-c to St. Louis, then a fixed charge of 75 units is added to the shipping cost.

**Table 6.13** Farms to Cities Network Problem

| From<br>Node | To<br>Node | Unit Shipping<br>Cost |    |    |    | Supply and Demand |      |     |     | Fixed<br>Charge |
|--------------|------------|-----------------------|----|----|----|-------------------|------|-----|-----|-----------------|
|              |            | 1                     | 2  | 3  | 4  | 1                 | 2    | 3   | 4   |                 |
| farm-a       | Chicago    | 20                    | 15 | 17 | 22 | 100               | 100  | 40  | .   | 100             |
| farm-b       | Chicago    | 15                    | 15 | 15 | 30 | 100               | 200  | 50  | 50  | 75              |
| farm-c       | Chicago    | 30                    | 30 | 10 | 10 | 40                | 100  | 75  | 100 | 100             |
| farm-a       | StLouis    | 30                    | 25 | 27 | 22 | .                 | .    | .   | .   | 150             |
| farm-c       | StLouis    | 10                    | 9  | 11 | 10 | .                 | .    | .   | .   | 75              |
| Chicago      | NY         | 75                    | 75 | 75 | 75 | -150              | -200 | -50 | -75 | 200             |
| StLouis      | NY         | 80                    | 80 | 80 | 80 | .                 | .    | .   | .   | 200             |

The following program is designed to take the data in the form given in the preceding table. It builds the node arc incidence matrix for a network given in this form and adds integer variables to capture the fixed charge using the type of constraints discussed in [Example 6.8](#). The program solves the model using PROC LP, saves the solution in the `PRIMALOUT=` data set named SOLUTION, and displays the solution. The DATA step can be easily modified to handle larger problems with similar structure.

```

title 'Multi-commodity Transshipment Problem with Fixed-Charges';
%macro dooversd;
  _coef_=sd{_i_};
  if sd{_i_}>0 then do;                                /* the node is a supply node */
    _row_=from||' commodity'||put(_i_,2.);
    if from^=' ' then output;
  end;
  else if sd{_i_}<0 then do;                            /* the node is a demand node */
    _row_=to||' commodity'||put(_i_,2.);
    if to^=' ' then output;
  end;
  else if from^=' ' & to^=' ' then do; /* a transshipment node */
    _coef_=0;
  end;
end;

```

```

        _row_=from||' commodity'||put(_i_,2.); output;
        _row_=to  ||' commodity'||put(_i_,2.); output;
    end;
%mend dooversd;

%macro dooverc;
    _col_=arc||' commodity'||put(_i_,2.);
    if from^=' ' & to^=' ' then do; /* add node arc incidence matrix */
        _type_='le'; _row_=from||' commodity'||put(_i_,2.);
        _coef_=1; output;
        _row_=to  ||' commodity'||put(_i_,2.);
        _coef_=-1; output;
        _type_=' '; _row_='obj';
        _coef_=c{_i_}; output;
        /* add fixed charge variables */
        _type_='le'; _row_=arc;
        _coef_=1; output;
        _col_='_rhs_';
        _type_=' ';
        _coef_=0; output;
        _col_=arc||'fx';
        _coef_=-M; output;
        _row_='int';
        _coef_=1; output;
        _row_='obj';
        _coef_=fx; output;
        _row_='upper';
        _coef_=1; output;
    end;
%mend dooverc;

data network;
retain M 1.0e6;
length _col_ $ 22 _row_ $ 22;
keep _type_ _col_ _row_ _coef_ ;
array sd sd1-sd4;
array c c1-c4;

input arc $10. from $ to $ c1 c2 c3 c4 sd1 sd2 sd3 sd4 fx;

/* for the first observation define some of the rows */

if _n_=1 then do;
    _type_='upperbd'; _row_='upper'; output;
    _type_='lowerbd'; _row_='lower'; output;
    _type_='min';     _row_='obj';   output;
    _type_='integer'; _row_='int';   output;
end;

_col_='_rhs_'; _type_='le';

do _i_ = 1 to dim(sd);
    %dooversd;

```

```

end;
do _i_ = 1 to dim(c);
    %dooverc;
end;

datalines;
a-Chicago    farm-a    Chicago    20 15 17 22    100 100 40    .    100
b-Chicago    farm-b    Chicago    15 15 15 30    100 200 50 50    75
c-Chicago    farm-c    Chicago    30 30 10 10    40 100 75 100 100
a-StLouis     farm-a    StLouis    30 25 27 22    .    .    .    .    150
c-StLouis     farm-c    StLouis    10 9 11 10    .    .    .    .    75
Chicago-NY    Chicago    NY        75 75 75 75    -150 -200 -50 -75 200
StLouis-NY    StLouis    NY        80 80 80 80    .    .    .    .    200
;

/* solve the model */

proc lp sparsedata pout=solution noprint;
run;

/* print the solution */

data;
    set solution;
    rename _var_=arc _value_=amount;
    if _value_>=0 & _type_='NON-NEG';
run;

proc print;
    id arc;
    var amount;
run;

```

The results from this example are shown in [Output 6.14.1](#). The **NOPRINT** option in the PROC LP statement suppresses the Variable and Constraint Summary sections. This is useful when solving large models for which a report program is available. Here, the solution is saved in data set SOLUTION and reported using PROC PRINT. The solution shows the amount that is shipped over each arc.

**Output 6.14.1** Multicommodity Transshipment Problem with Fixed Charges**Multi-commodity Transshipment Problem with Fixed-Charges**

| arc        |             | amount |
|------------|-------------|--------|
| a-Chicago  | commodity 1 | 10     |
| b-Chicago  | commodity 1 | 100    |
| b-Chicago  | commodity 2 | 100    |
| c-Chicago  | commodity 3 | 50     |
| c-Chicago  | commodity 4 | 75     |
| c-StLouis  | commodity 1 | 40     |
| c-StLouis  | commodity 2 | 100    |
| Chicago-NY | commodity 1 | 110    |
| Chicago-NY | commodity 2 | 100    |
| Chicago-NY | commodity 3 | 50     |
| Chicago-NY | commodity 4 | 75     |
| StLouis-NY | commodity 1 | 40     |
| StLouis-NY | commodity 2 | 100    |

**Example 6.15: Converting to an MPS-Format SAS Data Set**

This example demonstrates the use of the **MPSOUT=** option to convert problem data in PROC LP input format into an MPS-format SAS data set for use with the OPTLP procedure.

Consider the oil blending problem introduced in the section “[An Introductory Example](#)” on page 177. Suppose you have saved the problem data in dense format by using the following DATA step:

```
data exdata;
  input _id_ $17. a_light a_heavy brega naphthal naphthai
          heatingo jet_1 jet_2 _type_ $ _rhs_;
datalines;
profit          -175 -165 -205  0  0  0 300 300 max      .
naphtha_l_conv  .035 .030 .045 -1  0  0  0  0  eq      0
naphtha_i_conv  .100 .075 .135  0 -1  0  0  0  eq      0
heating_o_conv  .390 .300 .430  0  0 -1  0  0  eq      0
recipe_1        0    0    0  0 .3 .7 -1  0  eq      0
recipe_2        0    0    0 .2  0 .8  0 -1  eq      0
available       110  165  80  .  .  .  .  . upperbd .
;
```

If you decide to solve the problem by using the OPTLP procedure, you will need to convert the data set exdata from dense format to MPS format. You can accomplish this by using the following statements:

```
proc lp data=exdata mpsout=mpsdata;
run;
```

The MPS-format SAS data set mpsdata is shown in [Output 6.15.1](#).

**Output 6.15.1** Data Set mpsdata

| Obs | FIELD1  | FIELD2         | FIELD3         | FIELD4   | FIELD5         | FIELD6 |
|-----|---------|----------------|----------------|----------|----------------|--------|
| 1   | NAME    |                | PROBLEM        | .        |                | .      |
| 2   | ROWS    |                |                | .        |                | .      |
| 3   | MAX     | profit         |                | .        |                | .      |
| 4   | E       | naphtha_l_conv |                | .        |                | .      |
| 5   | E       | naphtha_i_conv |                | .        |                | .      |
| 6   | E       | heating_o_conv |                | .        |                | .      |
| 7   | E       | recipe_1       |                | .        |                | .      |
| 8   | E       | recipe_2       |                | .        |                | .      |
| 9   | COLUMNS |                |                | .        |                | .      |
| 10  |         | a_light        | profit         | -175.000 | naphtha_l_conv | 0.035  |
| 11  |         | a_light        | naphtha_i_conv | 0.100    | heating_o_conv | 0.390  |
| 12  |         | a_heavy        | profit         | -165.000 | naphtha_l_conv | 0.030  |
| 13  |         | a_heavy        | naphtha_i_conv | 0.075    | heating_o_conv | 0.300  |
| 14  |         | brega          | profit         | -205.000 | naphtha_l_conv | 0.045  |
| 15  |         | brega          | naphtha_i_conv | 0.135    | heating_o_conv | 0.430  |
| 16  |         | naphthal       | naphtha_l_conv | -1.000   | recipe_2       | 0.200  |
| 17  |         | naphthai       | naphtha_i_conv | -1.000   | recipe_1       | 0.300  |
| 18  |         | heatingo       | heating_o_conv | -1.000   | recipe_1       | 0.700  |
| 19  |         | heatingo       | recipe_2       | 0.800    |                | .      |
| 20  |         | jet_1          | profit         | 300.000  | recipe_1       | -1.000 |
| 21  |         | jet_2          | profit         | 300.000  | recipe_2       | -1.000 |
| 22  | BOUNDS  |                |                | .        |                | .      |
| 23  | UP      | .BOUNDS.       | a_light        | 110.000  |                | .      |
| 24  | UP      | .BOUNDS.       | a_heavy        | 165.000  |                | .      |
| 25  | UP      | .BOUNDS.       | brega          | 80.000   |                | .      |
| 26  | ENDATA  |                |                | .        |                | .      |

Now that the problem data are in MPS format, you can solve the problem by using the OPTLP procedure. For more information, see Chapter 10, “The OPTLP Procedure” (*SAS/OR User’s Guide: Mathematical Programming*).

## Example 6.16: Migration to OPTMODEL: Assignment

The following example shows how to solve [Example 6.12](#) using PROC OPTMODEL. The OBJECT, DEMAND, and RESOURCE data sets are the same as in that example. A new data set, GRADE, is added to aid in separating the data from the model.

```

title 'An Assignment Problem';

data grade(drop=i);
  do i = 1 to 6;
    grade = 'grade' || put(i,1.);
    output;
  end;
run;

```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called SOLUTION:

```
proc optmodel;
  /* declare index sets */
  set CUSTOMERS;
  set <str> GRADES;
  set MACHINES;

  /* declare parameters */
  num return {CUSTOMERS, GRADES, MACHINES} init 0;
  num demand {CUSTOMERS, GRADES};
  num cost {GRADES, MACHINES} init 0;
  num avail {MACHINES};

  /* read the set of grades */
  read data grade into GRADES=[grade];

  /* read the set of customers and their demands */
  read data demand
    into CUSTOMERS=[customer]
      {j in GRADES} <demand[customer,j]=col(j)>;

  /* read the set of machines, costs, and availability */
  read data resource nomiss
    into MACHINES=[machine]
      {j in GRADES} <cost[j,machine]=col(j)>
      avail;

  /* read objective data */
  read data object nomiss
    into [machine customer]
      {j in GRADES} <return[customer,j,machine]=col(j)>;

  /* declare the model */
  var AmountProduced {CUSTOMERS, GRADES, MACHINES} >= 0;
  max TotalReturn = sum {i in CUSTOMERS, j in GRADES, k in MACHINES}
    return[i,j,k] * AmountProduced[i,j,k];
  con req_demand {i in CUSTOMERS, j in GRADES}:
    sum {k in MACHINES} AmountProduced[i,j,k] = demand[i,j];
  con req_avail {k in MACHINES}:
    sum {i in CUSTOMERS, j in GRADES}
      cost[j,k] * AmountProduced[i,j,k] <= avail[k];

  /* call the solver and save the results */
  solve;
  create data solution
    from [customer grade machine] = {i in CUSTOMERS, j in GRADES,
      k in MACHINES: AmountProduced[i,j,k].sol ne 0}
    amount=AmountProduced;

  /* print optimal solution */
  print AmountProduced;
quit;
```

The statements use both numeric (NUM) and character (STR) index sets, which are populated from the corresponding data set variables in the READ DATA statements. The OPTMODEL parameters can be either single-dimensional (AVAIL) or multiple-dimensional (COST, DEMAND, RETURN). The RETURN and COST parameters are given initial values of 0, and the NOMISS option in the READ DATA statement tells OPTMODEL to read only the nonmissing values from the input data sets. The model declaration is nearly identical to the mathematical formulation. The logical condition `AmountProduced[i,j,k].sol ne 0` in the CREATE DATA statement makes sure that only the nonzero parts of the solution appear in the SOLUTION data set. In [Example 6.12](#), the creation of this data set required postprocessing of the PROC LP output data set.

The main point is that the PROC OPTMODEL statements are much easier to read and maintain than the corresponding DATA step statements required for PROC LP.

The SOLUTION data set can be processed by PROC TABULATE as follows to create a compact representation of the solution:

```
proc tabulate data=solution;
  class customer grade machine;
  var amount;
  table (machine*customer), (grade*amount=' '*sum=' ');
run;
```

The output is the same as [Output 6.12.2](#). The log is displayed in [Output 6.16.1](#).

#### Output 6.16.1 OPTMODEL Log

```
NOTE: There were 6 observations read from the data set WORK.GRADE.
NOTE: There were 5 observations read from the data set WORK.DEMAND.
NOTE: There were 4 observations read from the data set WORK.RESOURCE.
NOTE: There were 20 observations read from the data set WORK.OBJECT.
NOTE: The problem has 120 variables (0 free, 0 fixed).
NOTE: The problem has 34 linear constraints (4 LE, 30 EQ, 0 GE, 0 range).
NOTE: The problem has 220 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 43 variables and 7 constraints.
NOTE: The OPTLP presolver removed 66 constraint coefficients.
NOTE: The presolved problem has 77 variables, 27 constraints, and 154
      constraint coefficients.
NOTE: The DUAL SIMPLEX solver is called.
      Objective
      Phase Iteration Value
          2           1    2052796
          2          45    871426
NOTE: Optimal.
NOTE: Objective = 871426.038.
NOTE: The data set WORK.SOLUTION has 26 observations and 4 variables.
```



## Example 6.17: Migration to OPTMODEL: Multicommodity Transshipment

The following example shows how to solve [Example 6.14](#) using PROC OPTMODEL. Three data sets contain the input data used in that example.

```

title 'Multicommodity Transshipment Problem with Fixed Charges';

data commodity_data;
  do c = 1 to 4;
    output;
  end;
run;

data arc_data;
  input from $ to $ c1 c2 c3 c4 fx;
  datalines;
farm-a Chicago 20 15 17 22 100
farm-b Chicago 15 15 15 30 75
farm-c Chicago 30 30 10 10 100
farm-a StLouis 30 25 27 22 150
farm-c StLouis 10 9 11 10 75
Chicago NY 75 75 75 75 200
StLouis NY 80 80 80 80 200
;
run;

data supply_data;
  input node $ sd1 sd2 sd3 sd4;
  datalines;
farm-a 100 100 40 .
farm-b 100 200 50 50
farm-c 40 100 75 100
NY -150 -200 -50 -75
;
run;

```

The following PROC OPTMODEL statements read the data sets, print the input parameters, build the mixed-integer linear programming model, solve the model, and output the optimal solution to a SAS data set called SOLUTION:

```

proc optmodel;
  set COMMODITIES;
  read data commodity_data into COMMODITIES=[c];

  set <str,str> ARCS;
  num unit_cost {ARCS, COMMODITIES};
  num fixed_charge {ARCS};
  read data arc_data into ARCS=[from to] {c in COMMODITIES}
    <unit_cost[from,to,c]=col('c' || c)> fixed_charge=fx;
  print unit_cost fixed_charge;

  set <str> NODES = union {<i,j> in ARCS} {i,j};
  num supply {NODES, COMMODITIES} init 0;

```

```

read data supply_data nomiss into [node] {c in COMMODITIES}
  <supply[node,c]=col('sd' || c)>;
print supply;

var AmountShipped {ARCS, c in COMMODITIES} >= 0 <= sum {i in NODES}
  max(supply[i,c], 0);

/* UseArc[i,j] = 1 if arc (i,j) is used, 0 otherwise */
var UseArc {ARCS} binary;

/* TotalCost = variable costs + fixed charges */
min TotalCost = sum {<i,j> in ARCS, c in COMMODITIES}
  unit_cost[i,j,c] * AmountShipped[i,j,c]
  + sum {<i,j> in ARCS} fixed_charge[i,j] * UseArc[i,j];

con flow_balance {i in NODES, c in COMMODITIES}:
  sum {<(i),j> in ARCS} AmountShipped[i,j,c] -
  sum {<j,(i)> in ARCS} AmountShipped[j,i,c] <= supply[i,c];

/* if AmountShipped[i,j,c] > 0 then UseArc[i,j] = 1 */
con fixed_charge_def {<i,j> in ARCS, c in COMMODITIES}:
  AmountShipped[i,j,c] <= AmountShipped[i,j,c].ub * UseArc[i,j];

solve;

print AmountShipped;

create data solution from [from to commodity]={<i,j> in ARCS,
  c in COMMODITIES: AmountShipped[i,j,c].sol ne 0} amount=AmountShipped;
quit;

```

Although [Example 6.14](#) used  $M = 1.0e6$  in the `FIXED_CHARGE_DEF` constraint that links the continuous variable to the binary variable, it is numerically preferable to use a smaller, data-dependent value. Here, the upper bound on `AmountShipped[i,j,c]` is used instead. This upper bound is calculated in the first `VAR` statement as the sum of all positive supplies for commodity  $c$ . The logical condition `AmountShipped[i,j,k].sol ne 0` in the `CREATE DATA` statement makes sure that only the nonzero parts of the solution appear in the `SOLUTION` data set.

The optimal solution is the same as in [Output 6.14.1](#). The log is displayed in [Output 6.17.1](#).

### Output 6.17.1 OPTMODEL Log

```
NOTE: There were 4 observations read from the data set WORK.COMMODITY_DATA.
NOTE: There were 7 observations read from the data set WORK.ARC_DATA.
NOTE: There were 4 observations read from the data set WORK.SUPPLY_DATA.
NOTE: The problem has 35 variables (0 free, 0 fixed).
NOTE: The problem has 7 binary and 0 integer variables.
NOTE: The problem has 52 linear constraints (52 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 112 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTMILP presolver value AUTOMATIC is applied.
NOTE: The OPTMILP presolver removed 6 variables and 14 constraints.
NOTE: The OPTMILP presolver removed 26 constraint coefficients.
NOTE: The OPTMILP presolver modified 22 constraint coefficients.
NOTE: The presolved problem has 29 variables, 38 constraints, and 86 constraint
      coefficients.
NOTE: The MIXED INTEGER LINEAR solver is called.
```

| Node | Active | Sols | BestInteger   | BestBound     | Gap    | Time |
|------|--------|------|---------------|---------------|--------|------|
| 0    | 1      | 2    | 43180.0000000 | 26450.0000000 | 63.25% | 0    |
| 0    | 1      | 2    | 43180.0000000 | 42610.0000000 | 1.34%  | 0    |
| 0    | 1      | 3    | 42867.8571429 | 42825.0000000 | 0.10%  | 0    |
| 0    | 1      | 4    | 42825.0000000 | 42825.0000000 | 0.00%  | 0    |
| 0    | 0      | 4    | 42825.0000000 | .             | 0.00%  | 0    |

```
NOTE: OPTMILP added 7 cuts with 24 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 42825.
NOTE: The data set WORK.SOLUTION has 14 observations and 4 variables.
```

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# Chapter 7

## The NETFLOW Procedure

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## Overview: NETFLOW Procedure

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### Introduction

Constrained network models can be used to describe a wide variety of real-world applications ranging from production, inventory, and distribution problems to financial applications. These problems can be solved with the NETFLOW procedure.

These models are conceptually easy since they are based on network diagrams that represent the problem pictorially. PROC NETFLOW accepts the network specification in a format that is particularly suited to networks. This not only simplifies problem description but also aids in the interpretation of the solution.

Certain algebraic features of networks are exploited by a specialized version of the simplex method so that solution times are reduced. Another optimization algorithm, the interior point algorithm, has been implemented in PROC NETFLOW and can be used as an alternative to the simplex algorithm to solve network problems.

Should PROC NETFLOW detect there are no arcs and nodes in the model's data, (that is, there is no network component), it assumes it is dealing with a linear programming (LP) problem. The interior point algorithm is automatically selected to perform the optimization.

You can also solve LP problems by using the OPTLP procedure. The OPTLP procedure requires a linear program to be specified by using a SAS data set that adheres to the MPS format, a widely accepted format in the optimization community. You can use the **MPSOUT=** option in the NETFLOW procedure to convert typical PROC NETFLOW format data sets into MPS-format SAS data sets.

## Network Models

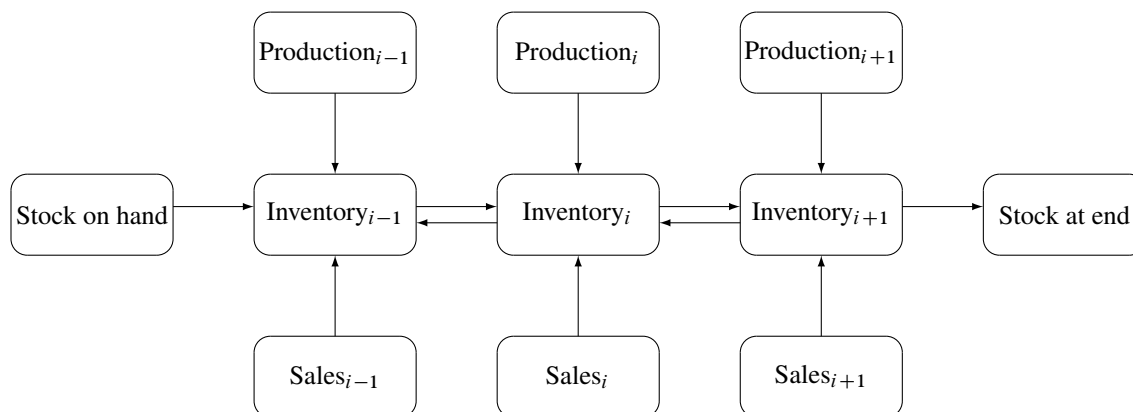
A network consists of a collection of nodes joined by a collection of arcs. The arcs connect nodes and convey flow of one or more commodities that are supplied at supply nodes and demanded at demand nodes in the network. Each arc has a cost per unit of flow, a flow capacity, and a lower flow bound associated with it. An important concept in network modeling is *conservation of flow*.

Conservation of flow means that the total flow in arcs directed toward a node, plus the supply at the node, minus the demand at the node, equals the total flow in arcs directed away from the node.

A network and its associated data can be described in SAS data sets. PROC NETFLOW uses this description and finds the flow through each arc in the network that minimizes the total cost of flow, meets the demand at demand nodes using the supply at supply nodes so that the flow through each arc is on or between the arc's lower flow bound and its capacity, and satisfies the conservation of flow.

One class of network models is the production-inventory-distribution problem. The diagram in Figure 7.1 illustrates this problem. The subscripts on the Production, Inventory, and Sales nodes indicate the time period. Notice that if you replicate sections of the model, the notion of time can be included.

**Figure 7.1** Production-Inventory-Distribution Problem



In this type of model, the nodes can represent a wide variety of facilities. Several examples are suppliers, spot markets, importers, farmers, manufacturers, factories, parts of a plant, production lines, waste disposal facilities, workstations, warehouses, coolstores, depots, wholesalers, export markets, ports, rail junctions, airports, road intersections, cities, regions, shops, customers, and consumers. The diversity of this selection demonstrates the richness of potential applications of this model.

Depending upon the interpretation of the nodes, the objectives of the modeling exercise can vary widely. Some common types of objectives are

- to reduce collection or purchase costs of raw materials
- to reduce inventory holding or backorder costs. Warehouses and other storage facilities sometimes have capacities, and there can be limits on the amount of goods that can be placed on backorder.



- to decide where facilities should be located and what the capacity of these should be. Network models have been used to help decide where factories, hospitals, ambulance and fire stations, oil and water wells, and schools should be sited.
- to determine the assignment of resources (machines, production capability, workforce) to tasks, schedules, classes, or files
- to determine the optimal distribution of goods or services. This usually means minimizing transportation costs, and reducing time in transit or distances covered.
- to find the shortest path from one location to another
- to ensure that demands (for example, production requirements, market demands, contractual obligations) are met
- to maximize profits from the sale of products or the charge for services
- to maximize production by identifying bottlenecks

Some specific applications are

- car distribution models. These help determine which models and numbers of cars should be manufactured in which factories and where to distribute cars from these factories to zones in the United States in order to meet customer demand at least cost.
- models in the timber industry. These help determine when to plant and mill forests, schedule production of pulp, paper and wood products, and distribute products for sale or export.
- military applications. The nodes can be theatres, bases, ammunition dumps, logistical suppliers, or radar installations. Some models are used to find the best ways to mobilize personnel and supplies and to evacuate the wounded in the least amount of time.
- communications applications. The nodes can be telephone exchanges, transmission lines, satellite links, and consumers. In a model of an electrical grid, the nodes can be transformers, powerstations, watersheds, reservoirs, dams, and consumers. Of concern might be the effect of high loads or outages.

---

## Side Constraints

Often all the details of a problem cannot be specified in a network model alone. In many of these cases, these details can be represented by the addition of side constraints to the model. Side constraints are a linear function of arc variables (variables containing flow through an arc) and nonarc variables (variables that are not part of the network). This enhancement to the basic network model allows for very general problems. In fact, any linear program can be represented with network models having these types of side constraints. The examples that follow help to clarify the notion of side constraints.

PROC NETFLOW enables you to specify side constraints. The data for a side constraint consist of coefficients of arcs and coefficients of nonarc variables, a constraint type (that is,  $\leq$ ,  $=$ , or  $\geq$ ) and a right-hand-side value (rhs). A nonarc variable has a name, an objective function coefficient analogous to an arc cost, an upper bound analogous to an arc capacity, and a lower bound analogous to an arc lower flow bound. PROC

NETFLOW finds the flow through the network and the values of any nonarc variables that minimize the total cost of the solution. Flow conservation is met, flow through each arc is on or between the arc's lower flow bound and capacity, the value of each nonarc variable is on or between the nonarc's lower and upper bounds, and the side constraints are satisfied. Note that, since many linear programs have large embedded networks, PROC NETFLOW is an attractive alternative to the LP procedure in many cases.

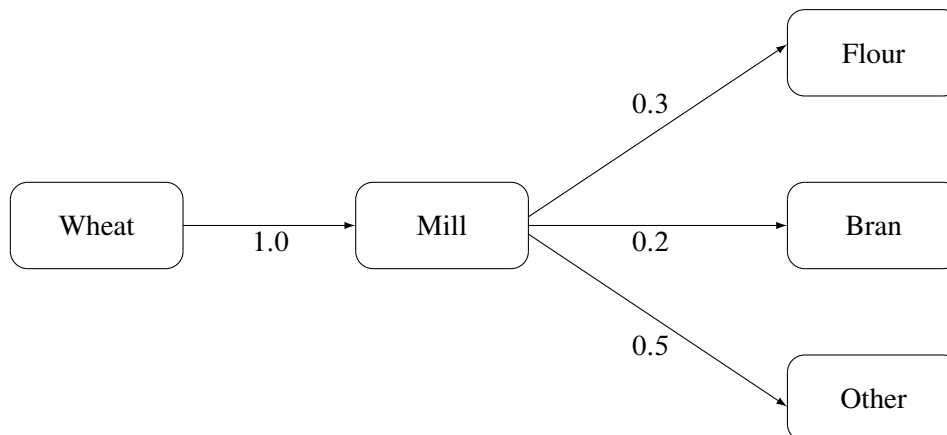
In order for arcs to be specified in side constraints, they must be named. By default, PROC NETFLOW names arcs using the names of the nodes at the head and tail of the arc. An arc is named with its tail node name followed by an underscore and its head node name. For example, an arc from node *from* to node *to* is called *from\_to*.

### Proportionality Constraints

Side constraints in network models fall into several categories that have special structure. They are frequently used when the flow through an arc must be proportional to the flow through another arc. Such constraints are called *proportionality constraints* and are useful in models where production is subject to refining or modification into different materials. The amount of each output, or any waste, evaporation, or reduction can be specified as a proportion of input.

Typically the arcs near the supply nodes carry raw materials and the arcs near the demand nodes carry refined products. For example, in a model of the milling industry, the flow through some arcs may represent quantities of wheat. After the wheat is processed, the flow through other arcs might be flour. For others it might be bran. The side constraints model the relationship between the amount of flour or bran produced as a proportion of the amount of wheat milled. Some of the wheat can end up as neither flour, bran, nor any useful product, so this waste is drained away via arcs to a waste node.

**Figure 7.2** Proportionality Constraints



Consider the network fragment in Figure 7.2. The arc *Wheat\_Mill* conveys the wheat milled. The cost of flow on this arc is the milling cost. The capacity of this arc is the capacity of the mill. The lower flow bound on this arc is the minimum quantity that must be milled for the mill to operate economically. The constraints

$$0.3 \text{ Wheat\_Mill} - \text{Mill\_Flour} = 0.0$$

$$0.2 \text{ Wheat\_Mill} - \text{Mill\_Bran} = 0.0$$

force every unit of wheat that is milled to produce 0.3 units of flour and 0.2 units of bran. Note that it is not necessary to specify the constraint

$$0.5 \text{Wheat\_Mill} - \text{Mill\_Other} = 0.0$$

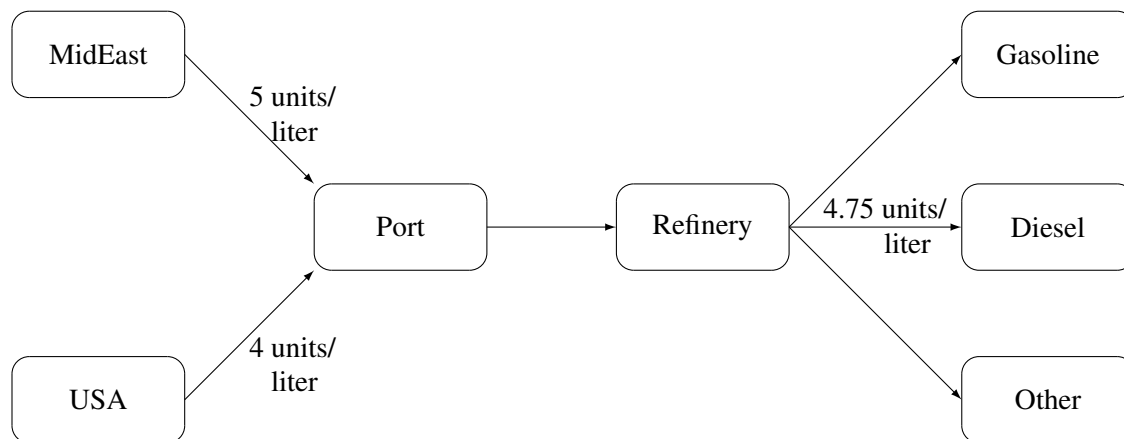
since flow conservation implies that any flow that does not traverse through Mill\_Flour or Mill\_Bran must be conveyed through Mill\_Other. And, computationally, it is better if this constraint is not specified, since there is one less side constraint and fewer problems with numerical precision. Notice that the sum of the proportions must equal 1.0 exactly; otherwise, flow conservation is violated.

## Blending Constraints

Blending or quality constraints can also influence the recipes or proportions of ingredients that are mixed. For example, different raw materials can have different properties. In an application of the oil industry, the amount of products that are obtained could be different for each type of crude oil. Furthermore, fuel might have a minimum octane requirement or limited sulphur or lead content, so that a blending of crudes is needed to produce the product.

The network fragment in Figure 7.3 shows an example of this.

**Figure 7.3** Blending Constraints



The arcs MidEast\_Port and USA\_Port convey crude oil from the two sources. The arc Port\_Refinery represents refining while the arcs Refinery\_Gasoline and Refinery\_Diesel carry the gas and diesel produced. The proportionality constraints

$$0.4 \text{Port\_Refinery} - \text{Refinery\_Gasoline} = 0.0$$

$$0.2 \text{Port\_Refinery} - \text{Refinery\_Diesel} = 0.0$$

capture the restrictions for producing gasoline and diesel from crude. Suppose that, if only crude from the Middle East is used, the resulting diesel would contain 5 units of sulphur per liter. If only crude from the USA is used, the resulting diesel would contain 4 units of sulphur per liter. Diesel can have at most 4.75 units of sulphur per liter. Some crude from the USA must be used if Middle East crude is used in order to meet the 4.75 sulphur per liter limit. The side constraint to model this requirement is

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 4.75 \text{ Port\_Refinery} \leq 0.0$$

Since  $\text{Port\_Refinery} = \text{MidEast\_Port} + \text{USA\_Port}$ , flow conservation allows this constraint to be simplified to

$$1 \text{ MidEast\_Port} - 3 \text{ USA\_Port} \leq 0.0$$

If, for example, 120 units of crude from the Middle East is used, then at least 40 units of crude from the USA must be used. The preceding constraint is simplified because you assume that the sulphur concentration of diesel is proportional to the sulphur concentration of the crude mix. If this is not the case, the relation

$$0.2 \text{ Port\_Refinery} = \text{Refinery\_Diesel}$$

is used to obtain

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 4.75 (1.0/0.2 \text{ Refinery\_Diesel}) \leq 0.0$$

which equals

$$5 \text{ MidEast\_Port} + 4 \text{ USA\_Port} - 23.75 \text{ Refinery\_Diesel} \leq 0.0$$

An example similar to this Oil Industry problem is solved in the section “[Introductory Example](#)” on page 321.

## Multicommodity Problems

Side constraints are also used in models in which there are capacities on transportation or some other shared resource, or there are limits on overall production or demand in multicommodity, multidivisional or multiperiod problems. Each commodity, division or period can have a separate network coupled to one main system by the side constraints. Side constraints are used to combine the outputs of subdivisions of a problem (either commodities, outputs in distinct time periods, or different process streams) to meet overall demands or to limit overall production or expenditures. This method is more desirable than doing separate *local* optimizations for individual commodity, process, or time networks and then trying to establish relationships between each when determining an overall policy if the *global* constraint is not satisfied. Of course, to make models more realistic, side constraints may be necessary in the local problems.

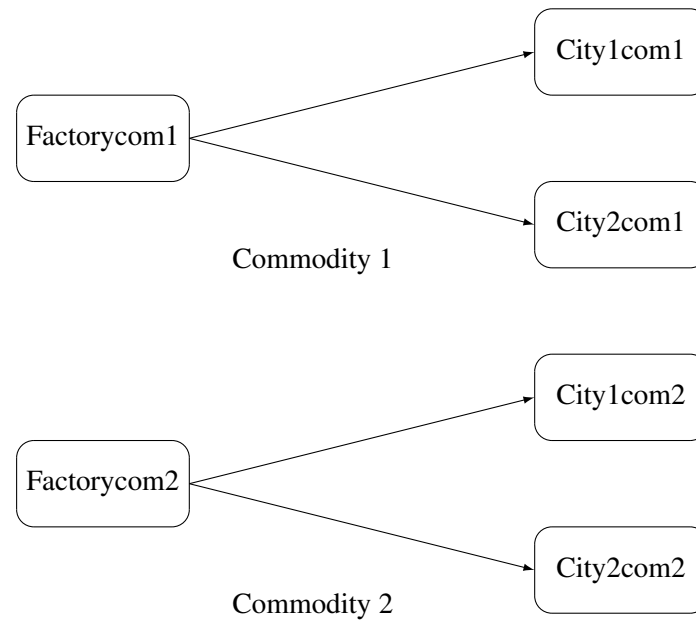
**Figure 7.4** Multicommodity Problem

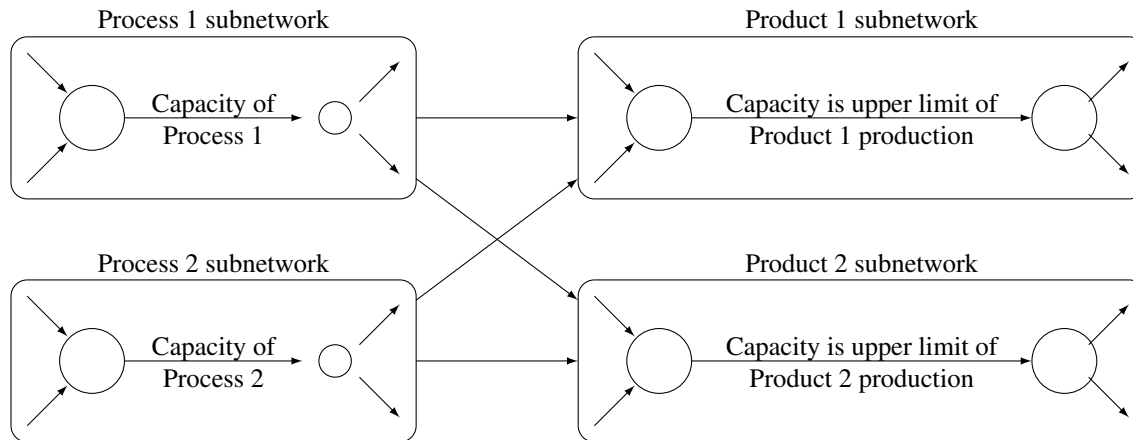
Figure 7.4 shows two network fragments. They represent identical production and distribution sites of two different commodities. Suffix *com1* represents commodity 1 and suffix *com2* represents commodity 2. The nodes *Factorycom1* and *Factorycom2* model the same factory, and nodes *City1com1* and *City1com2* model the same location, city 1. Similarly, *City2com1* and *City2com2* are the same location, city 2. Suppose that commodity 1 occupies 2 cubic meters, commodity 2 occupies 3 cubic meters, the truck dispatched to city 1 has a capacity of 200 cubic meters, and the truck dispatched to city 2 has a capacity of 250 cubic meters. How much of each commodity can be loaded onto each truck? The side constraints for this case are

$$2 \text{ Factorycom1\_City1com1} + 3 \text{ Factorycom2\_City1com2} \leq 200$$

$$2 \text{ Factorycom1\_City2com1} + 3 \text{ Factorycom2\_City2com2} \leq 250$$

## Large Modeling Strategy

In many cases, the flow through an arc might actually represent the flow or movement of a commodity from place to place or from time period to time period. However, sometimes an arc is included in the network as a method of capturing some aspect of the problem that you would not normally think of as part of a network model. For example, in a multiprocess, multiproduct model (Figure 7.5), there might be subnetworks for each process and each product. The subnetworks can be joined together by a set of arcs that have flows that represent the amount of product  $j$  produced by process  $i$ . To model an upper limit constraint on the total amount of product  $j$  that can be produced, direct all arcs carrying product  $j$  to a single node and from there through a single arc. The capacity of this arc is the upper limit of product  $j$  production. It is preferable to model this structure in the network rather than to include it in the side constraints because the efficiency of the optimizer is affected less by a reasonable increase in the size of the network.

**Figure 7.5** Multiprocess, Multiproduct Example

It is often a good strategy when starting a project to use a small network formulation and then use that model as a framework upon which to add detail. For example, in the multiprocess, multiproduct model, you might start with the network depicted in Figure 7.5. Then, for example, the process subnetwork can be enhanced to include the distribution of products. Other phases of the operation could be included by adding more subnetworks. Initially, these subnetworks can be single nodes, but in subsequent studies they can be expanded to include greater detail.

The NETFLOW procedure accepts the side constraints in the same *dense* and *sparse* formats that the LP procedure provides. Although PROC LP can solve network problems, the NETFLOW procedure generally solves network flow problems more efficiently than PROC LP.

---

## Advantages of Network Models over LP Models

Many linear programming problems have large embedded network structures. Such problems often result when modeling manufacturing processes, transportation or distribution networks, or resource allocation, or when deciding where to locate facilities. Often, some commodity is to be moved from place to place, so the more natural formulation in many applications is that of a constrained network rather than a linear program.

Using a network diagram to visualize a problem makes it possible to capture the important relationships in an easily understood picture form. The network diagram aids the communication between model builder and model user, making it easier to comprehend how the model is structured, how it can be changed, and how results can be interpreted.

If a network structure is embedded in a linear program, the problem is a network programming problem with side constraints (NPSC). When the network part of the problem is large compared to the nonnetwork part, especially if the number of side constraints is small, it is worthwhile to exploit this structure in the solution process. This is what PROC NETFLOW does. It uses a variant of the revised primal simplex algorithm that exploits the network structure to reduce solution time.

## Mathematical Description of NPSC

If a network programming problem with side constraints has  $n$  nodes,  $a$  arcs,  $g$  nonarc variables, and  $k$  side constraints, then the formal statement of the problem solved by PROC NETFLOW is

$$\begin{aligned} &\text{minimize} && c^T x + d^T z \\ &\text{subject to} && Fx = b \\ & && Hx + Qz \geq, =, \leq r \\ & && l \leq x \leq u \\ & && m \leq z \leq v \end{aligned}$$

where

- $c$  is the  $a \times 1$  arc variable objective function coefficient vector (the cost vector)
- $x$  is the  $a \times 1$  arc variable value vector (the flow vector)
- $d$  is the  $g \times 1$  nonarc variable objective function coefficient vector
- $z$  is the  $g \times 1$  nonarc variable value vector
- $F$  is the  $n \times a$  node-arc incidence matrix of the network, where

$$F_{i,j} = \begin{cases} -1, & \text{if arc } j \text{ is directed from node } i \\ 1, & \text{if arc } j \text{ is directed toward node } i \\ 0, & \text{otherwise} \end{cases}$$

- $b$  is the  $n \times 1$  node supply/demand vector, where

$$b_i = \begin{cases} s, & \text{if node } i \text{ has supply capability of } s \text{ units of flow} \\ -d, & \text{if node } i \text{ has demand of } d \text{ units of flow} \\ 0, & \text{if node } i \text{ is a trans-shipment node} \end{cases}$$

- $H$  is the  $k \times a$  side constraint coefficient matrix for arc variables, where  $H_{i,j}$  is the coefficient of arc  $j$  in the  $i$ th side constraint
- $Q$  is the  $k \times g$  side constraint coefficient matrix for nonarc variables, where  $Q_{i,j}$  is the coefficient of nonarc  $j$  in the  $i$ th side constraint
- $r$  is the  $k \times 1$  side constraint right-hand-side vector
- $l$  is the  $a \times 1$  arc lower flow bound vector
- $u$  is the  $a \times 1$  arc capacity vector
- $m$  is the  $g \times 1$  nonarc variable lower bound vector
- $v$  is the  $g \times 1$  nonarc variable upper bound vector

## Flow Conservation Constraints

The constraints  $Fx = b$  are referred to as the nodal flow conservation constraints. These constraints algebraically state that the sum of the flow through arcs directed toward a node plus that node's supply, if any, equals the sum of the flow through arcs directed away from that node plus that node's demand, if any. The flow conservation constraints are implicit in the network model and should not be specified explicitly in side constraint data when using PROC NETFLOW. The constrained problems most amenable to being solved by the NETFLOW procedure are those that, after the removal of the flow conservation constraints, have very few constraints. PROC NETFLOW is superior to linear programming optimizers when the network part of the problem is significantly larger than the nonnetwork part.

The NETFLOW procedure can also be used to solve an unconstrained network problem, that is, one in which  $H$ ,  $Q$ ,  $d$ ,  $r$ , and  $z$  do not exist.

## Nonarc Variables

If the constrained problem to be solved has no nonarc variables, then  $Q$ ,  $d$ , and  $z$  do not exist. However, nonarc variables can be used to simplify side constraints. For example, if a sum of flows appears in many constraints, it may be worthwhile to equate this expression with a nonarc variable and use this in the other constraints. By assigning a nonarc variable a nonzero objective function, it is then possible to incur a cost for using resources above some lowest feasible limit. Similarly, a profit (a negative objective function coefficient value) can be made if all available resources are not used.

In some models, nonarc variables are used in constraints to absorb excess resources or supply needed resources. Then, either the excess resource can be used or the needed resource can be supplied to another component of the model.

For example, consider a multicommodity problem of making television sets that have either 19- or 25-inch screens. In their manufacture, 3 and 4 chips, respectively, are used. Production occurs at 2 factories during March and April. The supplier of chips can supply only 2600 chips to factory 1 and 3750 chips to factory 2 each month. The names of arcs are in the form  $\text{Prod}n\_s\_m$ , where  $n$  is the factory number,  $s$  is the screen size, and  $m$  is the month. For example,  $\text{Prod1\_25\_Apr}$  is the arc that conveys the number of 25-inch TVs produced in factory 1 during April. You might have to determine similar systematic naming schemes for your application.

As described, the constraints are

$$3 \text{ Prod1\_19\_Mar} + 4 \text{ Prod1\_25\_Mar} \leq 2600$$

$$3 \text{ Prod2\_19\_Mar} + 4 \text{ Prod2\_25\_Mar} \leq 3750$$

$$3 \text{ Prod1\_19\_Apr} + 4 \text{ Prod1\_25\_Apr} \leq 2600$$

$$3 \text{ Prod2\_19\_Apr} + 4 \text{ Prod2\_25\_Apr} \leq 3750$$



If there are chips that could be obtained for use in March but not used for production in March, why not keep these unused chips until April? Furthermore, if the March excess chips at factory 1 could be used either at factory 1 or factory 2 in April, the model becomes

$$3 \text{ Prod1\_19\_Mar} + 4 \text{ Prod1\_25\_Mar} + \text{F1\_Unused\_Mar} = 2600$$

$$3 \text{ Prod2\_19\_Mar} + 4 \text{ Prod2\_25\_Mar} + \text{F2\_Unused\_Mar} = 3750$$

$$3 \text{ Prod1\_19\_Apr} + 4 \text{ Prod1\_25\_Apr} - \text{F1\_Kept\_Since\_Mar} = 2600$$

$$3 \text{ Prod2\_19\_Apr} + 4 \text{ Prod2\_25\_Apr} - \text{F2\_Kept\_Since\_Mar} = 3750$$

$$\text{F1\_Unused\_Mar} + \text{F2\_Unused\_Mar} \text{ (continued)}$$

$$- \text{F1\_Kept\_Since\_Mar} - \text{F2\_Kept\_Since\_Mar} \geq 0.0$$

where  $\text{F1\_Kept\_Since\_Mar}$  is the number of chips used during April at factory 1 that were obtained in March at either factory 1 or factory 2 and  $\text{F2\_Kept\_Since\_Mar}$  is the number of chips used during April at factory 2 that were obtained in March. The last constraint ensures that the number of chips used during April that were obtained in March does not exceed the number of chips not used in March. There may be a cost to hold chips in inventory. This can be modeled having a positive objective function coefficient for the nonarc variables  $\text{F1\_Kept\_Since\_Mar}$  and  $\text{F2\_Kept\_Since\_Mar}$ . Moreover, nonarc variable upper bounds represent an upper limit on the number of chips that can be held in inventory between March and April.

See [Example 7.4](#) through [Example 7.8](#) for a series of examples that use this TV problem. The use of nonarc variables as described previously is illustrated.

---

## Warm Starts

If you have a problem that has already been partially solved and is to be solved further to obtain a better, optimal solution, information describing the solution now available may be used as an initial solution. This is called *warm starting* the optimization, and the supplied solution data are called the *warm start*.

Some data can be changed between the time when a warm start is created and when it is used as a warm start for a subsequent PROC NETFLOW run. Elements in the arc variable cost vector, the nonarc variable objective function coefficient vector, and sometimes capacities, upper value bounds, and side constraint data can be changed between PROC NETFLOW calls. See the section “[Warm Starts](#)” on page 413. Also, see [Example 7.4](#) through [Example 7.8](#) (the TV problem) for a series of examples that show the use of warm starts.

## Getting Started: NETFLOW Procedure

To solve network programming problems with side constraints using PROC NETFLOW, you save a representation of the network and the side constraints in three SAS data sets. These data sets are then passed to PROC NETFLOW for solution. There are various forms that a problem's data can take. You can use any one or a combination of several of these forms.

The **NODEDATA=** data set contains the names of the supply and demand nodes and the supply or demand associated with each. These are the elements in the column vector  $b$  in problem (NPSC).

The **ARCDATA=** data set contains information about the variables of the problem. Usually these are arcs, but there can also be data related to nonarc variables in the **ARCDATA=** data set.

An arc is identified by the names of its tail node (where it originates) and head node (where it is directed). Each observation can be used to identify an arc in the network and, optionally, the cost per flow unit across the arc, the arc's capacity, lower flow bound, and name. These data are associated with the matrix  $F$  and the vectors  $c$ ,  $l$ , and  $u$  in problem (NPSC).

**NOTE:** Although  $F$  is a node-arc incidence matrix, it is specified in the **ARCDATA=** data set by arc definitions.

In addition, the **ARCDATA=** data set can be used to specify information about nonarc variables, including objective function coefficients, lower and upper value bounds, and names. These data are the elements of the vectors  $d$ ,  $m$ , and  $v$  in problem (NPSC). Data for an arc or nonarc variable can be given in more than one observation.

Supply and demand data also can be specified in the **ARCDATA=** data set. In such a case, the **NODEDATA=** data set may not be needed.

The **CONDATA=** data set describes the side constraints and their right-hand sides. These data are elements of the matrices  $H$  and  $Q$  and the vector  $r$ . Constraint types are also specified in the **CONDATA=** data set. You can include in this data set upper bound values or capacities, lower flow or value bounds, and costs or objective function coefficients. It is possible to give all information about some or all nonarc variables in the **CONDATA=** data set.

An arc is identified in this data set by its name. If you specify an arc's name in the **ARCDATA=** data set, then this name is used to associate data in the **CONDATA=** data set with that arc. Each arc also has a default name that is the name of the tail and head node of the arc concatenated together and separated by an underscore character; `tail_head`, for example.

If you use the **dense** side constraint input format (described in the section “**CONDATA= Data Set**” on page 387) and want to use the default arc names, these arc names are names of SAS variables in the **VAR** list of the **CONDATA=** data set.

If you use the **sparse** side constraint input format (see the section “**CONDATA= Data Set**” on page 387) and want to use the default arc names, these arc names are values of the **COLUMN** list SAS variable of the **CONDATA=** data set.

The execution of PROC NETFLOW has three stages. In the preliminary (zeroth) stage, the data are read from the **NODEDATA=** data set, the **ARCDATA=** data set, and the **CONDATA=** data set. Error checking is performed, and an initial basic feasible solution is found. If an unconstrained solution warm start is being used, then an initial basic feasible solution is obtained by reading additional data containing that information

in the **NODEDATA=** data set and the **ARCDATA=** data set. In this case, only constraint data and nonarc variable data are read from the **CONDATA=** data set.

In the first stage, an optimal solution to the network flow problem neglecting any side constraints is found. The primal and dual solutions for this relaxed problem can be saved in the **ARCOUT=** data set and the **NODEOUT=** data set, respectively. These data sets are named in the **PROC NETFLOW**, **RESET**, and **SAVE** statements.

In the second stage, an optimal solution to the network flow problem with side constraints is found. The primal and dual solutions for this side constrained problem are saved in the **CONOUT=** data set and the **DUALOUT=** data set, respectively. These data sets are also named in the **PROC NETFLOW**, **RESET**, and **SAVE** statements.

If a constrained solution warm start is being used, **PROC NETFLOW** does not perform the zeroth and first stages. This warm start can be obtained by reading basis data containing additional information in the **NODEDATA=** data set (also called the **DUALIN=** data set) and the **ARCDATA=** data set.

If warm starts are to be used in future optimizations, the **FUTURE1** and **FUTURE2** options must be used in addition to specifying names for the data sets that contain the primal and dual solutions in stages one and two. Then, most of the information necessary for restarting problems is available in the output data sets containing the primal and dual solutions of both the relaxed and side constrained network programs.

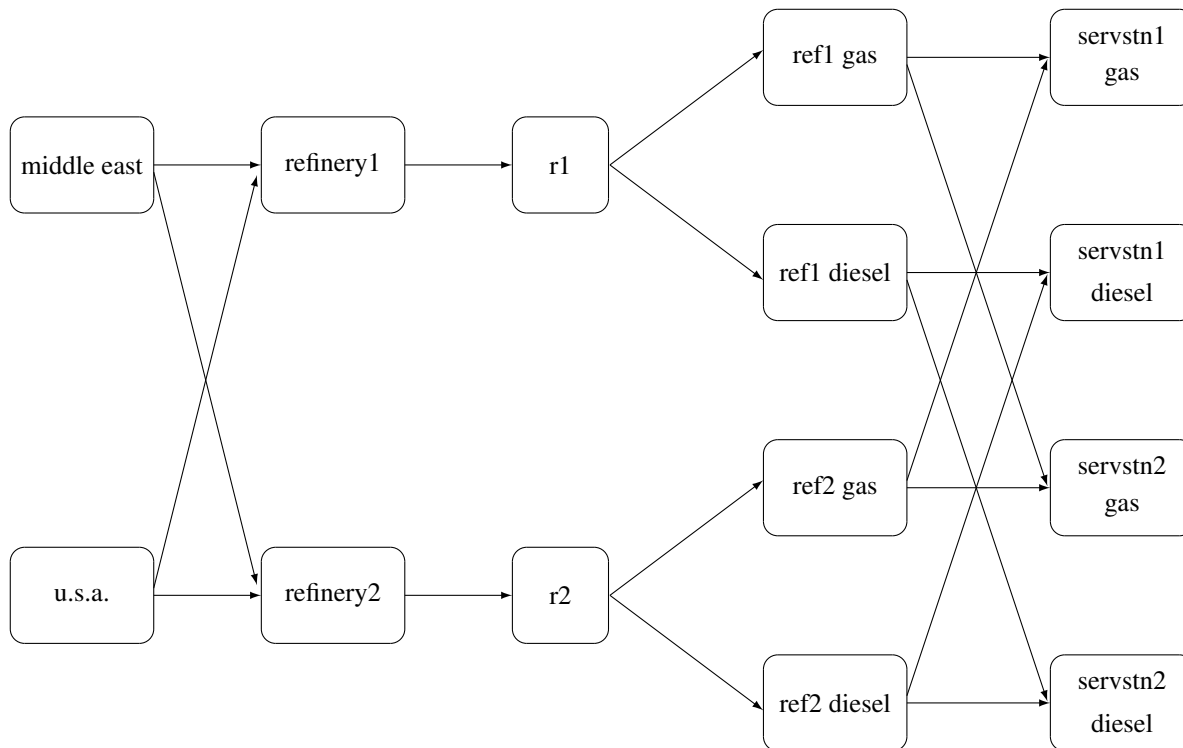
---

## Introductory Example

Consider the following trans-shipment problem for an oil company. Crude oil is shipped to refineries where it is processed into gasoline and diesel fuel. The gasoline and diesel fuel are then distributed to service stations. At each stage, there are shipping, processing, and distribution costs. Also, there are lower flow bounds and capacities.

In addition, there are two sets of side constraints. The first set is that two times the crude from the Middle East cannot exceed the throughput of a refinery plus 15 units. (The phrase “plus 15 units” that finishes the last sentence is used to enable some side constraints in this example to have a nonzero rhs.) The second set of constraints are necessary to model the situation that one unit of crude mix processed at a refinery yields three-fourths of a unit of gasoline and one-fourth of a unit of diesel fuel.

Because there are two products that are not independent in the way in which they flow through the network, a network programming problem with side constraints is an appropriate model for this example (see [Figure 7.6](#)). The side constraints are used to model the limitations on the amount of Middle Eastern crude that can be processed by each refinery and the conversion proportions of crude to gasoline and diesel fuel.

**Figure 7.6** Oil Industry Example

To solve this problem with PROC NETFLOW, save a representation of the model in three SAS data sets. In the **NODEDATA=** data set, you name the supply and demand nodes and give the associated supplies and demands. To distinguish demand nodes from supply nodes, specify demands as negative quantities. For the oil example, the **NODEDATA=** data set can be saved as follows:

```

title 'Oil Industry Example';
title3 'Setting Up Nodedata = Noded For Proc Netflow';
data noded;
  input  _node_&$15. _sd_;
  datalines;
middle east      100
u.s.a.           80
servstn1 gas     -95
servstn1 diesel -30
servstn2 gas     -40
servstn2 diesel -15
;

```

The **ARCADATA=** data set contains the rest of the information about the network. Each observation in the data set identifies an arc in the network and gives the cost per flow unit across the arc, the capacities of the arc, the lower bound on flow across the arc, and the name of the arc.

```

title3 'Setting Up Arcdata = Arcd1 For Proc Netflow';
data arcd1;
  input _from_&$11. _to_&$15. _cost_ _capac_ _lo_ _name_ $;
  datalines;
middle east      refinery 1      63      95      20      m_e_ref1
middle east      refinery 2      81      80      10      m_e_ref2
u.s.a.           refinery 1      55      .      .      .
u.s.a.           refinery 2      49      .      .      .
refinery 1       r1              200     175     50      thrupt1
refinery 2       r2              220     100     35      thrupt2
r1               ref1 gas        .      140     .      r1_gas
r1               ref1 diesel     .      75     .      .
r2               ref2 gas        .      100     .      r2_gas
r2               ref2 diesel     .      75     .      .
ref1 gas         servstn1 gas    15      70     .      .
ref1 gas         servstn2 gas    22      60     .      .
ref1 diesel      servstn1 diesel  18      .      .      .
ref1 diesel      servstn2 diesel  17      .      .      .
ref2 gas         servstn1 gas    17      35     5      .
ref2 gas         servstn2 gas    31      .      .      .
ref2 diesel      servstn1 diesel  36      .      .      .
ref2 diesel      servstn2 diesel  23      .      .      .
;

```

Finally, the `CONDATA=` data set contains the side constraints for the model.

```

title3 'Setting Up Condata = Cond1 For Proc Netflow';
data cond1;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
-2 . 1 . . . >= -15
. -2 . . 1 . GE -15
. . -3 4 . . EQ 0
. . . . -3 4 = 0
;

```

Note that the SAS variable names in the `CONDATA=` data set are the names of arcs given in the `ARCDATA=` data set. These are the arcs that have nonzero constraint coefficients in side constraints. For example, the proportionality constraint that specifies that one unit of crude at each refinery yields three-fourths of a unit of gasoline and one-fourth of a unit of diesel fuel is given for REFINERY 1 in the third observation and for REFINERY 2 in the last observation. The third observation requires that each unit of flow on arc THRUPT1 equals three-fourths of a unit of flow on arc R1\_GAS. Because all crude processed at REFINERY 1 flows through THRUPT1 and all gasoline produced at REFINERY 1 flows through R1\_GAS, the constraint models the situation. It proceeds similarly for REFINERY 2 in the last observation.

To find the minimum cost flow through the network that satisfies the supplies, demands, and side constraints, invoke PROC NETFLOW as follows:

```

proc netflow
  nodedata=noded      /* the supply and demand data */
  arcdata=arcd1       /* the arc descriptions      */
  condata=cond1       /* the side constraints      */
;

```

```
conout=solution;      /* the solution data set      */
run;
```

The following messages, which appear on the SAS log, summarize the model as read by PROC NETFLOW and note the progress toward a solution:

```
NOTE: Writing HTML Body file: sashtml.htm
NOTE: Number of nodes= 14 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 180 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of iterations performed (neglecting any constraints)= 14 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= 50600 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of arc and nonarc variable side constraint coefficients= 8 .
NOTE: Number of iterations, optimizing with constraints= 4 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum reached.
NOTE: Minimal total cost= 50875 .
NOTE: The data set WORK.SOLUTION has 18 observations and 14 variables.
```

Unlike PROC LP, which displays the solution and other information as output, PROC NETFLOW saves the optimum in output SAS data sets that you specify. For this example, the solution is saved in the SOLUTION data set. It can be displayed with the PRINT procedure as

```
proc print data=solution;
  var _from_ _to_ _cost_ _capac_ _lo_ _name_
      _supply_ _demand_ _flow_ _fcost_ _rcost_;
  sum _fcost_;
  title3 'Constrained Optimum';
run;
```

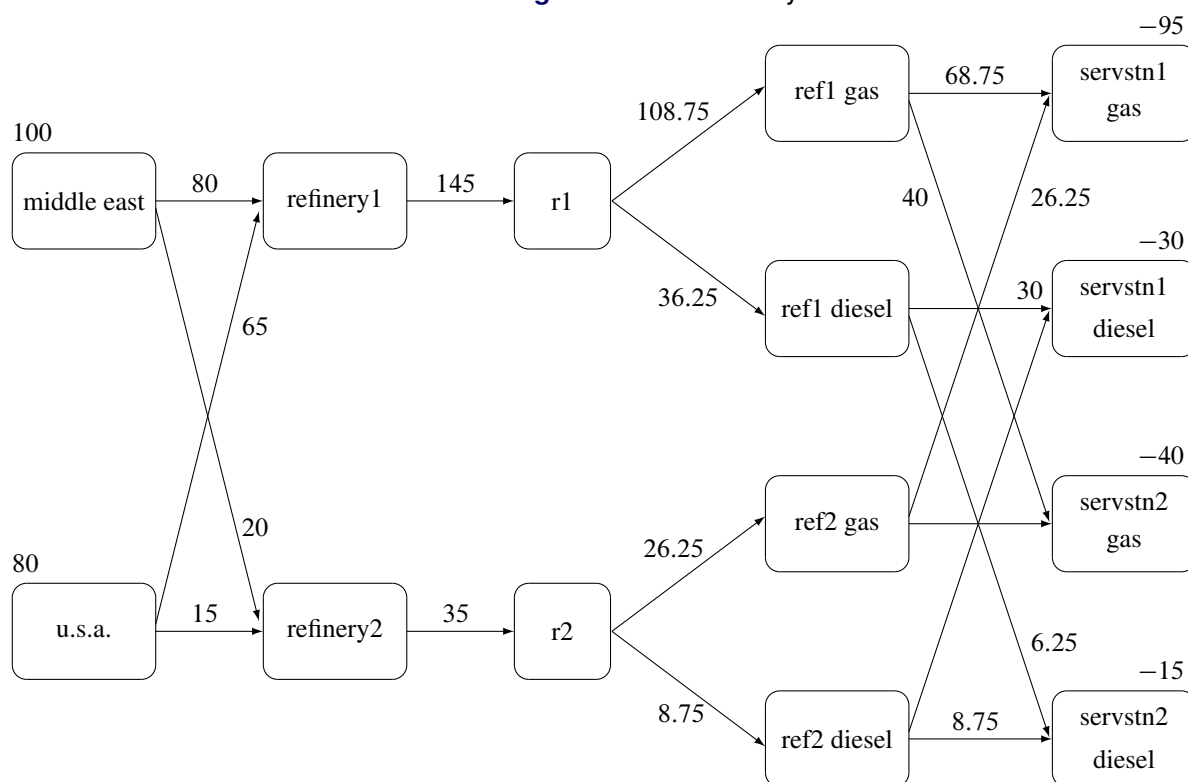
Figure 7.7 CONOUT=SOLUTION

| Oil Industry Example |             |                 |        |          |      |          |
|----------------------|-------------|-----------------|--------|----------|------|----------|
| Constrained Optimum  |             |                 |        |          |      |          |
| Obs                  | _from_      | _to_            | _cost_ | _capac_  | _lo_ | _name_   |
| 1                    | refinery 1  | r1              | 200    | 175      | 50   | thruput1 |
| 2                    | refinery 2  | r2              | 220    | 100      | 35   | thruput2 |
| 3                    | r1          | ref1 diesel     | 0      | 75       | 0    |          |
| 4                    | r1          | ref1 gas        | 0      | 140      | 0    | r1_gas   |
| 5                    | r2          | ref2 diesel     | 0      | 75       | 0    |          |
| 6                    | r2          | ref2 gas        | 0      | 100      | 0    | r2_gas   |
| 7                    | middle east | refinery 1      | 63     | 95       | 20   | m_e_ref1 |
| 8                    | u.s.a.      | refinery 1      | 55     | 99999999 | 0    |          |
| 9                    | middle east | refinery 2      | 81     | 80       | 10   | m_e_ref2 |
| 10                   | u.s.a.      | refinery 2      | 49     | 99999999 | 0    |          |
| 11                   | ref1 diesel | servstn1 diesel | 18     | 99999999 | 0    |          |
| 12                   | ref2 diesel | servstn1 diesel | 36     | 99999999 | 0    |          |
| 13                   | ref1 gas    | servstn1 gas    | 15     | 70       | 0    |          |
| 14                   | ref2 gas    | servstn1 gas    | 17     | 35       | 5    |          |
| 15                   | ref1 diesel | servstn2 diesel | 17     | 99999999 | 0    |          |
| 16                   | ref2 diesel | servstn2 diesel | 23     | 99999999 | 0    |          |
| 17                   | ref1 gas    | servstn2 gas    | 22     | 60       | 0    |          |
| 18                   | ref2 gas    | servstn2 gas    | 31     | 99999999 | 0    |          |

| Obs | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_  | _RCOST_ |
|-----|----------|----------|--------|----------|---------|
| 1   | .        | .        | 145.00 | 29000.00 | .       |
| 2   | .        | .        | 35.00  | 7700.00  | 29      |
| 3   | .        | .        | 36.25  | 0.00     | .       |
| 4   | .        | .        | 108.75 | 0.00     | .       |
| 5   | .        | .        | 8.75   | 0.00     | .       |
| 6   | .        | .        | 26.25  | 0.00     | .       |
| 7   | 100      | .        | 80.00  | 5040.00  | .       |
| 8   | 80       | .        | 65.00  | 3575.00  | .       |
| 9   | 100      | .        | 20.00  | 1620.00  | .       |
| 10  | 80       | .        | 15.00  | 735.00   | .       |
| 11  | .        | 30       | 30.00  | 540.00   | .       |
| 12  | .        | 30       | 0.00   | 0.00     | 12      |
| 13  | .        | 95       | 68.75  | 1031.25  | .       |
| 14  | .        | 95       | 26.25  | 446.25   | .       |
| 15  | .        | 15       | 6.25   | 106.25   | .       |
| 16  | .        | 15       | 8.75   | 201.25   | .       |
| 17  | .        | 40       | 40.00  | 880.00   | .       |
| 18  | .        | 40       | 0.00   | 0.00     | 7       |
|     |          |          |        | =====    |         |
|     |          |          |        | 50875.00 |         |

Notice that, in CONOUT=SOLUTION (Figure 7.7), the optimal flow through each arc in the network is given in the variable named `_FLOW_`, and the cost of flow through each arc is given in the variable `_FCOST_`.

**Figure 7.8** Oil Industry Solution



## Syntax: NETFLOW Procedure

Below are statements used in PROC NETFLOW, listed in alphabetical order as they appear in the text that follows.

```

PROC NETFLOW options ;
  CAPACITY variable ;
  COEF variables ;
  COLUMN variable ;
  CONOPT ; ;
  COST variable ;
  DEMAND variable ;
  HEADNODE variable ;
  ID variables ;
  LO variable ;
  NAME variable ;
  NODE variable ;
  PIVOT ; ;
  PRINT options ;
  QUIT ; ;
  RESET options ;
  RHS variables ;
  ROW variables ;
  RUN ; ;
  SAVE options ;
  SHOW options ;
  SUPDEM variable ;
  SUPPLY variable ;
  TAILNODE variable ;
  TYPE variable ;
  VAR variables ;

```

## Functional Summary

The following table outlines the options available for the NETFLOW procedure classified by function.

**Table 7.1** Functional Summary

| Description                            | Statement    | Option    |
|--|--------------|-----------|
| <b>Input Data Set Options:</b>         |              |           |
| Arcs input data set                    | PROC NETFLOW | ARCDATA=  |
| Nodes input data set                   | PROC NETFLOW | NODEDATA= |
| Constraint input data set              | PROC NETFLOW | CONDATA=  |
| <b>Output Data Set Options:</b>        |              |           |
| Unconstrained primal solution data set | PROC NETFLOW | ARCOUT=   |

| Description   | Statement    | Option            |
|---|--------------|-------------------|
| Unconstrained dual solution data set  | PROC NETFLOW | NODEOUT=          |
| Constrained primal solution data set  | PROC NETFLOW | CONOUT=           |
| Constrained dual solution data set  | PROC NETFLOW | DUALOUT=          |
| Convert sparse or dense format input data set into MPS format output data set | PROC NETFLOW | MPSOUT=           |
| <b>Data Set Read Options:</b>   |              |                   |
| CONDATA has <i>sparse</i> data format   | PROC NETFLOW | SPARSECONDATA     |
| Default constraint type   | PROC NETFLOW | DEFCONTYPE=       |
| Special COLUMN variable value   | PROC NETFLOW | TYPEOBS=          |
| Special COLUMN variable value   | PROC NETFLOW | RHSOBS=           |
| Used to interpret arc and nonarc variable names                               | PROC NETFLOW | NAMECTRL=         |
| No new nonarc variables   | PROC NETFLOW | SAME_NONARC_DATA  |
| No nonarc data in ARCDATA   | PROC NETFLOW | ARCS_ONLY_ARCDATA |
| Data for an arc found once in ARCDATA   | PROC NETFLOW | ARC_SINGLE_OBS    |
| Data for a constraint found once in CONDATA                                   | PROC NETFLOW | CON_SINGLE_OBS    |
| Data for a coefficient found once in CONDATA                                  | PROC NETFLOW | NON_REPLIC=       |
| Data are grouped, exploited during data read                                  | PROC NETFLOW | GROUPED=          |
| <b>Problem Size Specification Options:</b>                                    |              |                   |
| Approximate number of nodes   | PROC NETFLOW | NNODES=           |
| Approximate number of arcs  | PROC NETFLOW | NARCS=            |
| Approximate number of nonarc variables  | PROC NETFLOW | NNAS=             |
| Approximate number of coefficients  | PROC NETFLOW | NCOEFS=           |
| Approximate number of constraints   | PROC NETFLOW | NCONS=            |
| <b>Network Options:</b>   |              |                   |
| Default arc cost  | PROC NETFLOW | DEFCOST=          |
| Default arc capacity  | PROC NETFLOW | DEFCAPACITY=      |
| Default arc lower flow bound  | PROC NETFLOW | DEFMINFLOW=       |
| Network's only supply node  | PROC NETFLOW | SOURCE=           |
| SOURCE's supply capability  | PROC NETFLOW | SUPPLY=           |
| Network's only demand node  | PROC NETFLOW | SINK=             |
| SINK's demand   | PROC NETFLOW | DEMAND=           |
| Convey excess supply/demand through network                                   | PROC NETFLOW | THRUNET           |
| Find maximal flow between SOURCE and SINK                                     | PROC NETFLOW | MAXFLOW           |
| Cost of bypass arc for MAXFLOW problem  | PROC NETFLOW | BYPASSDIVIDE=     |
| Find shortest path from SOURCE to SINK  | PROC NETFLOW | SHORTPATH         |
| Specify generalized networks  | PROC NETFLOW | GENNET            |
| Specify excess demand or supply   | PROC NETFLOW | EXCESS=           |
| <b>Memory Control Options:</b>  |              |                   |
| Issue memory usage messages to SAS log  | PROC NETFLOW | MEMREP            |
| Number of bytes to use for main memory  | PROC NETFLOW | BYTES=            |
| Proportion of memory for arrays   | PROC NETFLOW | COREFACTOR=       |

| Description   | Statement    | Option          |
|---|--------------|-----------------|
| Memory allocated for LU factors                                   | PROC NETFLOW | DWIA=           |
| Linked list for updated column                                    | PROC NETFLOW | SPARSEP2        |
| Use 2-dimensional array for basis matrix                          | PROC NETFLOW | INVD_2D         |
| Maximum bytes for a single array                                  | PROC NETFLOW | MAXARRAYBYTES=  |
| <b>Simplex Options:</b>   |              |                 |
| Use big-M instead of two-phase method, stage 1                    | RESET        | BIGM1           |
| Use Big-M instead of two-phase method, stage 2                    | RESET        | BIGM2           |
| Anti-cycling option   | RESET        | CYCLEMULT1=     |
| Interchange first nonkey with leaving key arc                     | RESET        | INTFIRST        |
| Controls working basis matrix inversions                          | RESET        | INVREQ=         |
| Maximum number of L row operations allowed before refactorization | RESET        | MAXL=           |
| Maximum number of LU factor column updates                        | RESET        | MAXLUUPDATES=   |
| Anti-cycling option   | RESET        | MINBLOCK1=      |
| Use first eligible leaving variable, stage 1                      | RESET        | LRATIO1         |
| Use first eligible leaving variable, stage 2                      | RESET        | LRATIO2         |
| Negates <a href="#">INTFIRST</a>                                  | RESET        | NOINTFIRST      |
| Negates <a href="#">LRATIO1</a>                                   | RESET        | NOLRATIO1       |
| Negates <a href="#">LRATIO2</a>                                   | RESET        | NOLRATIO2       |
| Negates <a href="#">PERTURB1</a>                                  | RESET        | NOPERTURB1      |
| Anti-cycling option   | RESET        | PERTURB1        |
| Controls working basis matrix refactorization                     | RESET        | REFACTREQ=      |
| Use two-phase instead of big-M method, stage 1                    | RESET        | TWOPHASE1       |
| Use two-phase instead of big-M method, stage 2                    | RESET        | TWOPHASE2       |
| Pivot element selection parameter                                 | RESET        | U=              |
| Zero tolerance, stage 1   | RESET        | ZERO1=          |
| Zero tolerance, stage 2   | RESET        | ZERO2=          |
| Zero tolerance, real number comparisons                           | RESET        | ZEROTOL=        |
| <b>Pricing Options:</b>   |              |                 |
| Frequency of dual value calculation                               | RESET        | DUALREQ=        |
| Pricing strategy, stage 1   | RESET        | PRICETYPE1=     |
| Pricing strategy, stage 2   | RESET        | PRICETYPE2=     |
| Used when <a href="#">P1SCAN</a> =PARTIAL                         | RESET        | P1NPARTIAL=     |
| Controls search for entering candidate, stage 1                   | RESET        | P1SCAN=         |
| Used when <a href="#">P2SCAN</a> =PARTIAL                         | RESET        | P2NPARTIAL=     |
| Controls search for entering candidate, stage 2                   | RESET        | P2SCAN=         |
| Initial queue size, stage 1                                       | RESET        | QSIZE1=         |
| Initial queue size, stage 2                                       | RESET        | QSIZE2=         |
| Used when <a href="#">Q1FILLSCAN</a> =PARTIAL                     | RESET        | Q1FILLNPARTIAL= |
| Controls scan when filling queue, stage 1                         | RESET        | Q1FILLSCAN=     |
| Used when <a href="#">Q2FILLSCAN</a> =PARTIAL                     | RESET        | Q2FILLNPARTIAL= |
| Controls scan when filling queue, stage 2                         | RESET        | Q2FILLSCAN=     |
| Queue size reduction factor, stage 1                              | RESET        | REDUCEQSIZE1=   |

| Description                                      | Statement    | Option           |
|--|--------------|------------------|
| Queue size reduction factor, stage 2             | RESET        | REDUCEQSIZE2=    |
| Frequency of refreshing queue, stage 1           | RESET        | REFRESHQ1=       |
| Frequency of refreshing queue, stage 2           | RESET        | REFRESHQ2=       |
| <b>Optimization Termination Options:</b>         |              |                  |
| Pause after stage 1; do not start stage 2        | RESET        | ENDPAUSE1        |
| Pause when feasible, stage 1                     | RESET        | FEASIBLEPAUSE1   |
| Pause when feasible, stage 2                     | RESET        | FEASIBLEPAUSE2   |
| Maximum number of iterations, stage 1            | RESET        | MAXIT1=          |
| Maximum number of iterations, stage 2            | RESET        | MAXIT2=          |
| Negates ENDPAUSE1                                | RESET        | NOENDPAUSE1      |
| Negates FEASIBLEPAUSE1                           | RESET        | NOFEASIBLEPAUSE1 |
| Negates FEASIBLEPAUSE2                           | RESET        | NOFEASIBLEPAUSE2 |
| Pause every PAUSE1 iterations, stage 1           | RESET        | PAUSE1=          |
| Pause every PAUSE2 iterations, stage 2           | RESET        | PAUSE2=          |
| <b>Interior Point Algorithm Options:</b>         |              |                  |
| Use interior point algorithm                     | PROC NETFLOW | INTPOINT         |
| Factorization method                             | RESET        | FACT_METHOD=     |
| Allowed amount of dual infeasibility             | RESET        | TOLDINF=         |
| Allowed amount of primal infeasibility           | RESET        | TOLPINF=         |
| Allowed total amount of dual infeasibility       | RESET        | TOLTOTDINF=      |
| Allowed total amount of primal infeasibility     | RESET        | TOLTOTPINF=      |
| Cut-off tolerance for Cholesky factorization     | RESET        | CHOLTINYTOL=     |
| Density threshold for Cholesky processing        | RESET        | DENSETHR=        |
| Step-length multiplier                           | RESET        | PDSTEPMULT=      |
| Preprocessing type                               | RESET        | PRSLTYPE=        |
| Print optimization progress on SAS log           | RESET        | PRINTLEVEL2=     |
| <b>Interior Point Stopping Criteria Options:</b> |              |                  |
| Maximum number of interior point iterations      | RESET        | MAXITERB=        |
| Primal-dual (duality) gap tolerance              | RESET        | PDGAPTOL=        |
| Stop because of complementarity                  | RESET        | STOP_C=          |
| Stop because of duality gap                      | RESET        | STOP_DG=         |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | STOP_IB=         |
| Stop because of <i>infeas<sub>c</sub></i>        | RESET        | STOP_IC=         |
| Stop because of <i>infeas<sub>d</sub></i>        | RESET        | STOP_ID=         |
| Stop because of complementarity                  | RESET        | AND_STOP_C=      |
| Stop because of duality gap                      | RESET        | AND_STOP_DG=     |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | AND_STOP_IB=     |
| Stop because of <i>infeas<sub>c</sub></i>        | RESET        | AND_STOP_IC=     |
| Stop because of <i>infeas<sub>d</sub></i>        | RESET        | AND_STOP_ID=     |
| Stop because of complementarity                  | RESET        | KEEPPGOING_C=    |
| Stop because of duality gap                      | RESET        | KEEPPGOING_DG=   |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | KEEPPGOING_IB=   |

| Description  | Statement | Option             |
|--|-----------|--------------------|
| Stop because of <i>infeas<sub>c</sub></i>                                      | RESET     | KEEPPGOING_IC=     |
| Stop because of <i>infeas<sub>d</sub></i>                                      | RESET     | KEEPPGOING_ID=     |
| Stop because of complementarity  | RESET     | AND_KEEPPGOING_C=  |
| Stop because of duality gap  | RESET     | AND_KEEPPGOING_DG= |
| Stop because of <i>infeas<sub>b</sub></i>                                      | RESET     | AND_KEEPPGOING_IB= |
| Stop because of <i>infeas<sub>c</sub></i>                                      | RESET     | AND_KEEPPGOING_IC= |
| Stop because of <i>infeas<sub>d</sub></i>                                      | RESET     | AND_KEEPPGOING_ID= |
| <b>PRINT Statement Options:</b>  |           |                    |
| Display everything   | PRINT     | PROBLEM            |
| Display arc information  | PRINT     | ARCS               |
| Display nonarc variable information  | PRINT     | NONARCS            |
| Display variable information   | PRINT     | VARIABLES          |
| Display constraint information   | PRINT     | CONSTRAINTS        |
| Display information for some arcs  | PRINT     | SOME_ARCS          |
| Display information for some nonarc variables                                  | PRINT     | SOME_NONARCS       |
| Display information for some variables   | PRINT     | SOME_VARIABLES     |
| Display information for some constraints                                       | PRINT     | SOME_CONS          |
| Display information for some constraints associated with some arcs             | PRINT     | CON_ARCS           |
| Display information for some constraints associated with some nonarc variables | PRINT     | CON_NONARCS        |
| Display information for some constraints associated with some variables        | PRINT     | CON_VARIABLES      |
| <b>PRINT Statement Qualifiers:</b>   |           |                    |
| Produce a short report   | PRINT     | / SHORT            |
| Produce a long report  | PRINT     | / LONG             |
| Display arcs/variables with zero flow/value                                    | PRINT     | / ZERO             |
| Display arcs/variables with nonzero flow/value                                 | PRINT     | / NONZERO          |
| Display basic arcs/variables   | PRINT     | / BASIC            |
| Display nonbasic arcs/variables  | PRINT     | / NONBASIC         |
| <b>SHOW Statement Options:</b>   |           |                    |
| Show problem, optimization status  | SHOW      | STATUS             |
| Show network model parameters  | SHOW      | NETSTMT            |
| Show data sets that have been or will be created                               | SHOW      | DATASETS           |
| Show options that pause optimization   | SHOW      | PAUSE              |
| Show simplex algorithm options   | SHOW      | SIMPLEX            |
| Show pricing strategy options  | SHOW      | PRICING            |
| Show miscellaneous options   | SHOW      | MISC               |
| <b>SHOW Statement Qualifiers:</b>  |           |                    |
| Display information only on relevant options                                   | SHOW      | / RELEVANT         |
| Display options for current stage only   | SHOW      | / STAGE            |

| Description   | Statement    | Option      |
|---|--------------|-------------|
| <b>Miscellaneous Options:</b>   |              |             |
| Infinity value  | PROC NETFLOW | INFINITY=   |
| Scale constraint row, nonarc variable column coefficients, or both                | PROC NETFLOW | SCALE=      |
| Maximization instead of minimization  | PROC NETFLOW | MAXIMIZE    |
| Use warm start solution   | PROC NETFLOW | WARM        |
| All-artificial starting solution  | PROC NETFLOW | ALLART      |
| Output complete basis information to <b>ARCOUT=</b> and <b>NODEOUT=</b> data sets | RESET        | FUTURE1     |
| Output complete basis information to <b>CONOUT=</b> and <b>DUALOUT=</b> data sets | RESET        | FUTURE2     |
| Turn off infeasibility or optimality flags  | RESET        | MOREOPT     |
| Negates <b>FUTURE1</b>  | RESET        | NOFUTURE1   |
| Negates <b>FUTURE2</b>  | RESET        | NOFUTURE2   |
| Negates <b>SCRATCH</b>  | RESET        | NOSCRATCH   |
| Negates <b>ZTOL1</b>  | RESET        | NOZTOL1     |
| Negates <b>ZTOL2</b>  | RESET        | NOZTOL2     |
| Write optimization time to SAS log  | RESET        | OPTIM_TIMER |
| No stage 1 optimization; do stage 2 optimization                                  | RESET        | SCRATCH     |
| Suppress similar SAS log messages   | RESET        | VERBOSE=    |
| Use zero tolerance, stage 1   | RESET        | ZTOL1       |
| Use zero tolerance, stage 2   | RESET        | ZTOL2       |

## Interactivity

PROC NETFLOW can be used interactively. You begin by giving the **PROC NETFLOW** statement, and you must specify the **ARCDATA=** data set. The **CONDATA=** data set must also be specified if the problem has side constraints. If necessary, specify the **NODEDATA=** data set.

The variable lists should be given next. If you have variables in the input data sets that have special names (for example, a variable in the **ARCDATA=** data set named **\_TAIL\_** that has tail nodes of arcs as values), it may not be necessary to have many or any variable lists.

The **CONOPT**, **PIVOT**, **PRINT**, **QUIT**, **SAVE**, **SHOW**, **RESET**, and **RUN** statements follow and can be listed in any order. The **CONOPT** and **QUIT** statements can be used only once. The others can be used as many times as needed.

Use the **RESET** or **SAVE** statement to change the names of the output data sets. With **RESET**, you can also indicate the reasons why optimization should stop (for example, you can indicate the maximum number of stage 1 or stage 2 iterations that can be performed). PROC NETFLOW then has a chance to either execute the next statement, or, if the next statement is one that PROC NETFLOW does not recognize (the next PROC or DATA step in the SAS session), do any allowed optimization and finish. If no new statement has been

submitted, you are prompted for one. Some options of the **RESET** statement enable you to control aspects of the primal simplex algorithm. Specifying certain values for these options can reduce the time it takes to solve a problem. Note that any of the **RESET** options can be specified in the **PROC NETFLOW** statement.

The **RUN** statement starts or resumes optimization. The **PIVOT** statement makes PROC NETFLOW perform one simplex iteration. The **QUIT** statement immediately stops PROC NETFLOW. The **CONOPT** statement forces PROC NETFLOW to consider constraints when it next performs optimization. The **SAVE** statement has options that enable you to name output data sets; information about the current solution is put in these output data sets. Use the **SHOW** statement if you want to examine the values of options of other statements. Information about the amount of optimization that has been done and the **STATUS** of the current solution can also be displayed using the **SHOW** statement.

The **PRINT** statement instructs PROC NETFLOW to display parts of the problem. **PRINT ARCS** produces information on all arcs. **PRINT SOME\_ARCS** limits this output to a subset of arcs. There are similar **PRINT** statements for nonarc variables and constraints:

```
print nonarcs;
print some_nonarcs;
print constraints;
print some_cons;
```

**PRINT CON\_ARCS** enables you to limit constraint information that is obtained to members of a set of arcs that have nonzero constraint coefficients in a set of constraints. **PRINT CON\_NONARCS** is the corresponding statement for nonarc variables.

For example, an interactive PROC NETFLOW run might look something like this:

```
proc netflow arcdata=data set
    other options;
    variable list specifications; /* if necessary */
    reset options;
    print options;      /* look at problem          */
    run;                /* do some optimization          */
    /* suppose that optimization stopped for */
    /* some reason or you manually stopped it */
    print options;      /* look at the current solution */
    save options;       /* keep current solution        */
    show options;       /* look at settings             */
    reset options;      /* change some settings, those that */
                      /* caused optimization to stop */
    run;               /* do more optimization          */
    print options;     /* look at the optimal solution */
    save options;      /* keep optimal solution        */
```

If you are interested only in finding the optimal solution, have used SAS variables that have special names in the input data sets, and want to use default settings for everything, then the following statement is all you need:

```
PROC NETFLOW ARCDATA= data set ;
```



## PROC NETFLOW Statement

**PROC NETFLOW** *options* ;

This statement invokes the procedure. The following options and the options listed with the [RESET](#) statement can appear in the PROC NETFLOW statement.

### Data Set Options

This section briefly describes all the input and output data sets used by PROC NETFLOW. The [ARCDATA=](#) data set, [NODEDATA=](#) data set, and [CONDATA=](#) data set can contain SAS variables that have special names, for instance `_CAPAC_`, `_COST_`, and `_HEAD_`. PROC NETFLOW looks for such variables if you do not give explicit variable list specifications. If a SAS variable with a special name is found and that SAS variable is not in another variable list specification, PROC NETFLOW determines that values of the SAS variable are to be interpreted in a special way. By using SAS variables that have special names, you may not need to have any variable list specifications.

#### **ARCDATA=SAS-data-set**

names the data set that contains arc and, optionally, nonarc variable information and nodal supply/demand data. The ARCDATA= data set must be specified in all PROC NETFLOW statements.

#### **ARCOUT=SAS-data-set**

#### **AOUT=SAS-data-set**

names the output data set that receives all arc and nonarc variable data, including flows or values, and other information concerning the unconstrained optimal solution. The supply and demand information can also be found in the ARCOUT= data set. Once optimization that considers side constraints starts, you are not able to obtain an ARCOUT= data set. Instead, use the [CONOUT=](#) data set to get the current solution. See the section “[ARCOUT= and CONOUT= Data Sets](#)” on page 395 for more information.

#### **CONDATA=SAS-data-set**

names the data set that contains the side constraint data. The data set can also contain other data such as arc costs, capacities, lower flow bounds, nonarc variable upper and lower bounds, and objective function coefficients. PROC NETFLOW needs a CONDATA= data set to solve a constrained problem or a linear programming problem. See the section “[CONDATA= Data Set](#)” on page 387 for more information.

#### **CONOUT=SAS-data-set**

#### **COUT=SAS-data-set**

names the output data set that receives an optimal primal solution to the problem obtained by performing optimization that considers the side constraints. See the section “[ARCOUT= and CONOUT= Data Sets](#)” on page 395 for more information.

#### **DUALOUT=SAS-data-set**

#### **DOUT=SAS-data-set**

names the output data set that receives an optimal dual solution to the problem obtained by performing optimization that considers the side constraints. See the section “[NODEOUT= and DUALOUT= Data Sets](#)” on page 397 for more information.



**NODEDATA=SAS-data-set****DUALIN=SAS-data-set**

names the data set that contains the node supply and demand specifications. You do not need observations in the NODEDATA= data set for trans-shipment nodes. (Trans-shipment nodes neither supply nor demand flow.) All nodes are assumed to be trans-shipment nodes unless supply or demand data indicate otherwise. It is acceptable for some arcs to be directed toward supply nodes or away from demand nodes.

The use of the NODEDATA= data set is optional in the PROC NETFLOW statement provided that, if the NODEDATA= data set is not used, supply and demand details are specified by other means. Other means include using the [MAXFLOW](#) or [SHORTPATH](#) option, [SUPPLY](#) or [DEMAND](#) list variables (or both) in the [ARCDATA=](#) data set, and the [SOURCE=](#), [SUPPLY=](#), [SINK=](#), or [DEMAND=](#) option in the PROC NETFLOW statement.

**NODEOUT=SAS-data-set**

names the output data set that receives all information about nodes (supply and demand and nodal dual variable values) and other information concerning the optimal solution found by the optimizer when neglecting side constraints. Once optimization that considers side constraints starts, you are not able to obtain a NODEOUT= data set. Instead, use the [DUALOUT=](#) data set to get the current solution dual information. See the section “[NODEOUT= and DUALOUT= Data Sets](#)” on page 397 for a more complete description.

**MPSOUT=SAS-data-set**

names the SAS data set that contains converted sparse or dense format input data in MPS format. Invoking this option directs the NETFLOW procedure to halt before attempting optimization. For more information about the MPSOUT= option, see the section “[Converting Any PROC NETFLOW Format to an MPS-Format SAS Data Set](#)” on page 398. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User’s Guide: Mathematical Programming*),.

## General Options

The following is a list of options you can use with PROC NETFLOW. The options are listed in alphabetical order.

**ALLART**

indicates that PROC NETFLOW uses an all artificial initial solution (Kennington and Helgason 1980, p. 68) instead of the default *good path* method for determining an initial solution (Kennington and Helgason 1980, p. 245). The ALLART initial solution is generally not as good; more iterations are usually required before the optimal solution is obtained. However, because less time is used when setting up an ALLART start, it can offset the added expenditure of CPU time in later computations.

**ARCS\_ONLY\_ARCDATA**

indicates that data for only arcs are in the [ARCDATA=](#) data set. When PROC NETFLOW reads the data in [ARCDATA=](#) data set, memory would not be wasted to receive data for nonarc variables. The read might then be performed faster. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**ARC\_SINGLE\_OBS**

indicates that for all arcs and nonarc variables, data for each arc or nonarc variable is found in only one observation of the **ARCDATA=** data set. When reading the data in the **ARCDATA=** data set, PROC NETFLOW knows that the data in an observation is for an arc or a nonarc variable that has not had data previously read that needs to be checked for consistency. The read might then be performed faster.

If you specify **ARC\_SINGLE\_OBS**, PROC NETFLOW automatically works as if **GROUPED=ARCDATA** is also specified. See the section “How to Make the Data Read of PROC NETFLOW More Efficient” on page 416.

**BYPASSDIVIDE=b****BYPASSDIV=b****BPD=b**

should be used only when the **MAXFLOW** option has been specified; that is, PROC NETFLOW is solving a maximal flow problem. PROC NETFLOW prepares to solve maximal flow problems by setting up a bypass arc. This arc is directed from the **SOURCE** to the **SINK** and will eventually convey flow equal to **INFINITY** minus the maximal flow through the network. The cost of the bypass arc must be expensive enough to drive flow through the network, rather than through the bypass arc. However, the cost of the bypass arc must be less than the cost of artificial variables (otherwise these might have nonzero optimal value and a false infeasibility error will result). Also, the cost of the bypass arc must be greater than the eventual total cost of the maximal flow, which can be nonzero if some network arcs have nonzero costs. The cost of the bypass is set to the value of the **INFINITY=** option. Valid values for the **BYPASSDIVIDE=** option must be greater than or equal to 1.1.

If there are no nonzero costs of arcs in the **MAXFLOW** problem, the cost of the bypass arc is set to 1.0 (-1.0 if maximizing) if you do not specify the **BYPASSDIVIDE=** option. The reduced costs in the **ARCOUT=** data set and the **CONOUT=** data set will correctly reflect the value that would be added to the maximal flow if the capacity of the arc is increased by one unit. If there are nonzero costs, or if you specify the **BYPASSDIVIDE=** option, the reduced costs may be contaminated by the cost of the bypass arc and no economic interpretation can be given to reduced cost values. The default value for the **BYPASSDIVIDE=** option (in the presence of nonzero arc costs) is 100.0.

**BYTES=b**

indicates the size of the main working memory (in bytes) that PROC NETFLOW will allocate. The default value for the **BYTES=** option is near to the number of bytes of the largest contiguous memory that can be allocated for this purpose. The working memory is used to store all the arrays and buffers used by PROC NETFLOW. If this memory has a size smaller than what is required to store all arrays and buffers, PROC NETFLOW uses various schemes that page information between memory and disk.

PROC NETFLOW uses more memory than the main working memory. The additional memory requirements cannot be determined at the time when the main working memory is allocated. For example, every time an output data set is created, some additional memory is required. Do not specify a value for the **BYTES=** option equal to the size of available memory.

**CON\_SINGLE\_OBS**

improves how the **CONDATA=** data set is read. How it works depends on whether the **CONDATA** has a dense or sparse format.

If **CONDATA** has the **dense** format, specifying **CON\_SINGLE\_OBS** indicates that, for each constraint, data can be found in only one observation of **CONDATA**.

If **CONDATA** has a *sparse* format, and data for each arc and nonarc variable can be found in only one observation of **CONDATA**, then specify the **CON\_SINGLE\_OBS** option. If there are  $n$  SAS variables in the **ROW** and **COEF** list, then each arc or nonarc can have at most  $n$  constraint coefficients in the model. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

### **COREFACTOR=*c***

#### **CF=*c***

enables you to specify the maximum proportion of memory to be used by the arrays frequently accessed by PROC NETFLOW. PROC NETFLOW strives to maintain all information required during optimization in core. If the amount of available memory is not great enough to store the arrays completely in core, either initially or as memory requirements grow, PROC NETFLOW can change the memory management scheme it uses. Large problems can still be solved. When necessary, PROC NETFLOW transfers data from random access memory (RAM) or core that can be accessed quickly but is of limited size to slower access large capacity disk memory. This is called *paging*.

Some of the arrays and buffers used during constrained optimization either vary in size, are not required as frequently as other arrays, or are not required throughout the simplex iteration. Let  $a$  be the amount of memory in bytes required to store frequently accessed arrays of nonvarying size. Specify the **MEMREP** option in the PROC NETFLOW statement to get the value for  $a$  and a report of memory usage. If the size of the main working memory **BYTES**= $b$  multiplied by **COREFACTOR**= $c$  is greater than  $a$ , PROC NETFLOW keeps the frequently accessed arrays of nonvarying size resident in core throughout the optimization. If the other arrays cannot fit into core, they are paged in and out of the remaining part of the main working memory.

If  $b$  multiplied by  $c$  is less than  $a$ , PROC NETFLOW uses a different memory scheme. The working memory is used to store only the arrays needed in the part of the algorithm being executed. If necessary, these arrays are read from disk into the main working area. Paging, if required, is done for all these arrays, and sometimes information is written back to disk at the end of that part of the algorithm. This memory scheme is not as fast as the other memory schemes. However, problems can be solved with memory that is too small to store every array.

PROC NETFLOW is capable of solving very large problems in a modest amount of available memory. However, as more time is spent doing input/output operations, the speed of PROC NETFLOW decreases. It is important to choose the value of the **COREFACTOR**= option carefully. If the value is too small, the memory scheme that needs to be used might not be as efficient as another that could have been used had a larger value been specified. If the value is too large, too much of the main working memory is occupied by the frequently accessed, nonvarying sized arrays, leaving too little for the other arrays. The amount of input/output operations for these other arrays can be so high that another memory scheme might have been used more beneficially.

The valid values of **COREFACTOR**= $c$  are between 0.0 and 0.95, inclusive. The default value for  $c$  is 0.75 when there are over 200 side constraints, and 0.9 when there is only one side constraint. When the problem has between 2 and 200 constraints, the value of  $c$  lies between the two points (1, 0.9) and (201, 0.75).

### **DEFCAPACITY=*c***

#### **DC=*c***

requests that the default arc capacity and the default nonarc variable value upper bound be  $c$ . If this option is not specified, then **DEFCAPACITY**= **INFINITY**.

**DEFCTYPE=*c*****DEFTYPE=*c*****DCT=*c***

specifies the default constraint type. This default constraint type is either *less than or equal to* or is the type indicated by DEFCTYPE=*c*. Valid values for this option are

|            |                                     |
|------------|-------------------------------------|
| LE, le, <= | for <i>less than or equal to</i>    |
| EQ, eq, =  | for <i>equal to</i>                 |
| GE, ge, >= | for <i>greater than or equal to</i> |

The values do not need to be enclosed in quotes.

**DEFCOST=*c***

requests that the default arc cost and the default nonarc variable objective function coefficient be *c*. If this option is not specified, then DEFCOST=0.0.

**DEFMINFLOW=*m*****DMF=*m***

requests that the default lower flow bound through arcs and the default lower value bound of nonarc variables be *m*. If a value is not specified, then DEFMINFLOW=0.0.

**DEMAND=*d***

specifies the demand at the **SINK** node specified by the **SINK=** option. The DEMAND= option should be used only if the **SINK=** option is given in the PROC NETFLOW statement and neither the **SHORTPATH** option nor the **MAXFLOW** option is specified. If you are solving a minimum cost network problem and the **SINK=** option is used to identify the sink node, but the DEMAND= option is not specified, then the demand at the sink node is made equal to the network's total supply.

**DWIA=*i***

controls the initial amount of memory to be allocated to store the **LU** factors of the working basis matrix. DWIA stands for *D<sub>W</sub> initial allocation* and *i* is the number of nonzeros and matrix row operations in the **LU** factors that can be stored in this memory. Due to fill-in in the **U** factor and the growth in the number of row operations, it is often necessary to move information about elements of a particular row or column to another location in the memory allocated for the **LU** factors. This process leaves some memory temporarily unoccupied. Therefore, DWIA=*i* must be greater than the memory required to store only the **LU** factors.

Occasionally, it is necessary to compress the **U** factor so that it again occupies contiguous memory. Specifying too large a value for DWIA means that more memory is required by PROC NETFLOW. This might cause more expensive memory mechanisms to be used than if a smaller but adequate value had been specified for DWIA=. Specifying too small a value for the DWIA= option can make time-consuming compressions more numerous. The default value for the DWIA= option is eight times the number of side constraints.

**EXCESS=option**

enables you to specify how to handle excess supply or demand in a network, if it exists.

For pure networks EXCESS=ARCS and EXCESS=SLACKS are valid options. By default EXCESS=ARCS is used. Note that if you specify EXCESS=SLACKS, then the interior point solver is

used and you need to specify the output data set using the CONOUT= data set. For more details see the section “[Using the New EXCESS= Option in Pure Networks: NETFLOW Procedure](#)” on page 462.

For generalized networks you can either specify EXCESS=DEMAND or EXCESS=SUPPLY to indicate that the network has excess demand or excess supply, respectively. For more details see the section “[Using the New EXCESS= Option in Generalized Networks: NETFLOW Procedure](#)” on page 469.

## GENNET

This option is necessary if you need to solve a generalized network flow problem and there are no arc multipliers specified in the ARCDATA= data set.

## GROUPED=grouped

PROC NETFLOW can take a much shorter time to read data if the data have been grouped prior to the PROC NETFLOW call. This enables PROC NETFLOW to conclude that, for instance, a new NAME list variable value seen in an ARCDATA= data set grouped by the values of the NAME list variable before PROC NETFLOW was called is new. PROC NETFLOW does not need to check that the NAME has been read in a previous observation. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

- GROUPED=ARCDATA indicates that the ARCDATA= data set has been grouped by values of the NAME list variable. If \_NAME\_ is the name of the NAME list variable, you could use PROC SORT DATA=ARCDATA; BY \_NAME\_; prior to calling PROC NETFLOW. Technically, you do not have to sort the data, only ensure that all similar values of the NAME list variable are grouped together. If you specify the ARCS\_ONLY\_ARCDATA option, PROC NETFLOW automatically works as if GROUPED=ARCDATA is also specified.
- GROUPED=CONDATA indicates that the CONDATA= data set has been grouped.  
If the CONDATA= data set has a dense format, GROUPED=CONDATA indicates that the CONDATA= data set has been grouped by values of the ROW list variable. If \_ROW\_ is the name of the ROW list variable, you could use PROC SORT DATA=CONDATA; BY \_ROW\_; prior to calling PROC NETFLOW. Technically, you do not have to sort the data, only ensure that all similar values of the ROW list variable are grouped together. If you specify the CON\_SINGLE\_OBS option, or if there is no ROW list variable, PROC NETFLOW automatically works as if GROUPED=CONDATA has been specified.  
If the CONDATA= data set has the sparse format, GROUPED=CONDATA indicates that the CONDATA= data set has been grouped by values of the COLUMN list variable. If \_COL\_ is the name of the COLUMN list variable, you could use PROC SORT DATA=CONDATA; BY \_COL\_; prior to calling PROC NETFLOW. Technically, you do not have to sort the data, only ensure that all similar values of the COLUMN list variable are grouped together.
- GROUPED=BOTH indicates that both GROUPED=ARCDATA and GROUPED=CONDATA are TRUE.
- GROUPED=NONE indicates that the data sets have not been grouped, that is, neither GROUPED=ARCDATA nor GROUPED=CONDATA is TRUE. This is the default, but it is much better if GROUPED=ARCDATA, or GROUPED=CONDATA, or GROUPED=BOTH.

A data set like

```
... _xxxxx_ ....
```

```

bbb
bbb
aaa
ccc
ccc

```

is a candidate for the GROUPED= option. Similar values are grouped together. When PROC NETFLOW is reading the  $i$ th observation, either the value of the `_XXXXX_` variable is the same as the  $(i - 1)$ st (that is, the previous observation's) `_XXXXX_` value, or it is a new `_XXXXX_` value not seen in any previous observation. This also means that if the  $i$ th `_XXXXX_` value is different from the  $(i - 1)$ st `_XXXXX_` value, the value of the  $(i - 1)$ st `_XXXXX_` variable will not be seen in any observations  $i, i + 1, \dots$

#### **INFINITY=*i***

#### **INF=*i***

is the largest number used by PROC NETFLOW in computations. A number too small can adversely affect the solution process. You should avoid specifying an enormous value for the INFINITY= option because numerical roundoff errors can result. If a value is not specified, then INFINITY=99999999. The INFINITY= option cannot be assigned a value less than 9999.

#### **INTPOINT**

indicates that the interior point algorithm is to be used. The INTPOINT option must be specified if you want the interior point algorithm to be used for solving network problems, otherwise the simplex algorithm is used instead. For linear programming problems (problems with no network component), PROC NETFLOW must use the interior point algorithm, so you need not specify the INTPOINT option.

#### **INVD\_2D**

controls the way in which the inverse of the working basis matrix is stored. How this matrix is stored affects computations as well as how the working basis or its inverse is updated. The working basis matrix is defined in the section “[Details: NETFLOW Procedure](#)” on page 387. If INVD\_2D is specified, the working basis matrix inverse is stored as a matrix. Typically, this memory scheme is best when there are few side constraints or when the working basis is dense.

If INVD\_2D is not specified, lower (**L**) and upper (**U**) factors of the working basis matrix are used. **U** is an upper triangular matrix and **L** is a lower triangular matrix corresponding to a sequence of elementary matrix row operations. The sparsity-exploiting variant of the Bartels-Golub decomposition is used to update the **LU** factors. This scheme works well when the side constraint coefficient matrix is sparse or when many side constraints are nonbinding.

#### **MAXARRAYBYTES=*m***

specifies the maximum number of bytes an individual array can occupy. This option is of most use when solving large problems and the amount of available memory is insufficient to store all arrays at once. Specifying the MAXARRAYBYTES= option ensures that arrays that need a large amount of memory do not consume too much memory at the expense of other arrays.

There is one array that contains information about nodes and the network basis spanning tree description. This tree description enables computations involving the network part of the basis to be performed very quickly and is the reason why PROC NETFLOW is more suited to solving constrained network problems than PROC LP. It is beneficial that this array be stored in core when possible, otherwise this



array must be paged, slowing down the computations. Try not to specify a `MAXARRAYBYTES=m` value smaller than the amount of memory needed to store the main node array. You are told what this memory amount is on the SAS log if you specify the `MEMREP` option in the PROC NETFLOW statement.

## MAXFLOW

### MF

specifies that PROC NETFLOW solve a maximum flow problem. In this case, the PROC NETFLOW procedure finds the maximum flow from the node specified by the `SOURCE=` option to the node specified by the `SINK=` option. PROC NETFLOW automatically assigns an `INFINITY=` option supply to the `SOURCE=` option node and the `SINK=` option is assigned the `INFINITY=` option demand. In this way, the MAXFLOW option sets up a maximum flow problem as an equivalent minimum cost problem.

You can use the MAXFLOW option when solving any flow problem (not necessarily a maximum flow problem) when the network has one supply node (with infinite supply) and one demand node (with infinite demand). The MAXFLOW option can be used in conjunction with all other options (except `SHORTPATH`, `SUPPLY=`, and `DEMAND=`) and capabilities of PROC NETFLOW.

## MAXIMIZE

### MAX

specifies that PROC NETFLOW find the maximum cost flow through the network. If both the MAXIMIZE and the `SHORTPATH` options are specified, the solution obtained is the longest path between the `SOURCE=` and `SINK=` nodes. Similarly, MAXIMIZE and `MAXFLOW` together cause PROC NETFLOW to find the minimum flow between these two nodes; this is zero if there are no nonzero lower flow bounds.

## MEMREP

indicates that information on the memory usage and paging schemes (if necessary) is reported by PROC NETFLOW on the SAS log. As optimization proceeds, you are informed of any changes in the memory requirements and schemes used by PROC NETFLOW.

## NAMECTRL=*i*

is used to interpret arc and nonarc variable names in the `CONDATA=` data set.

In the `ARCDATA=` data set, an arc is identified by its tail and head node. In the `CONDATA=` data set, arcs are identified by names. You can give a name to an arc by having a `NAME` list specification that indicates a SAS variable in the `ARCDATA=` data set that has names of arcs as values.

PROC NETFLOW requires arcs that have information about them in the `CONDATA=` data set to have names, but arcs that do not have information about them in the `CONDATA=` data set can also have names. Unlike a nonarc variable whose name uniquely identifies it, an arc can have several different names. An arc has a default name in the form *tail\_head*, that is, the name of the arc's tail node followed by an underscore and the name of the arc's head node.

In the `CONDATA=` data set, if the `dense` data format is used, (described in the section “`CONDATA= Data Set`” on page 387) a name of an arc or a nonarc variable is the *name* of a SAS variable listed in the `VAR` list specification. If the `sparse` data format of the `CONDATA=` data set is used, a name of an arc or a nonarc variable is a *value* of the SAS variable listed in the `COLUMN` list specification.

The NAMECTRL= option is used when a name of an arc or nonarc variable in the `CONDATA=` data set (either a `VAR` list SAS variable name or value of the `COLUMN` list SAS variable) is in the form

*tail\_head* and there exists an arc with these end nodes. If *tail\_head* has not already been tagged as belonging to an arc or nonarc variable in the **ARCDATA=** data set, PROC NETFLOW needs to know whether *tail\_head* is the name of the arc or the name of a nonarc variable.

If you specify NAMECTRL=1, a name that is not defined in the **ARCDATA=** data set is assumed to be the name of a nonarc variable. NAMECTRL=2 treats *tail\_head* as the name of the arc with these endnodes, provided no other name is used to associate data in the **CONDATA=** data set with this arc. If the arc does have other names that appear in the **CONDATA=** data set, *tail\_head* is assumed to be the name of a nonarc variable. If you specify NAMECTRL=3, *tail\_head* is assumed to be a name of the arc with these end nodes, whether the arc has other names or not. The default value of NAMECTRL is 3. Note that if you use the **dense** side constraint input format, the default arc name *tail\_head* is not recognized (regardless of the NAMECTRL value) unless the head node and tail node names contain no lowercase letters.

If the **dense** format is used for the **CONDATA=** data set, the SAS System converts SAS variable names in a SAS program to uppercase. The **VAR** list variable names are uppercased. Because of this, PROC NETFLOW automatically uppercases names of arcs and nonarc variables (the values of the **NAME** list variable) in the **ARCDATA=** data set. The names of arcs and nonarc variables (the values of the **NAME** list variable) appear uppercased in the **ARCOUT=** data set and the **CONOUT=** data set, and in the **PRINT** statement output.

Also, if the **dense** format is used for the **CONDATA=** data set, be careful with default arc names (names in the form *tailnode\_headnode*). Node names (values in the **TAILNODE** and **HEADNODE** list variables) in the **ARCDATA=** data set are not uppercased by PROC NETFLOW. Consider the following code:

```
data arcdata;
    input _from_ $ _to_ $ _name $ ;
    datalines;
from to1 .
from to2 arc2
TAIL TO3 .
;
data densecon;
    input from_to1 from_to2 arc2 tail_to3;
    datalines;
2 3 3 5
;
proc netflow
    arcdata=arcdata conddata=densecon;
run;
```

The SAS System does not uppercase character string values. PROC NETFLOW never uppercases node names, so the arcs in observations 1, 2, and 3 in the preceding **ARCDATA=** data set have the default names “from\_to1”, “from\_to2”, and “TAIL\_TO3”, respectively. When the **dense** format of the **CONDATA=** data set is used, PROC NETFLOW does uppercase values of the **NAME** list variable, so the name of the arc in the second observation of the **ARCDATA=** data set is “ARC2”. Thus, the second arc has two names: its default “from\_to2” and the other that was specified “ARC2”.

As the SAS System does uppercase program code, you must think of the input statement

```
input from_to1 from_to2 arc2 tail_to3;
```



as really being

```
INPUT FROM_TO1 FROM_TO2 ARC2 TAIL_TO3;
```

The SAS variables named “FROM\_TO1” and “FROM\_TO2” are *not* associated with any of the arcs in the preceding `ARC DATA=` data set. The values “FROM\_TO1” and “FROM\_TO2” are different from all of the arc names “from\_to1”, “from\_to2”, “TAIL\_TO3”, and “ARC2”. “FROM\_TO1” and “FROM\_TO2” could end up being the names of two nonarc variables. It is sometimes useful to specify `PRINT NONARCS`; before commencing optimization to ensure that the model is correct (has the right set of nonarc variables).

The SAS variable named “ARC2” is the name of the second arc in the `ARC DATA=` data set, even though the name specified in the `ARC DATA=` data set looks like “arc2”. The SAS variable named “TAIL\_TO3” is the default name of the third arc in the `ARC DATA=` data set.

**NARCS=*n***

specifies the approximate number of arcs. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**NCOEFS=*n***

specifies the approximate number of constraint coefficients. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**NCONS=*n***

specifies the approximate number of constraints. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**NNAS=*n***

specifies the approximate number of nonarc variables. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**NNODES=*n***

specifies the approximate number of nodes. See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**NON\_REPLIC=*non\_replic***

prevents PROC NETFLOW from doing unnecessary checks of data previously read.

- NON\_REPLIC=COEFS indicates that each constraint coefficient is specified *once* in the `CON DATA=` data set.
- NON\_REPLIC=NONE indicates that constraint coefficients can be specified more than once in the `CON DATA=` data set. NON\_REPLIC=NONE is the default.

See the section “[How to Make the Data Read of PROC NETFLOW More Efficient](#)” on page 416.

**RHSOBS=*charstr***

specifies the keyword that identifies a right-hand-side observation when using the `sparse` format for data in the `CON DATA=` data set. The keyword is expected as a value of the SAS variable in the `CON DATA=` data set named in the `COLUMN` list specification. The default value of the RHSOBS= option is `_RHS_` or `_rhs_`. If *charstr* is not a valid SAS variable name, enclose it in single quotes.

**SAME\_NONARC\_DATA****SND**

If all nonarc variable data are given in the **ARC**DATA= data set, or if the problem has no nonarc variables, the unconstrained warm start can be read more quickly if the option **SAME\_NONARC\_DATA** is specified. **SAME\_NONARC\_DATA** indicates that any nonconstraint nonarc variable data in the **COND**ATA= data set is to be ignored. Only side constraint data in the **COND**ATA= data set are read.

If you use an unconstrained warm start and **SAME\_NONARC\_DATA** is not specified, any nonarc variable objective function coefficient, upper bound, or lower bound can be changed. Any nonarc variable data in the **COND**ATA= data set overrides (without warning messages) corresponding data in the **ARC**DATA= data set. You can possibly introduce new nonarc variables to the problem, that is, nonarc variables that were not in the problem when the warm start was generated.

**SAME\_NONARC\_DATA** should be specified if nonarc variable data in the **COND**ATA= data set are to be deliberately ignored. Consider

```
proc netflow options arcdata=arc0 nodedata=node0
    condata=con0
        /* this data set has nonarc variable          */
        /* objective function coefficient data        */
    future1 arcout=arc1 nodeout=node1;
run;

data arc2;
    reset arc1;    /* this data set has nonarc variable obs */
    if _cost_<50.0 then _cost_=_cost_*1.25;
        /* some objective coefficients of nonarc */
        /* variable might be changed              */
proc netflow options
    warm arcdata=arc2 nodedata=node1
    condata=con0 same_nonarc_data
        /* This data set has old nonarc variable      */
        /* obj, fn. coefficients. same_nonarc_data    */
        /* indicates that the "new" coeffs in the    */
        /* arcdata=arc2 are to be used.              */
run;
```

**SCALE=scale**

indicates that the side constraints are to be scaled. Scaling is useful when some coefficients of a constraint or nonarc variable are either much larger or much smaller than other coefficients. Scaling might make all coefficients have values that have a smaller range, and this can make computations more stable numerically. Try the **SCALE=** option if PROC NETFLOW is unable to solve a problem because of numerical instability. Specify

- **SCALE=ROW**, **SCALE=CON**, or **SCALE=CONSTRAINT** if the largest absolute value of coefficients in each constraint is about 1.0
- **SCALE=COL**, **SCALE=COLUMN**, or **SCALE=NONARC** if nonarc variable columns are scaled so that the absolute value of the largest constraint coefficient of a nonarc variable is near to 1
- **SCALE=BOTH** if the largest absolute value of coefficients in each constraint, and the absolute value of the largest constraint coefficient of a nonarc variable is near to 1. This is the default.

- SCALE=NONE if no scaling should be done

## SHORTPATH

### SP

specifies that PROC NETFLOW solve a shortest path problem. The NETFLOW procedure finds the shortest path between the nodes specified in the **SOURCE=** option and the **SINK=** option. The costs of arcs are their *lengths*. PROC NETFLOW automatically assigns a supply of one flow unit to the **SOURCE=** node, and the **SINK=** node is assigned to have a one flow unit demand. In this way, the SHORTPATH option sets up a shortest path problem as an equivalent minimum cost problem.

If a network has one supply node (with supply of one unit) and one demand node (with demand of one unit), you could specify the SHORTPATH option, with the **SOURCE=** and **SINK=** nodes, even if the problem is not a shortest path problem. You then should not provide any supply or demand data in the **NODEDATA=** data set or the **ARCADATA=** data set.

**SINK=***sinkname*

**SINKNODE=***sinkname*

identifies the demand node. The **SINK=** option is useful when you specify the **MAXFLOW** option or the **SHORTPATH** option and need to specify toward which node the shortest path or maximum flow is directed. The **SINK=** option also can be used when a minimum cost problem has only one demand node. Rather than having this information in the **ARCADATA=** data set or the **NODEDATA=** data set, use the **SINK=** option with an accompanying **DEMAND=** specification for this node. The **SINK=** option must be the name of a head node of at least one arc; thus, it must have a character value. If the value of the **SINK=** option is not a valid SAS character variable name, it must be enclosed in single quotes and can contain embedded blanks.

**SOURCE=***sourcename*

**SOURCENODE=***sourcename*

identifies a supply node. The **SOURCE=** option is useful when you specify the **MAXFLOW** or the **SHORTPATH** option and need to specify from which node the shortest path or maximum flow originates. The **SOURCE=** option also can be used when a minimum cost problem has only one supply node. Rather than having this information in the **ARCADATA=** data set or the **NODEDATA=** data set, use the **SOURCE=** option with an accompanying **SUPPLY=** amount of supply at this node. The **SOURCE=** option must be the name of a tail node of at least one arc; thus, it must have a character value. If the value of the **SOURCE=** option is not a valid SAS character variable name, it must be enclosed in single quotes and can contain embedded blanks.

## SPARSECONDATA

### SCDATA

indicates that the **CONDATA=** data set has data in the *sparse* data format. Otherwise, it is assumed that the data are in the *dense* format.

**NOTE:** If the SPARSECONDATA option is not specified, and you are running SAS software Version 6 or you have specified options **validvarname=v6**;, all **NAME** list variable values in the **ARCADATA=** data set are uppercased. See the section “Case Sensitivity” on page 399.

## SPARSEP2

**SP2**

indicates that the new column of the working basis matrix that replaces another column be held in a linked list. If the SPARSEP2 option is not specified, a one-dimensional array is used to store this column's information, that can contain elements that are 0.0 and use more memory than the linked list. The linked list mechanism requires more work if the column has numerous nonzero elements in many iterations. Otherwise, it is superior. Sometimes, specifying SPARSEP2 is beneficial when the side constrained coefficient matrix is very sparse or when some paging is necessary.

**SUPPLY=s**

specifies the supply at the source node specified by the **SOURCE=** option. The **SUPPLY=** option should be used only if the **SOURCE=** option is given in the PROC NETFLOW statement and neither the **SHORTPATH** option nor the **MAXFLOW** option is specified. If you are solving a minimum cost network problem and the **SOURCE=** option is used to identify the source node and the **SUPPLY=** option is not specified, then by default the supply at the source node is made equal to the network's total demand.

**THRUNET**

tells PROC NETFLOW to force through the network any excess supply (the amount by which total supply exceeds total demand) or any excess demand (the amount by which total demand exceeds total supply) as is required. If a network problem has unequal total supply and total demand and the THRUNET option is not specified, PROC NETFLOW drains away the excess supply or excess demand in an optimal manner. The consequences of specifying or not specifying THRUNET are discussed in the section “Balancing Total Supply and Total Demand” on page 412.

**TYPEOBS=charstr**

specifies the keyword that identifies a type observation when using the **sparse** format for data in the **CONDATA=** data set. The keyword is expected as a value of the SAS variable in the **CONDATA=** data set named in the **COLUMN** list specification. The default value of the **TYPEOBS=** option is **\_TYPE\_** or **\_type\_**. If *charstr* is not a valid SAS variable name, enclose it in single quotes.

**WARM**

indicates that the **NODEDATA=** data set or the **DUALIN=** data set and the **ARCDATA=** data set contain extra information of a warm start to be used by PROC NETFLOW. See the section “Warm Starts” on page 413.

---

## CAPACITY Statement

**CAPACITY** *variable* ;

**CAPAC** *variable* ;

**UPPERBD** *variable* ;

The CAPACITY statement identifies the SAS variable in the **ARCDATA=** data set that contains the maximum feasible flow or capacity of the network arcs. If an observation contains nonarc variable information, the CAPACITY list variable is the upper value bound for the nonarc variable named in the **NAME** list variable in that observation. The CAPACITY list variable must have numeric values. It is not necessary to have a CAPACITY statement if the name of the SAS variable is **\_CAPAC\_**, **\_UPPER\_**, **\_UPPERBD**, or **\_HI\_**.

---

## COEF Statement

**COEF** *variables* ;

The COEF list is used with the *sparse* input format of the **CONDATA=** data set. The COEF list can contain more than one SAS variable, each of which must have numeric values. If the COEF statement is not specified, the **CONDATA=** data set is searched and SAS variables with names beginning with **\_COE** are used. The number of SAS variables in the COEF list must be no greater than the number of SAS variables in the **ROW** list.

The values of the COEF list variables in an observation can be interpreted differently than these variables' values in other observations. The values can be coefficients in the side constraints, costs and objective function coefficients, bound data, constraint type data, or rhs data. If the **COLUMN** list variable has a value that is a name of an arc or nonarc variable, the *i*th COEF list variable is associated with the constraint or special row name named in the *i*th **ROW** list variable. Otherwise, the COEF list variables indicate type values, rhs values, or missing values.

---

## COLUMN Statement

**COLUMN** *variable* ;

The COLUMN list is used with the *sparse* input format of side constraints. This list consists of one SAS variable in the **CONDATA=** data set that has as values the names of arc variables, nonarc variables, or missing values. Some, if not all of these values, also can be values of the **NAME** list variables of the **ARCDATA=** data set. The COLUMN list variable can have other special values (refer to the **TYPEOBS=** and **RHSOBS=** options). If the COLUMN list is not specified after the **PROC NETFLOW** statement, the **CONDATA=** data set is searched and a SAS variable named **\_COLUMN\_** is used. The COLUMN list variable must have character values.

---

## CONOPT Statement

**CONOPT** ;

The CONOPT statement has no options. It is equivalent to specifying **RESET SCRATCH**;. The CONOPT statement should be used before stage 2 optimization commences. It indicates that the optimization performed next should consider the side constraints.

Usually, the optimal unconstrained network solution is used as a starting solution for constrained optimization. Finding the unconstrained optimum usually reduces the amount of stage 2 optimization. Furthermore, the unconstrained optimum is almost always “closer” to the constrained optimum than the initial basic solution determined before any optimization is performed. However, as the optimum is approached during stage 1 optimization, the flow change candidates become scarcer and a solution good enough to start stage 2 optimization may already be at hand. You should then specify the CONOPT statement.

---

## COST Statement

**COST** *variable* ;

**OBJFN** *variable* ;

The COST statement identifies the SAS variable in the **ARC DATA=** data set that contains the per unit flow cost through an arc. If an observation contains nonarc variable information, the value of the COST list variable is the objective function coefficient of the nonarc variable named in the **NAME** list variable in that observation. The COST list variable must have numeric values. It is not necessary to specify a COST statement if the name of the SAS variable is **\_COST\_** or **\_LENGTH\_**.

---

## DEMAND Statement

**DEMAND** *variable* ;

The DEMAND statement identifies the SAS variable in the **ARC DATA=** data set that contains the demand at the node named in the corresponding **HEADNODE** list variable. The DEMAND list variable must have numeric values. It is not necessary to have a DEMAND statement if the name of this SAS variable is **\_DEMAND\_**.

---

## HEADNODE Statement

**HEADNODE** *variable* ;

**HEAD** *variable* ;

**TONODE** *variable* ;

**TO** *variable* ;

The HEADNODE statement specifies the SAS variable that must be present in the **ARC DATA=** data set that contains the names of nodes toward which arcs are directed. It is not necessary to have a HEADNODE statement if the name of the SAS variable is **\_HEAD\_** or **\_TO\_**. The HEADNODE variable must have character values.

---

## ID Statement

**ID** *variables* ;

The ID statement specifies SAS variables containing values for pre- and post-optimal processing and analysis. These variables are not processed by PROC NETFLOW but are read by the procedure and written in the **ARC OUT=** and **CON OUT=** data sets and the output of **PRINT** statements. For example, imagine a network used to model a distribution system. The SAS variables listed on the ID statement can contain information on type of vehicle, transportation mode, condition of road, time to complete journey, name of driver, or other ancillary information useful for report writing or describing facets of the operation that do not have bearing on the optimization. The ID variables can be character, numeric, or both.

If no ID list is specified, the procedure forms an ID list of all SAS variables not included in any other implicit or explicit list specification. If the ID list is specified, any SAS variables in the **ARCDATA=** data set not in any list are dropped and do not appear in the **ARCOUT=** or **CONOUT=** data sets, or in the **PRINT** statement output.

---

## LO Statement

**LO** *variable* ;

**LOWERBD** *variable* ;

**MINFLOW** *variable* ;

The LO statement identifies the SAS variable in the **ARCDATA=** data set that contains the minimum feasible flow or lower flow bound for arcs in the network. If an observation contains nonarc variable information, the LO list variable has the value of the lower bound for the nonarc variable named in the **NAME** list variable. The LO list variables must have numeric values. It is not necessary to have a LO statement if the name of this SAS variable is **\_LOWER\_**, **\_LO\_**, **\_LOWERBD**, or **\_MINFLOW**.

---

## MULT Statement

**MULT** *variables* ;

**MULTIPLIER** *variables* ;

The MULT statement identifies the SAS variable in the **ARCDATA=** data set associated with the values of arc multipliers in the network. These values must be positive real numbers. It is not necessary to have a MULT statement if the name of this SAS variable is **\_MULT\_**.

---

## NAME Statement

**NAME** *variable* ;

**ARCNAME** *variable* ;

**VARNAME** *variable* ;

Each arc and nonarc variable that has data in the **CONDATA=** data set must have a unique name. This variable is identified in the **ARCDATA=** data set. The NAME list variable must have character values (see the **NAMECTRL=** option in the **PROC NETFLOW** statement for more information). It is not necessary to have a NAME statement if the name of this SAS variable is **\_NAME\_**.

---

## NODE Statement

**NODE** *variable* ;

The NODE list variable, which must be present in the **NODEDATA=** data set, has names of nodes as values. These values must also be values of the **TAILNODE** list variable, the **HEADNODE** list variable, or both. If

this list is not explicitly specified, the **NODEDATA=** data set is searched for a SAS variable with the name **\_NODE\_**. The **NODE** list variable must have character values.

---

## PIVOT Statement

**PIVOT ;**

The **PIVOT** statement has no options. It indicates that one simplex iteration is to be performed. The **PIVOT** statement forces a simplex iteration to be performed in spite of the continued presence of any reasons or solution conditions that caused optimization to be halted. For example, if the number of iterations performed exceeds the value of the **MAXIT1=** or **MAXIT2=** option and you issue a **PIVOT** statement, the iteration is performed even though the **MAXIT1=** or **MAXIT2=** value has not yet been changed using a **RESET** statement.

---

## PRINT Statement

**PRINT** *options / qualifiers ;*

The options available with the **PRINT** statement of **PROC NETFLOW** are summarized by purpose in the following table.

**Table 7.2** Functional Summary, **PRINT** Statement

| Description  | Statement | Option         |
|--|-----------|----------------|
| <b>PRINT Statement Options:</b>  |           |                |
| Display everything   | PRINT     | PROBLEM        |
| Display arc information  | PRINT     | ARCS           |
| Display nonarc variable information  | PRINT     | NONARCS        |
| Display variable information   | PRINT     | VARIABLES      |
| Display constraint information   | PRINT     | CONSTRAINTS    |
| Display information for some arcs  | PRINT     | SOME_ARCS      |
| Display information for some nonarc variables                                  | PRINT     | SOME_NONARCS   |
| Display information for some variables   | PRINT     | SOME_VARIABLES |
| Display information for some constraints                                       | PRINT     | SOME_CONS      |
| Display information for some constraints associated with some arcs             | PRINT     | CON_ARCS       |
| Display information for some constraints associated with some nonarc variables | PRINT     | CON_NONARCS    |
| Display information for some constraints associated with some variables        | PRINT     | CON_VARIABLES  |
| <b>PRINT Statement Qualifiers:</b>   |           |                |
| Produce a short report   | PRINT     | / SHORT        |
| Produce a long report  | PRINT     | / LONG         |
| Display arcs/variables with zero flow/value                                    | PRINT     | / ZERO         |



| Description                                    | Statement | Option     |
|--|-----------|------------|
| Display arcs/variables with nonzero flow/value | PRINT     | / NONZERO  |
| Display basic arcs/variables                   | PRINT     | / BASIC    |
| Display nonbasic arcs/variables                | PRINT     | / NONBASIC |

The PRINT statement enables you to examine part or all of the problem. You can limit the amount of information displayed when a PRINT statement is processed by specifying PRINT statement options. The name of the PRINT option indicates what part of the problem is to be examined. If no options are specified, or PRINT PROBLEM is specified, information about the entire problem is produced.

The amount of displayed information can be limited further by following any PRINT statement options with a slash (/) and one or more of the qualifiers SHORT or LONG, ZERO or NONZERO, BASIC or NONBASIC.

Some of the PRINT statement options require you to specify a list of some type of entity, thereby enabling you to indicate what entities are of interest. The entities of interest are the ones you want to display. These entities might be tail node names, head node names, nonarc variable names, or constraint names. The entity list is made up of one or more of the following constructs. Each construct can add none, one, or more entities to the set of entities to be displayed.

- **\_ALL\_**  
Display all entities in the required list.
- **entity**  
Display the named entity that is interesting.
- **entity1 - entity2** (one hyphen)  
**entity1 -- entity2** (two hyphens)  
**entity1 - CHARACTER - entity2** or  
**entity1 - CHAR - entity2**  
Both entity1 and entity2 have names made up of the same character string prefix followed by a numeric suffix. The suffixes of both entity1 and entity2 have the same number of numerals but can have different values. A specification of entity1 - entity2 indicates that all entities with the same prefix and suffixes with values on or between the suffixes of entity1 and entity2 are to be put in the set of entities to be displayed. The numeric suffix of both entity1 and entity2 can be followed by a character string. For example, **\_OBS07\_ - \_OBS13\_** is a valid construct of the forms entity1 - entity2.
- **part\_of\_entity\_name:**  
Display all entities in the required list that have names beginning with the character string preceding the colon.

The following options can appear in the PRINT statement:

## ARCS

indicates that you want to have displayed information about all arcs.

**SOME\_ARCS** (*taillist, headlist*)

is similar to the statement PRINT ARCS except that, instead of displaying information about all arcs, only arcs directed from nodes in a specified set of tail nodes to nodes in a specified set of head nodes are included. The nodes or node constructs belonging to the *taillist* list are separated by blanks. The nodes or node constructs belonging to the *headlist* list are also separated by blanks. The lists are separated by a comma.

**NONARCS****VARIABLES**

indicates that information is to be displayed about all nonarc variables.

**SOME\_NONARCS** (*nonarclist*)

is similar to the PRINT NONARCS statement except that, instead of displaying information about all nonarc variables, only those belonging to a specified set of nonarc variables have information displayed. The nonarc variables or nonarc variable constructs belonging to the *nonarclist* list are separated by blanks.

**CONSTRAINTS**

indicates that you want to have displayed information about all constraint coefficients.

**SOME\_CONS** (*conlist*)

displays information for coefficients in a specified set of constraints. The constraints or constraint constructs belonging to the *conlist* list are separated by blanks.

**CON\_ARCS** (*taillist, headlist*)

is similar to the PRINT SOME\_CONS (*conlist*) statement except that, instead of displaying information about all coefficients in specified constraints, information about only those coefficients that are associated with arcs directed from a set of specified tail nodes toward a set of specified head nodes is displayed. The constraints or constraint constructs belonging to the *conlist* list are separated by blanks; so too are the nodes or node constructs belonging to the *taillist* list and the nodes or node constructs belonging to the *headlist* list. The lists are separated by commas.

**CON\_NONARCS** (*conlist, nonarclist*)**CON\_VARIABLES** (*conlist, variablelist*)

is similar to the PRINT SOME\_CONS (*conlist*) statement except that, instead of displaying information about all coefficients in specified constraints, information about only those coefficients that are associated with nonarc variables in a specified set is displayed. The constraints or constraint constructs belonging to the *conlist* list are separated by blanks. The nonarc variables or nonarc variable constructs belonging to the *nonarclist* list are separated by blanks. The lists are separated by a comma.

**PROBLEM**

is equivalent to the statement PRINT ARCS NONARCS CONSTRAINTS.

Following a slash (/), the qualifiers SHORT or LONG, ZERO or NONZERO, BASIC or NONBASIC can appear in any PRINT statement. These qualifiers are described below.

- **BASIC**

Only rows that are associated with arcs or nonarc variables that are basic are displayed. The `_STATUS_` column values are `KEY_ARC BASIC` or `NONKEY ARC BASIC` for arcs, and `NONKEY_BASIC` for nonarc variables.

- **LONG**  
All table columns are displayed (the default when no qualifier is used).
- **NONBASIC**  
Only rows that are associated with arcs or nonarc variables that are nonbasic are displayed. The `_STATUS_` column values are LOWERBD NONBASIC or UPPERBD NONBASIC.
- **NONZERO**  
Only rows that have nonzero `_FLOW_` column values (nonzero arc flows, nonzero nonarc variable values) are displayed.
- **SHORT**  
The table columns are `_N_`, `_FROM_`, `_TO_`, `_COST_`, `_CAPAC_`, `_LO_`, `_NAME_`, and `_FLOW_`, or the names of the SAS variables specified in the corresponding variable lists ([TAILNODE](#), [HEADNODE](#), [COST](#), [CAPACITY](#), [LO](#), and [NAME](#) lists). `_COEF_` or the name of the SAS variable in the [COEF](#) list specification will head a column when the SHORT qualifier is used in PRINT CONSTRAINTS, SOME\_CONS, CON\_ARCS, or CON\_NONARCS.
- **ZERO**  
Only rows that have zero `_FLOW_` column values (zero arc flows, zero nonarc variable values) are displayed.

The default qualifiers are BASIC, NONBASIC, ZERO, NONZERO, and LONG.

## Displaying Information On All Constraints

In the oil refinery problem, if you had entered

```
print constraints;
```

after the [RUN](#) statement, the output in [Figure 7.9](#) would have been produced.

## Displaying Information About Selected Arcs

In the oil refinery problem, if you had entered

```
print some_arcs(refin:,_all_)/short;
```

after the [RUN](#) statement, the output in [Figure 7.10](#) would have been produced.

Figure 7.9 PRINT CONSTRAINTS

| Oil Industry Example  |                |                |                 |                 |                 |               |               |
|-----------------------|----------------|----------------|-----------------|-----------------|-----------------|---------------|---------------|
| Constrained Optimum   |                |                |                 |                 |                 |               |               |
| The NETFLOW Procedure |                |                |                 |                 |                 |               |               |
| <u>_N_</u>            | <u>_CON_</u>   | <u>_type_</u>  | <u>_rhs_</u>    | <u>_name_</u>   | <u>_from_</u>   | <u>_to_</u>   |               |
| 1                     | <u>_OBS1_</u>  | GE             | -15             | m_e_ref1        | middle east     | refinery 1    |               |
| 2                     | <u>_OBS1_</u>  | GE             | -15             | thruput1        | refinery 1      | r1            |               |
| 3                     | <u>_OBS2_</u>  | GE             | -15             | m_e_ref2        | middle east     | refinery 2    |               |
| 4                     | <u>_OBS2_</u>  | GE             | -15             | thruput2        | refinery 2      | r2            |               |
| 5                     | <u>_OBS3_</u>  | EQ             | 0               | thruput1        | refinery 1      | r1            |               |
| 6                     | <u>_OBS3_</u>  | EQ             | 0               | r1_gas          | r1              | ref1 gas      |               |
| 7                     | <u>_OBS4_</u>  | EQ             | 0               | thruput2        | refinery 2      | r2            |               |
| 8                     | <u>_OBS4_</u>  | EQ             | 0               | r2_gas          | r2              | ref2 gas      |               |
| <u>_N_</u>            | <u>_cost_</u>  | <u>_capac_</u> | <u>_lo_</u>     | <u>_SUPPLY_</u> | <u>_DEMAND_</u> | <u>_FLOW_</u> | <u>_COEF_</u> |
| 1                     | 63             | 95             | 20              | 100             | .               | 80            | -2            |
| 2                     | 200            | 175            | 50              | .               | .               | 145           | 1             |
| 3                     | 81             | 80             | 10              | 100             | .               | 20            | -2            |
| 4                     | 220            | 100            | 35              | .               | .               | 35            | 1             |
| 5                     | 200            | 175            | 50              | .               | .               | 145           | -3            |
| 6                     | 0              | 140            | 0               | .               | .               | 108.75        | 4             |
| 7                     | 220            | 100            | 35              | .               | .               | 35            | -3            |
| 8                     | 0              | 100            | 0               | .               | .               | 26.25         | 4             |
| <u>_N_</u>            | <u>_FCOST_</u> | <u>_RCOST_</u> | <u>_STATUS_</u> |                 |                 |               |               |
| 1                     | 5040           | .              | KEY_ARC         | BASIC           |                 |               |               |
| 2                     | 29000          | .              | KEY_ARC         | BASIC           |                 |               |               |
| 3                     | 1620           | .              | NONKEY          | ARC             | BASIC           |               |               |
| 4                     | 7700           | 29             | LOWERBD         | NONBASIC        |                 |               |               |
| 5                     | 29000          | .              | KEY_ARC         | BASIC           |                 |               |               |
| 6                     | 0              | .              | KEY_ARC         | BASIC           |                 |               |               |
| 7                     | 7700           | 29             | LOWERBD         | NONBASIC        |                 |               |               |
| 8                     | 0              | .              | KEY_ARC         | BASIC           |                 |               |               |

Figure 7.10 PRINT SOME\_ARCS

| Oil Industry Example  |            |      |        |         |      |         |
|-----------------------|------------|------|--------|---------|------|---------|
| Constrained Optimum   |            |      |        |         |      |         |
| The NETFLOW Procedure |            |      |        |         |      |         |
| _N_                   | _from_     | _to_ | _cost_ | _capac_ | _lo_ | _name_  |
| 1                     | refinery 1 | r1   | 200    | 175     | 50   | thrput1 |
| 2                     | refinery 2 | r2   | 220    | 100     | 35   | thrput2 |
|                       |            |      |        |         |      |         |
| _N_                   | _FLOW_     |      |        |         |      |         |
| 1                     | 145        |      |        |         |      |         |
| 2                     | 35         |      |        |         |      |         |

### Displaying Information About Selected Constraints

In the oil refinery problem, if you had entered

```
print some_cons(_obs3_ _obs4_)/nonzero short;
```

after the [RUN](#) statement, the output in [Figure 7.11](#) would have been produced.

Figure 7.11 PRINT SOME\_CONS

| Oil Industry Example  |        |         |       |         |            |          |
|-----------------------|--------|---------|-------|---------|------------|----------|
| Constrained Optimum   |        |         |       |         |            |          |
| The NETFLOW Procedure |        |         |       |         |            |          |
| _N_                   | _CON_  | _type_  | _rhs_ | _name_  | _from_     | _to_     |
| 1                     | _OBS3_ | EQ      | 0     | thrput1 | refinery 1 | r1       |
| 2                     | _OBS3_ | EQ      | 0     | r1_gas  | r1         | ref1 gas |
| 3                     | _OBS4_ | EQ      | 0     | thrput2 | refinery 2 | r2       |
| 4                     | _OBS4_ | EQ      | 0     | r2_gas  | r2         | ref2 gas |
|                       |        |         |       |         |            |          |
| _N_                   | _cost_ | _capac_ | _lo_  | _FLOW_  | _COEF_     |          |
| 1                     | 200    | 175     | 50    | 145     | -3         |          |
| 2                     | 0      | 140     | 0     | 108.75  | 4          |          |
| 3                     | 220    | 100     | 35    | 35      | -3         |          |
| 4                     | 0      | 100     | 0     | 26.25   | 4          |          |

If you had entered

```
print con_arcs(_all_, r1 r2, _all_)/short;
```

after the **RUN** statement, the output in Figure 7.12 would have been produced. Constraint information about arcs directed from selected tail nodes is displayed.

**Figure 7.12** PRINT CON\_ARCS

| Oil Industry Example  |        |         |       |        |        |          |
|-----------------------|--------|---------|-------|--------|--------|----------|
| Constrained Optimum   |        |         |       |        |        |          |
| The NETFLOW Procedure |        |         |       |        |        |          |
| _N_                   | _CON_  | _type_  | _rhs_ | _name_ | _from_ | _to_     |
| 1                     | _OBS3_ | EQ      | 0     | r1_gas | r1     | ref1 gas |
| 2                     | _OBS4_ | EQ      | 0     | r2_gas | r2     | ref2 gas |
|                       |        |         |       |        |        |          |
| _N_                   | _cost_ | _capac_ | _lo_  | _FLOW_ | _COEF_ |          |
| 1                     | 0      | 140     | 0     | 108.75 | 4      |          |
| 2                     | 0      | 100     | 0     | 26.25  | 4      |          |

## Cautions

This subsection has two parts; the first part is applicable if you are running Version 7 or later of the SAS System, and the second part is applicable if you are running Version 6. You can get later versions to “act” like Version 6 by specifying

```
options validvarname=v6;
```

For Version 7 onward, PROC NETFLOW strictly respects case sensitivity. The PRINT statements of PROC NETFLOW that require lists of entities will work properly *only* if the entities have the same case as in the input data sets. Entities that contain blanks must be enclosed in single or double quotes. For example,

```
print some_arcs (_all_, "Ref1 Gas");
```

In this example, a head node of an arc in the model is “Ref1 Gas” (without the quotes). If you omit the quotes, PROC NETFLOW issues a message on the SAS log:

```
WARNING: The node Ref1 in the list of head nodes in the PRINT
SOME_ARCS or PRINT CON_ARCS is not a node in the
problem. This statement will be ignored.
```

If you had specified

```
print some_arcs (_all_, "ref1 Gas");
```

(note the small r), you would have been warned

**WARNING:** The node `ref1 Gas` in the list of head nodes in the `PRINT SOME_ARCS` or `PRINT CON_ARCS` is not a node in the problem. This statement will be ignored.

If you are running Version 6, or if you are running a later version and you have specified

```
options validvarname=v6;
```

when information is parsed to procedures, the SAS System converts the text that makes up statements into uppercase. The `PRINT` statements of `PROC NETFLOW` that require lists of entities will work properly *only* if the entities are uppercase in the input data sets. If you do not want this uppercasing to occur, you must enclose the entity in single or double quotes.

```
print some_arcs('lowercase tail', 'lowercase head');
print some_cons('factory07'-'factory12');
print some_cons('_factory07'-'_factory12_');
print some_nonarcs("CO2 content");
```

Entities that contain blanks must be enclosed in single or double quotes.

---

## QUIT Statement

**QUIT ;**

The `QUIT` statement indicates that `PROC NETFLOW` is to be terminated immediately. The solution is not saved in the current output data sets. The `QUIT` statement has no options.

---

## RESET Statement

**RESET** *options* ;

**SET** *options* ;

The `RESET` statement is used to change options after `PROC NETFLOW` has started execution. Any of the following options can appear in the [PROC NETFLOW](#) statement.

Another name for the `RESET` statement is `SET`. You can use `RESET` when you are resetting options and `SET` when you are setting options for the first time. The following options fall roughly into five categories:

- output data set specifications
- options that indicate conditions under which optimization is to be halted temporarily, giving you an opportunity to use `PROC NETFLOW` interactively
- options that control aspects of the operation of the network primal simplex optimization
- options that control the pricing strategies of the network simplex optimizer
- miscellaneous options

If you want to examine the setting of any options, use the **SHOW** statement. If you are interested in looking at only those options that fall into a particular category, the **SHOW** statement has options that enable you to do this.

The execution of PROC NETFLOW has three stages. In stage zero the problem data are read from the **NODEDATA=**, **ARCDATA=**, and **CONDATA=** data sets. If a warm start is not available, an initial basic feasible solution is found. Some options of the **PROC NETFLOW** statement control what occurs in stage zero. By the time the first **RESET** statement is processed, stage zero has already been completed.

In the first stage, an optimal solution to the network flow problem neglecting any side constraints is found. The primal and dual solutions for this relaxed problem can be saved in the **ARCOUT=** data set and the **NODEOUT=** data set, respectively.

In the second stage, the side constraints are examined and some initializations occur. Some preliminary work is also needed to commence optimization that considers the constraints. An optimal solution to the network flow problem with side constraints is found. The primal and dual solutions for this side-constrained problem are saved in the **CONOUT=** data set and the **DUALOUT=** data set, respectively.

Many options in the **RESET** statement have the same name except that they have as a suffix the numeral 1 or 2. Such options have much the same purpose, but option1 controls what occurs during the first stage when optimizing the network neglecting any side constraints and option2 controls what occurs in the second stage when PROC NETFLOW is performing constrained optimization.

Some options can be turned off by the option prefixed by the word **NO**. For example, **FEASIBLEPAUSE1** may have been specified in a **RESET** statement and in a later **RESET** statement, you can specify **NOFEASIBLEPAUSE1**. In a later **RESET** statement, you can respecify **FEASIBLEPAUSE1** and, in this way, toggle this option.

The options available with the **RESET** statement are summarized by purpose in the following table.

**Table 7.3** Functional Summary, RESET Statement

| Description   | Statement | Option        |
|---|-----------|---------------|
| <b>Output Data Set Options:</b>                                   |           |               |
| Unconstrained primal solution data set                            | RESET     | ARCOUT=       |
| Unconstrained dual solution data set                              | RESET     | NODEOUT=      |
| Constrained primal solution data set                              | RESET     | CONOUT=       |
| Constrained dual solution data set                                | RESET     | DUALOUT=      |
| <b>Simplex Options:</b>   |           |               |
| Use big-M instead of two-phase method, stage 1                    | RESET     | BIGM1         |
| Use Big-M instead of two-phase method, stage 2                    | RESET     | BIGM2         |
| Anti-cycling option   | RESET     | CYCLEMULT1=   |
| Interchange first nonkey with leaving key arc                     | RESET     | INTFIRST      |
| Controls working basis matrix inversions                          | RESET     | INVREQ=       |
| Maximum number of L row operations allowed before refactorization | RESET     | MAXL=         |
| Maximum number of LU factor column updates                        | RESET     | MAXLUUPDATES= |
| Anti-cycling option   | RESET     | MINBLOCK1=    |
| Use first eligible leaving variable, stage 1                      | RESET     | LRATIO1       |



| Description                                     | Statement | Option           |
|---|-----------|------------------|
| Use first eligible leaving variable, stage 2    | RESET     | LRATIO2          |
| Negates INTFIRST                                | RESET     | NOINTFIRST       |
| Negates LRATIO1                                 | RESET     | NOLRATIO1        |
| Negates LRATIO2                                 | RESET     | NOLRATIO2        |
| Negates PERTURB1                                | RESET     | NOPERTURB1       |
| Anti-cycling option                             | RESET     | PERTURB1         |
| Controls working basis matrix refactorization   | RESET     | REFACTFREQ=      |
| Use two-phase instead of big-M method, stage 1  | RESET     | TWOPHASE1        |
| Use two-phase instead of big-M method, stage 2  | RESET     | TWOPHASE2        |
| Pivot element selection parameter               | RESET     | U=               |
| Zero tolerance, stage 1                         | RESET     | ZERO1=           |
| Zero tolerance, stage 2                         | RESET     | ZERO2=           |
| Zero tolerance, real number comparisons         | RESET     | ZEROTOL=         |
| <b>Pricing Options:</b>                         |           |                  |
| Frequency of dual value calculation             | RESET     | DUALFREQ=        |
| Pricing strategy, stage 1                       | RESET     | PRICETYPE1=      |
| Pricing strategy, stage 2                       | RESET     | PRICETYPE2=      |
| Used when P1SCAN=PARTIAL                        | RESET     | P1NPARTIAL=      |
| Controls search for entering candidate, stage 1 | RESET     | P1SCAN=          |
| Used when P2SCAN=PARTIAL                        | RESET     | P2NPARTIAL=      |
| Controls search for entering candidate, stage 2 | RESET     | P2SCAN=          |
| Initial queue size, stage 1                     | RESET     | QSIZE1=          |
| Initial queue size, stage 2                     | RESET     | QSIZE2=          |
| Used when Q1FILLSCAN=PARTIAL                    | RESET     | Q1FILLNPARTIAL=  |
| Controls scan when filling queue, stage 1       | RESET     | Q1FILLSCAN=      |
| Used when Q2FILLSCAN=PARTIAL                    | RESET     | Q2FILLNPARTIAL=  |
| Controls scan when filling queue, stage 2       | RESET     | Q2FILLSCAN=      |
| Queue size reduction factor, stage 1            | RESET     | REDUCEQSIZE1=    |
| Queue size reduction factor, stage 2            | RESET     | REDUCEQSIZE2=    |
| Frequency of refreshing queue, stage 1          | RESET     | REFRESHQ1=       |
| Frequency of refreshing queue, stage 2          | RESET     | REFRESHQ2=       |
| <b>Optimization Termination Options:</b>        |           |                  |
| Pause after stage 1; do not start stage 2       | RESET     | ENDPAUSE1        |
| Pause when feasible, stage 1                    | RESET     | FEASIBLEPAUSE1   |
| Pause when feasible, stage 2                    | RESET     | FEASIBLEPAUSE2   |
| Maximum number of iterations, stage 1           | RESET     | MAXIT1=          |
| Maximum number of iterations, stage 2           | RESET     | MAXIT2=          |
| Negates ENDPAUSE1                               | RESET     | NOENDPAUSE1      |
| Negates FEASIBLEPAUSE1                          | RESET     | NOFEASIBLEPAUSE1 |
| Negates FEASIBLEPAUSE2                          | RESET     | NOFEASIBLEPAUSE2 |
| Pause every PAUSE1 iterations, stage 1          | RESET     | PAUSE1=          |
| Pause every PAUSE2 iterations, stage 2          | RESET     | PAUSE2=          |

| Description   | Statement | Option             |
|---|-----------|--------------------|
| <b>Interior Point Algorithm Options:</b>                            |           |                    |
| Factorization method  | RESET     | FACT_METHOD=       |
| Allowed amount of dual infeasibility                                | RESET     | TOLDINF=           |
| Allowed amount of primal infeasibility                              | RESET     | TOLPINF=           |
| Allowed total amount of dual infeasibility                          | RESET     | TOLTOTDINF=        |
| Allowed total amount of primal infeasibility                        | RESET     | TOLTOTPINF=        |
| Cut-off tolerance for Cholesky factorization                        | RESET     | CHOLTINYTOL=       |
| Density threshold for Cholesky processing                           | RESET     | DENSETHR=          |
| Step-length multiplier  | RESET     | PDSTEPMULT=        |
| Preprocessing type  | RESET     | PRSLTYPE=          |
| Print optimization progress on SAS log                              | RESET     | PRINTLEVEL2=       |
| <b>Interior Point Stopping Criteria Options:</b>                    |           |                    |
| Maximum number of interior point iterations                         | RESET     | MAXITERB=          |
| Primal-dual (duality) gap tolerance                                 | RESET     | PDGAPTOL=          |
| Stop because of complementarity                                     | RESET     | STOP_C=            |
| Stop because of duality gap   | RESET     | STOP_DG=           |
| Stop because of <i>infeas<sub>b</sub></i>                           | RESET     | STOP_IB=           |
| Stop because of <i>infeas<sub>c</sub></i>                           | RESET     | STOP_IC=           |
| Stop because of <i>infeas<sub>d</sub></i>                           | RESET     | STOP_ID=           |
| Stop because of complementarity                                     | RESET     | AND_STOP_C=        |
| Stop because of duality gap   | RESET     | AND_STOP_DG=       |
| Stop because of <i>infeas<sub>b</sub></i>                           | RESET     | AND_STOP_IB=       |
| Stop because of <i>infeas<sub>c</sub></i>                           | RESET     | AND_STOP_IC=       |
| Stop because of <i>infeas<sub>d</sub></i>                           | RESET     | AND_STOP_ID=       |
| Stop because of complementarity                                     | RESET     | KEEPGOING_C=       |
| Stop because of duality gap   | RESET     | KEEPGOING_DG=      |
| Stop because of <i>infeas<sub>b</sub></i>                           | RESET     | KEEPGOING_IB=      |
| Stop because of <i>infeas<sub>c</sub></i>                           | RESET     | KEEPGOING_IC=      |
| Stop because of <i>infeas<sub>d</sub></i>                           | RESET     | KEEPGOING_ID=      |
| Stop because of complementarity                                     | RESET     | AND_KEEPPGOING_C=  |
| Stop because of duality gap   | RESET     | AND_KEEPPGOING_DG= |
| Stop because of <i>infeas<sub>b</sub></i>                           | RESET     | AND_KEEPPGOING_IB= |
| Stop because of <i>infeas<sub>c</sub></i>                           | RESET     | AND_KEEPPGOING_IC= |
| Stop because of <i>infeas<sub>d</sub></i>                           | RESET     | AND_KEEPPGOING_ID= |
| <b>Miscellaneous Options:</b>                                       |           |                    |
| Output complete basis information to ARCOU= and NODEOUT= data sets  | RESET     | FUTURE1            |
| Output complete basis information to CONOUT= and DUALOUT= data sets | RESET     | FUTURE2            |
| Turn off infeasibility or optimality flags                          | RESET     | MOREOPT            |
| Negates FUTURE1   | RESET     | NOFUTURE1          |
| Negates FUTURE2   | RESET     | NOFUTURE2          |
| Negates SCRATCH   | RESET     | NOSCRATCH          |

| Description                                      | Statement | Option      |
|--|-----------|-------------|
| Negates ZTOL1                                    | RESET     | NOZTOL1     |
| Negates ZTOL2                                    | RESET     | NOZTOL2     |
| Write optimization time to SAS log               | RESET     | OPTIM_TIMER |
| No stage 1 optimization; do stage 2 optimization | RESET     | SCRATCH     |
| Suppress similar SAS log messages                | RESET     | VERBOSE=    |
| Use zero tolerance, stage 1                      | RESET     | ZTOL1       |
| Use zero tolerance, stage 2                      | RESET     | ZTOL2       |

## Output Data Set Specifications

In a RESET statement, you can specify an **ARCOUT=** data set, a **NODEOUT=** data set, a **CONOUT=** data set, or a **DUALOUT=** data set. You are advised to specify these output data sets early because if you make a syntax error when using PROC NETFLOW interactively or, for some other reason, PROC NETFLOW encounters or does something unexpected, these data sets will contain information about the solution that was reached. If you had specified the **FUTURE1** or **FUTURE2** option in a RESET statement, PROC NETFLOW may be able to resume optimization in a subsequent run.

You can turn off these current output data set specifications by specifying **ARCOUT=NULL**, **NODEOUT=NULL**, **CONOUT=NULL**, or **DUALOUT=NULL**.

If PROC NETFLOW is outputting observations to an output data set and you want this to stop, press the keys used to stop SAS procedures. PROC NETFLOW waits, if necessary, and then executes the next statement.

### **ARCOUT=SAS-data-set**

#### **AOUT=SAS-data-set**

names the output data set that receives all information concerning arc and nonarc variables, including flows and other information concerning the current solution and the supply and demand information. The current solution is the latest solution found by the optimizer when the optimization neglecting side constraints is halted or the unconstrained optimum is reached.

You can specify an **ARCOUT=** data set in any RESET statement before the unconstrained optimum is found (even at commencement). Once the unconstrained optimum has been reached, use the **SAVE** statement to produce observations in an **ARCOUT=** data set. Once optimization that considers constraints starts, you will be unable to obtain an **ARCOUT=** data set. Instead, use a **CONOUT=** data set to get the current solution. See the section “**ARCOUT= and CONOUT= Data Sets**” on page 395 for more information.

### **CONOUT=SAS-data-set**

#### **COOUT=SAS-data-set**

names the output data set that contains the primal solution obtained after optimization considering side constraints reaches the optimal solution. You can specify a **CONOUT=** data set in any RESET statement before the constrained optimum is found (even at commencement or while optimizing neglecting constraints). Once the constrained optimum has been reached, or during stage 2 optimization, use the **SAVE** statement to produce observations in a **CONOUT=** data set. See the section “**ARCOUT= and CONOUT= Data Sets**” on page 395 for more information.

**DUALOUT=SAS-data-set****DOUT=SAS-data-set**

names the output data set that contains the dual solution obtained after doing optimization that considers side constraints reaches the optimal solution. You can specify a DUALOUT= data set in any RESET statement before the constrained optimum is found (even at commencement or while optimizing neglecting constraints). Once the constrained optimum has been reached, or during stage 2 optimization, use the **SAVE** statement to produce observations in a DUALOUT= data set. See the section “**NODEOUT= and DUALOUT= Data Sets**” on page 397 for more information.

**NODEOUT=SAS-data-set****NOUT=SAS-data-set**

names the output data set that receives all information about nodes (supply/demand and nodal dual variable values) and other information concerning the unconstrained optimal solution.

You can specify a NODEOUT= data set in any RESET statement before the unconstrained optimum is found (even at commencement). Once the unconstrained optimum has been reached, or during stage 1 optimization, use the **SAVE** statement to produce observations in a NODEOUT= data set. Once optimization that considers constraints starts, you will not be able to obtain a NODEOUT= data set. Instead use a DUALOUT= data set to get the current solution. See the section “**NODEOUT= and DUALOUT= Data Sets**” on page 397 for more information.

## Options to Halt Optimization

The following options indicate conditions when optimization is to be halted. You then have a chance to use PROC NETFLOW interactively. If the NETFLOW procedure is optimizing and you want optimization to halt immediately, press the CTRL-BREAK key combination used to stop SAS procedures. Doing this is equivalent to PROC NETFLOW finding that some prespecified condition of the current solution under which optimization should stop has occurred.

If optimization does halt, you may need to change the conditions for when optimization should stop again. For example, if the number of iterations exceeded **MAXIT2**, use the RESET statement to specify a larger value for the **MAXIT2=** option before the next **RUN** statement. Otherwise, PROC NETFLOW will immediately find that the number of iterations still exceeds **MAXIT2** and halt without doing any additional optimization.

**ENDPAUSE1**

indicates that PROC NETFLOW will pause after the unconstrained optimal solution has been obtained and information about this solution has been output to the current **ARCOUT=** data set, **NODEOUT=** data set, or both. The procedure then executes the next statement, or waits if no subsequent statement has been specified.

**FEASIBLEPAUSE1****FP1**

indicates that unconstrained optimization should stop once a feasible solution is reached. PROC NETFLOW checks for feasibility every 10 iterations. A solution is feasible if there are no artificial arcs having nonzero flow assigned to be conveyed through them. The presence of artificial arcs with nonzero flows means that the current solution does not satisfy all the nodal flow conservation constraints implicit in network problems.

**MAXIT1=*m***

specifies the maximum number of primal simplex iterations PROC NETFLOW is to perform in stage 1. The default value for the MAXIT1= option is 1000. If MAXIT1=*m* iterations are performed and you want to continue unconstrained optimization, reset MAXIT1= to a number larger than the number of iterations already performed and issue another **RUN** statement.

**NOENDPAUSE1****NOEP1**

negates the **ENDPAUSE1** option.

**NOFEASIBLEPAUSE1****NOFP1**

negates the **FEASIBLEPAUSE1** option.

**PAUSE1=*p***

indicates that PROC NETFLOW will halt unconstrained optimization and pause when the remainder of the number of stage 1 iterations divided by the value of the PAUSE1= option is zero. If present, the next statement is executed; if not, the procedure waits for the next statement to be specified. The default value for PAUSE1= is 999999.

**FEASIBLEPAUSE2****FP2****NOFEASIBLEPAUSE2****NOFP2****PAUSE2=*p*****MAXIT2=*m***

are the stage 2 constrained optimization counterparts of the options described previously and having as a suffix the numeral 1.

## Options Controlling the Network Simplex Optimization

**BIGM1****NOTWOPHASE1****TWOPHASE1****NOBIGM1**

BIGM1 indicates that the “big-M” approach to optimization is used. Artificial variables are treated like real arcs, slacks, surpluses and nonarc variables. Artificial variables have very expensive costs. BIGM1 is the default.

TWOPHASE1 indicates that the two-phase approach is used instead of the big-M approach. At first, artificial variables are the only variables to have nonzero objective function coefficients. An artificial variable’s objective function coefficient is temporarily set to 1 and PROC NETFLOW minimizes. When all artificial variables have zero value, PROC NETFLOW has found a feasible solution, and phase 2 commences. Arcs and nonarc variables have their real costs and objective function coefficients.

Before all artificial variables are driven to have zero value, you can toggle between the big-M and the two-phase approaches by specifying BIGM1 or TWOPHASE1 in a RESET statement. The option NOTWOPHASE1 is synonymous with BIGM1, and NOBIGM1 is synonymous with TWOPHASE1.

**CYCLEMULT1=c****MINBLOCK1=m****NOPERTURB1****PERTURB1**

In an effort to reduce the number of iterations performed when the problem is highly degenerate, PROC NETFLOW has in stage 1 optimization adopted an algorithm outlined in Ryan and Osborne (1988).

If the number of consecutive degenerate pivots (those with no progress toward the optimum) performed equals the value of the CYCLEMULT1= option times the number of nodes, the arcs that were “blocking” (can leave the basis) are added to a list. In subsequent iterations, of the arcs that now can leave the basis, the one chosen to leave is an arc on the list of arcs that could have left in the previous iteration. In other words, preference is given to arcs that “block” many iterations. After several iterations, the list is cleared.

If the number of blocking arcs is less than the value of the MINBLOCK1= option, a list is not kept. Otherwise, if PERTURB1 is specified, the arc flows are perturbed by a random quantity, so that arcs on the list that block subsequent iterations are chosen to leave the basis randomly. Although perturbation often pays off, it is computationally expensive. Periodically, PROC NETFLOW has to clear out the lists and un-perturb the solution. You can specify NOPERTURB1 to prevent perturbation.

Defaults are CYCLEMULT1=0.15, MINBLOCK1=2, and NOPERTURB1.

**LRATIO1**

specifies the type of ratio test to use in determining which arc leaves the basis in stage 1. In some iterations, more than one arc is eligible to leave the basis. Of those arcs that can leave the basis, the leaving arc is the first encountered by the algorithm if the LRATIO1 option is specified. Specifying the LRATIO1 option can decrease the chance of cycling but can increase solution times. The alternative to the LRATIO1 option is the [NOLRATIO1](#) option, which is the default.

**LRATIO2**

specifies the type of ratio test to use in determining what leaves the basis in stage 2. In some iterations, more than one arc, constraint slack, surplus, or nonarc variable is eligible to leave the basis. If the LRATIO2 option is specified, the leaving arc, constraint slack, surplus, or nonarc variable is the one that is eligible to leave the basis first encountered by the algorithm. Specifying the LRATIO2 option can decrease the chance of cycling but can increase solution times. The alternative to the LRATIO2 option is the [NOLRATIO2](#) option, which is the default.

**NOLRATIO1**

specifies the type of ratio test to use in determining which arc leaves the basis in stage 1. If the NOLRATIO1 option is specified, of those arcs that can leave the basis, the leaving arc has the minimum (maximum) cost if the leaving arc is to be nonbasic with flow capacity equal to its capacity (lower flow bound). If more than one possible leaving arc has the minimum (maximum) cost, the first such arc encountered is chosen. Specifying the NOLRATIO1 option can decrease solution times, but can increase the chance of cycling. The alternative to the NOLRATIO1 option is the [LRATIO1](#) option. The NOLRATIO1 option is the default.

**NOLRATIO2**

specifies the type of ratio test to use in determining which arc leaves the basis in stage 2. If the NOLRATIO2 option is specified, the leaving arc, constraint slack, surplus, or nonarc variable is the one eligible to leave the basis with the minimum (maximum) cost or objective function coefficient if

the leaving arc, constraint slack or nonarc variable is to be nonbasic with flow or value equal to its capacity or upper value bound (lower flow or value bound), respectively. If several possible leaving arcs, constraint slacks, surpluses, or nonarc variables have the minimum (maximum) cost or objective function coefficient, then the first encountered is chosen. Specifying the NOLRATIO2 option can decrease solution times, but can increase the chance of cycling. The alternative to the NOLRATIO2 option is the LRATIO2 option. The NOLRATIO2 option is the default.

## Options Applicable to Constrained Optimization

The INVREQ= option is relevant only if INVD\_2D is specified in the PROC NETFLOW statement; that is, the inverse of the working basis matrix is being stored and processed as a two-dimensional array. The REFACTREQ=, U=, MAXLUUPDATES=, and MAXL= options are relevant if the INVD\_2D option is not specified in the PROC NETFLOW statement; that is, if the working basis matrix is LU factored.

### BIGM2

### NOTWOPHASE2

### TWOPHASE2

### NOBIGM2

are the stage 2 constrained optimization counterparts of the options BIGM1, NOTWOPHASE1, TWOPHASE1, and NOBIGM1.

The TWOPHASE2 option is often better than the BIGM2 option when the problem has many side constraints.

### INVREQ=*n*

recalculates the working basis matrix inverse whenever *n* iterations have been performed where *n* is the value of the INVREQ= option. Although a relatively expensive task, it is prudent to do as roundoff errors accumulate, especially affecting the elements of this matrix inverse. The default is INVREQ=50. The INVREQ= option should be used only if the INVD\_2D option is specified in the PROC NETFLOW statement.

### INTFIRST

In some iterations, it is found that what must leave the basis is an arc that is part of the spanning tree representation of the network part of the basis (called a *key* arc). It is necessary to interchange another basic arc not part of the tree (called a *nonkey* arc) with the tree arc that leaves to permit the basis update to be performed efficiently. Specifying the INTFIRST option indicates that of the nonkey arcs eligible to be swapped with the leaving key arc, the one chosen to do so is the first encountered by the algorithm. If the INTFIRST option is not specified, all such arcs are examined and the one with the best cost is chosen.

The terms *key* and *nonkey* are used because the algorithm used by PROC NETFLOW for network optimization considering side constraints (GUB-based, Primal Partitioning, or Factorization) is a variant of an algorithm originally developed to solve linear programming problems with generalized upper bounding constraints. The terms *key* and *nonkey* were coined then. The STATUS SAS variable in the ARCOUT= and CONOUT= data sets and the STATUS column in tables produced when PRINT statements are processed indicate whether basic arcs are key or nonkey. Basic nonarc variables are always nonkey.



**MAXL=*m***

If the working basis matrix is **LU** factored, **U** is an upper triangular matrix and **L** is a lower triangular matrix corresponding to a sequence of elementary matrix row operations required to change the working basis matrix into **U**. **L** and **U** enable substitution techniques to be used to solve the linear systems of the simplex algorithm. Among other things, the **LU** processing strives to keep the number of **L** elementary matrix row operation matrices small. A buildup in the number of these could indicate that fill-in is becoming excessive and the computations involving **L** and **U** will be hampered. Refactorization should be performed to restore **U** sparsity and reduce **L** information. When the number of **L** matrix row operations exceeds the value of the **MAXL=** option, a refactorization is done rather than one or more updates. The default value for **MAXL=** is 10 times the number of side constraints. The **MAXL=** option should not be used if **INVD\_2D** is specified in the **PROC NETFLOW** statement.

**MAXLUUPDATES=*m*****MLUU=*m***

In some iterations, **PROC NETFLOW** must either perform a series of single column updates or a complete refactorization of the working basis matrix. More than one column of the working basis matrix must change before the next simplex iteration can begin. The single column updates can often be done faster than a complete refactorization, especially if few updates are necessary, the working basis matrix is sparse, or a refactorization has been performed recently. If the number of columns that must change is less than the value specified in the **MAXLUUPDATES=** option, the updates are attempted; otherwise, a refactorization is done. Refactorization also occurs if the sum of the number of columns that must be changed and the number of **LU** updates done since the last refactorization exceeds the value of the **REFACTFREQ=** option. The **MAXLUUPDATES=** option should not be used if the **INVD\_2D** option is specified in the **PROC NETFLOW** statement.

In some iterations, a series of single column updates are not able to complete the changes required for a working basis matrix because, ideally, all columns should change at once. If the update cannot be completed, **PROC NETFLOW** performs a refactorization. The default value is 5.

**NOINTFIRST**

indicates that of the arcs eligible to be swapped with the leaving arc, the one chosen to do so has the best cost. See the **INTFIRST** option.

**REFACTFREQ=*r*****RFF=*r***

specifies the maximum number of **L** and **U** updates between refactorization of the working basis matrix to reinitialize **LU** factors. In most iterations, one or several Bartels-Golub updates can be performed. An update is performed more quickly than a complete refactorization. However, after a series of updates, the sparsity of the **U** factor is degraded. A refactorization is necessary to regain sparsity and to make subsequent computations and updates more efficient. The default value is 50. The **REFACTFREQ=** option should not be used if **INVD\_2D** is specified in the **PROC NETFLOW** statement.

**U=*u***

controls the choice of pivot during **LU** decomposition or Bartels-Golub update. When searching for a pivot, any element less than the value of the **U=** option times the largest element in its matrix row is excluded, or matrix rows are interchanged to improve numerical stability. The **U=** option should have values on or between **ZERO2** and 1.0. Decreasing the value of the **U=** option biases the algorithm toward maintaining sparsity at the expense of numerical stability and vice-versa. Reid (1975) suggests



that the value of 0.01 is acceptable and this is the default for the U= option. This option should not be used if `INVD_2D` is specified in the `PROC NETFLOW` statement.

## Pricing Strategy Options

There are three main types of pricing strategies:

- `PRICETYPEx=NOQ`
- `PRICETYPEx=BLAND`
- `PRICETYPEx=Q`

The one that usually performs better than the others is `PRICETYPEx=Q`, so this is the default.

Because the pricing strategy takes a lot of computational time, you should experiment with the following options to find the optimum specification. These options influence how the pricing step of the simplex iteration is performed. See the section “[Pricing Strategies](#)” on page 400 for further information.

`PRICETYPEx=BLAND` or `PTYPEx=BLAND`

`PRICETYPEx=NOQ` or `PTYPEx=NOQ`

- `PxSCAN=BEST`
- `PxSCAN=FIRST`
- `PxSCAN=PARTIAL` and `PxNPARTIAL=p`

`PRICETYPEx=Q` or `PTYPEx=Q`

`QSIZEx=q` or `Qx=q`

`REFRESHQx=r`

`REDUCEQSIZEx=r`

`REDUCEQx=r`

- `PxSCAN=BEST`
- `PxSCAN=FIRST`
- `PxSCAN=PARTIAL` and `PxNPARTIAL=p`
- `QxFILLSCAN=BEST`
- `QxFILLSCAN=FIRST`
- `QxFILLSCAN=PARTIAL` and `QxFILLNPARTIAL=q`

For stage 2 optimization, you can specify `P2SCAN=ANY`, which is used in conjunction with the `DUAL-FREQ=` option.

## Miscellaneous Options

### FUTURE1

signals that PROC NETFLOW must output extra observations to the **NODEOUT=** and **ARCOUT=** data sets. These observations contain information about the solution found by doing optimization neglecting any side constraints. These two data sets then can be used as the **NODEDATA=** and **ARCDATA=** data sets, respectively, in subsequent PROC NETFLOW runs with the **WARM** option specified. See the section “Warm Starts” on page 413.

### FUTURE2

signals that PROC NETFLOW must output extra observations to the **DUALOUT=** and **CONOUT=** data sets. These observations contain information about the solution found by optimization that considers side constraints. These two data sets can then be used as the **NODEDATA=** data set (also called the **DUALIN=** data set) and the **ARCDATA=** data sets, respectively, in subsequent PROC NETFLOW runs with the **WARM** option specified. See the section “Warm Starts” on page 413.

### MOREOPT

The MOREOPT option turns off all optimality and infeasibility flags that may have been raised. Unless this is done, PROC NETFLOW will not do any optimization when a **RUN** statement is specified.

If PROC NETFLOW determines that the problem is infeasible, it will not do any more optimization unless you specify MOREOPT in a RESET statement. At the same time, you can try resetting options (particularly zero tolerances) in the hope that the infeasibility was raised incorrectly.

Consider the following example:

```
proc netflow
  nodedata=noded      /* supply and demand data */
  arcdata=arcd1       /* the arc descriptions   */
  conddata=cond1      /* the side constraints  */
  conout=solution;    /* output the solution   */
run;
/* Netflow states that the problem is infeasible. */
/* You suspect that the zero tolerance is too large */
reset zero2=1.0e-10 moreopt;
run;
/* Netflow will attempt more optimization. */
/* After this, if it reports that the problem is */
/* infeasible, the problem really might be infeasible */
```

If PROC NETFLOW finds an optimal solution, you might want to do additional optimization to confirm that an optimum has really been reached. Specify the MOREOPT option in a RESET statement. Reset options, but in this case tighten zero tolerances.

### NOFUTURE1

negates the **FUTURE1** option.

### NOFUTURE2

negates the **FUTURE2** option.

**NOSCRATCH**

negates the [SCRATCH](#) option.

**NOZTOL1**

indicates that the majority of tests for roundoff error should not be done. Specifying the NOZTOL1 option and obtaining the same optimal solution as when the NOZTOL1 option is not specified in the [PROC NETFLOW](#) statement (or the [ZTOL1](#) option is specified), verifies that the zero tolerances were not too high. Roundoff error checks that are critical to the successful functioning of PROC NETFLOW and any related readjustments are always done.

**NOZTOL2**

indicates that the majority of tests for roundoff error are not to be done during an optimization that considers side constraints. The reasons for specifying the NOZTOL2 option are the same as those for specifying the [NOZTOL1](#) option for stage 1 optimization (see the [NOZTOL1](#) option).

**OPTIM\_TIMER**

indicates that the procedure is to issue a message to the SAS log giving the CPU time spent doing optimization. This includes the time spent preprocessing, performing optimization, and postprocessing. Not counted in that time is the rest of the procedure execution, which includes reading the data and creating output SAS data sets.

The time spent optimizing can be small compared to the total CPU time used by the procedure. This is especially true when the problem is quite small (e.g., fewer than 10,000 variables).

**SCRATCH**

specifies that you do not want PROC NETFLOW to enter or continue stage 1 of the algorithm. Rather than specify RESET SCRATCH, you can use the [CONOPT](#) statement.

**VERBOSE=*v***

limits the number of similar messages that are displayed on the SAS log.

For example, when reading the [ARCDATA=](#) data set, PROC NETFLOW might have caused to issue the following message many times:

```
ERROR: The HEAD list variable value in obs i in ARCDATA is
       missing and the TAIL list variable value of this obs
       is nonmissing. This is an incomplete arc specification.
```

If there are many observations that have this fault, messages that are similar are issued for only the first VERBOSE= such observations. After the [ARCDATA=](#) data set has been read, PROC NETFLOW will issue the message

```
NOTE: More messages similar to the ones immediately above
      could have been issued but were suppressed as
      VERBOSE=v.
```

If observations in the [ARCDATA=](#) data set have this error, PROC NETFLOW stops and you have to fix the data. Imagine that this error is only a warning and PROC NETFLOW proceeded to other operations such as reading the [CONDATA=](#) data set. If PROC NETFLOW finds there are numerous errors when reading that data set, the number of messages issued to the SAS log are also limited by the VERBOSE= option.

If you have a problem with a large number of side constraints and for some reason you stop stage 2 optimization early, PROC NETFLOW indicates that constraints are violated by the current solution. Specifying `VERBOSE=v` allows at most *v* violated constraints to be written to the log. If there are more, these are not displayed.

When PROC NETFLOW finishes and messages have been suppressed, the message

**NOTE:** To see all messages, specify `VERBOSE=vmin`.

is issued. The value of *vmin* is the smallest value that should be specified for the `VERBOSE=` option so that *all* messages are displayed if PROC NETFLOW is run again with the same data and everything else (except the `VERBOSE=` option) unchanged. No messages are suppressed.

The default value for the `VERBOSE=` option is 12.

### **ZERO1=z**

#### **Z1=z**

specifies the zero tolerance level in stage 1. If the `NOZTOL1` option is not specified, values within *z* of zero are set to 0.0, where *z* is the value of the `ZERO1=` option. Flows close to the lower flow bound or capacity of arcs are reassigned those exact values. Two values are deemed to be close if one is within *z* of the other. The default value for the `ZERO1=` option is 0.000001. Any value specified for the `ZERO1=` option that is  $< 0.0$  or  $> 0.0001$  is invalid.

### **ZERO2=z**

#### **Z2=z**

specifies the zero tolerance level in stage 2. If the `NOZTOL2` option is not specified, values within *z* of zero are set to 0.0, where *z* is the value of the `ZERO2=` option. Flows close to the lower flow bound or capacity of arcs are reassigned those exact values. If there are nonarc variables, values close to the lower or upper value bound of nonarc variables are reassigned those exact values. Two values are deemed to be close if one is within *z* of the other. The default value for the `ZERO2=` option is 0.000001. Any value specified for the `ZERO2=` option that is  $< 0.0$  or  $> 0.0001$  is invalid.

### **ZEROTOL=z**

specifies the zero tolerance used when PROC NETFLOW must compare any real number with another real number, or zero. For example, if *x* and *y* are real numbers, then for *x* to be considered greater than *y*, *x* must be at least  $y + z$ . The `ZEROTOL=` option is used throughout any PROC NETFLOW run.

`ZEROTOL=z` controls the way PROC NETFLOW performs all double precision comparisons; that is, whether a double precision number is equal to, not equal to, greater than (or equal to), or less than (or equal to) zero or some other double precision number. A double precision number is deemed to be the same as another such value if the absolute difference between them is less than or equal to the value of the `ZEROTOL=` option.

The default value for the `ZEROTOL=` option is  $1.0E-14$ . You can specify the `ZEROTOL=` option in the `NETFLOW` or `RESET` statement. Valid values for the `ZEROTOL=` option must be  $> 0.0$  and  $< 0.0001$ . Do not specify a value too close to zero as this defeats the purpose of the `ZEROTOL=` option. Neither should the value be too large, as comparisons might be incorrectly performed.

The `ZEROTOL=` option is different from the `ZERO1=` and `ZERO2=` options in that `ZERO1=` and `ZERO2=` options work when determining whether optimality has been reached, whether an entry in the updated column in the ratio test of the simplex method is zero, whether a flow is the same as the arc's

capacity or lower bound, or whether the value of a nonarc variable is at a bound. The ZEROTOL= option is used in all other general double precision number comparisons.

#### ZTOL1

indicates that all tests for roundoff error are performed during stage 1 optimization. Any alterations are carried out. The opposite of the ZTOL1 option is the NOZTOL1 option.

#### ZTOL2

indicates that all tests for roundoff error are performed during stage 2 optimization. Any alterations are carried out. The opposite of the ZTOL2 option is the NOZTOL2 option.

### Interior Point Algorithm Options

#### FACT\_METHOD=*f*

enables you to choose the type of algorithm used to factorize and solve the main linear systems at each iteration of the interior point algorithm.

FACT\_METHOD=LEFT\_LOOKING is new for SAS 9.1.2. It uses algorithms described in George, Liu, and Ng (2001). Left looking is one of the main methods used to perform Cholesky optimization and, along with some recently developed implementation approaches, can be faster and require less memory than other algorithms.

Specify FACT\_METHOD=USE\_OLD if you want the procedure to use the only factorization available prior to SAS 9.1.2.

#### TOLDINF=*t*

#### RTOLDINF=*t*

specifies the allowed amount of dual infeasibility. In the section “Interior Point Algorithmic Details” on page 436, the vector *infeas<sub>d</sub>* is defined. If all elements of this vector are  $\leq t$ , the solution is deemed feasible. *infeas<sub>d</sub>* is replaced by a zero vector, making computations faster. This option is the dual equivalent to the TOLPINF= option. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

#### TOLPINF=*t*

#### RTOLPINF=*t*

specifies the allowed amount of primal infeasibility. This option is the primal equivalent to the TOLDINF= option. In the section “Interior Point: Upper Bounds” on page 443, the vector *infeas<sub>b</sub>* is defined. In the section “Interior Point Algorithmic Details” on page 436, the vector *infeas<sub>c</sub>* is defined. If all elements in these vectors are  $\leq t$ , the solution is deemed feasible. *infeas<sub>b</sub>* and *infeas<sub>c</sub>* are replaced by zero vectors, making computations faster. Increasing the value of the TOLPINF= option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

#### TOLTOTDINF=*t*

#### RTOLTOTDINF=*t*

specifies the allowed total amount of dual infeasibility. In the section “Interior Point Algorithmic Details” on page 436, the vector *infeas<sub>d</sub>* is defined. If  $\sum_{i=1}^n \text{infeas}_{di} \leq t$ , the solution is deemed feasible. *infeas<sub>d</sub>* is replaced by a zero vector, making computations faster. This option is the dual equivalent to the TOLTOTPINF= option. Valid values for *t* are greater than 1.0E–12. The default is 1.0E–7.

**TOLTOTPINF=*t*****RTOLTOTPINF=*t***

specifies the allowed total amount of primal infeasibility. This option is the primal equivalent to the **TOLTOTDINF=** option. In the section “Interior Point: Upper Bounds” on page 443, the vector  $infeas_b$  is defined. In the section “Interior Point Algorithmic Details” on page 436, the vector  $infeas_c$  is defined. If  $\sum_{i=1}^n infeas_{bi} \leq t$  and  $\sum_{i=1}^m infeas_{ci} \leq t$ , the solution is deemed feasible.  $infeas_b$  and  $infeas_c$  are replaced by zero vectors, making computations faster. Increasing the value of the **TOLTOTPINF=** option too much can lead to instability, but a modest increase can give the algorithm added flexibility and decrease the iteration count. Valid values for  $t$  are greater than  $1.0E-12$ . The default is  $1.0E-7$ .

**CHOLTINYTOL=*c*****RCHOLTINYTOL=*c***

specifies the cut-off tolerance for Cholesky factorization of the  $A\Theta A^{-1}$ . If a diagonal value drops below  $c$ , the row is essentially treated as dependent and is ignored in the factorization. Valid values for  $c$  are between  $1.0E-30$  and  $1.0E-6$ . The default value is  $1.0E-8$ .

**DENSETHR=*d*****RDENSETHR=*d***

specifies the density threshold for Cholesky processing. When the **symbolic factorization** encounters a column of  $L$  that has **DENSETHR=** proportion of nonzeros and the remaining part of  $L$  is at least  $12 \times 12$ , the remainder of  $L$  is treated as dense. In practice, the lower right part of the Cholesky triangular factor  $L$  is quite dense and it can be computationally more efficient to treat it as 100% dense. The default value for  $d$  is 0.7. A specification of  $d \leq 0.0$  causes all dense processing;  $d \geq 1.0$  causes all sparse processing.

**PDSTEPMULT=*p*****RPDSTEPMULT=*p***

specifies the step-length multiplier. The maximum feasible step-length chosen by the Primal-Dual with Predictor-Corrector algorithm is multiplied by the value of the **PDSTEPMULT=** option. This number must be less than 1 to avoid moving beyond the barrier. An actual step length greater than 1 indicates numerical difficulties. Valid values for  $p$  are between 0.01 and 0.999999. The default value is 0.99995.

In the section “Interior Point Algorithmic Details” on page 436, the solution of the next iteration is obtained by moving along a **direction** from the current iteration’s solution:

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

where  $\alpha$  is the maximum feasible step-length chosen by the interior point algorithm. If  $\alpha \leq 1$ , then  $\alpha$  is reduced slightly by multiplying it by  $p$ .  $\alpha$  is a value as large as possible but  $\leq 1.0$  and not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  of some variable  $i$  is “too close” to zero.

**PRSLTYPE=*p*****IPRSLTYPE=*p***

Preprocessing the linear programming problem often succeeds in allowing some variables and constraints to be temporarily eliminated from the LP that must be solved. This reduces the solution time and possibly also the chance that the optimizer will run into numerical difficulties. The task of preprocessing is inexpensive to do.

You control how much preprocessing to do by specifying **PRSLTYPE=*p***, where  $p$  can be  $-1, 0, 1, 2$ , or  $3$ .

- 1 Do not perform preprocessing. For most problems, specifying PRSLTYPE=–1 is *not* recommended.
- 0 Given upper and lower bounds on each variable, the greatest and least contribution to the row activity of each variable is computed. If these are within the limits set by the upper and lower bounds on the row activity, then the row is redundant and can be discarded. Try to tighten the bounds on any of the variables it can. For example, if all coefficients in a constraint are positive and all variables have zero lower bounds, then the row's smallest contribution is zero. If the rhs value of this constraint is zero, then if the constraint type is = or  $\leq$ , all the variables in that constraint can be fixed to zero. These variables and the constraint can be removed. If the constraint type is  $\geq$ , the constraint is redundant. If the rhs is negative and the constraint is  $\leq$ , the problem is infeasible. If just one variable in a row is not fixed, use the row to impose an implicit upper or lower bound on the variable and then eliminate the row. The preprocessor also tries to tighten the bounds on constraint right-hand sides.
- 1 When there are exactly two unfixed variables with coefficients in an equality constraint, solve for one in terms of the other. The problem will have one less variable. The new matrix will have at least two fewer coefficients and one less constraint. In other constraints where both variables appear, two coefs are combined into one. PRSLTYPE=0 reductions are also done.
- 2 It may be possible to determine that an equality constraint is not constraining a variable. That is, if all variables are nonnegative, then  $x - \sum_i y_i = 0$  does not constrain  $x$ , since it must be nonnegative if all the  $y_i$ 's are nonnegative. In this case, eliminate  $x$  by subtracting this equation from all others containing  $x$ . This is useful when the only other entry for  $x$  is in the objective function. Perform this reduction if there is at most one other nonobjective coefficient. PRSLTYPE=0 reductions are also done.
- 3 All possible reductions are performed. PRSLTYPE=3 is the default.

Preprocessing is iterative. As variables are fixed and eliminated, and constraints are found to be redundant and they too are eliminated, and as variable bounds and constraint right-hand sides are tightened, the LP to be optimized is modified to reflect these changes. Another iteration of preprocessing of the modified LP may reveal more variables and constraints that can be eliminated.

#### PRINTLEVEL2=*p*

is used when you want to see PROC NETFLOW's progress to the optimum. PROC NETFLOW will produce a table on the SAS log. A row of the table is generated during each iteration and may consist of values of

- the [affine step](#) complementarity
- the [complementarity](#) of the solution for the next iteration
- the total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the [infeas<sub>b</sub>](#) array in the section “[Interior Point: Upper Bounds](#)” on page 443)
- the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the [infeas<sub>c</sub>](#) array in the section “[Interior Point Algorithmic Details](#)” on page 436)



- the total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the  $\text{infeas}_d$  array in the section “Interior Point Algorithmic Details” on page 436)

As optimization progresses, the values in all columns should converge to zero. If you specify PRINTLEVEL2=2, all columns will appear in the table. If PRINTLEVEL2=1 is specified, only the [affine step complementarity](#) and the [complementarity](#) of the solution for the next iteration will appear. Some time is saved by not calculating the infeasibility values.

## Interior Point Algorithm Options: Stopping Criteria

**MAXITERB=*m***

**IMAXITERB=*m***

specifies the maximum number of iterations of the interior point algorithm that can be performed. The default value for *m* is 100. One of the most remarkable aspects of the interior point algorithm is that for most problems, it usually needs to do a small number of iterations, *no matter the size of the problem*.

**PDGAPTOL=*p***

**RPDGAPTOL=*p***

specifies the primal-dual gap or [duality gap](#) tolerance. [Duality gap](#) is defined in the section “Interior Point Algorithmic Details” on page 436. If the relative gap ( $\text{duality gap} / (c^T x)$ ) between the primal and dual objectives is smaller than the value of the PDGAPTOL= option and both the primal and dual problems are feasible, then PROC NETFLOW stops optimization with a solution that is deemed optimal. Valid values for *p* are between 1.0E–12 and 1.0E–1. The default is 1.0E–7.

**STOP\_C=*s***

is used to determine whether optimization should stop. At the beginning of each iteration, if [complementarity](#) (the value of the Complem-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**STOP\_DG=*s***

is used to determine whether optimization should stop. At the beginning of each iteration, if the [duality gap](#) (the value of the Duality\_gap column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**STOP\_IB=*s***

is used to determine whether optimization should stop. At the beginning of each iteration, if total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the  $\text{infeas}_b$  array in the section “Interior Point: Upper Bounds” on page 443; this value appears in the Tot\_infeasb column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**STOP\_IC=*s***

is used to determine whether optimization should stop. At the beginning of each iteration, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the  $\text{infeas}_c$  array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasc column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.



**STOP\_ID=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasd column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_STOP\_C=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if complementarity (the value of the Complem-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_STOP\_DG=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if the duality gap (the value of the Duality\_gap column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_STOP\_IB=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 443; this value appears in the Tot\_infeasb column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $\leq s$ , and the conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_STOP\_IC=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasc column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , and the conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_STOP\_ID=s**

is used to determine whether optimization should stop. At the beginning of each iteration, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasd column in the table produced when you specify PRINTLEVEL2=2) is  $\leq s$ , and the conditions related to other AND\_STOP parameters are also satisfied, optimization will stop. This option is discussed in the section “Stopping Criteria” on page 440.

**KEEPPGOING\_C=s**

is used to determine whether optimization should stop. If a stopping condition is met, if complementarity (the value of the Complem-ity column in the table produced when you specify PRINTLEVEL2=1 or PRINTLEVEL2=2) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**KEEPPGOING\_DG=s**

is used to determine whether optimization should stop. If a stopping condition is met, if the **duality gap** (the value of the Duality\_gap column in the table produced when you specify **PRINTLEVEL2=1** or **PRINTLEVEL2=2**) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**KEEPPGOING\_IB=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total bound infeasibility  $\sum_{i=1}^n infeas_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 443; this value appears in the Tot\_infeasb column in the table produced when you specify **PRINTLEVEL2=1** or **PRINTLEVEL2=2**) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**KEEPPGOING\_IC=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total constraint infeasibility  $\sum_{i=1}^m infeas_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasc column in the table produced when you specify **PRINTLEVEL2=2**) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**KEEPPGOING\_ID=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total dual infeasibility  $\sum_{i=1}^n infeas_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeasd column in the table produced when you specify **PRINTLEVEL2=2**) is  $> s$ , optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_KEEPPGOING\_C=s**

is used to determine whether optimization should stop. If a stopping condition is met, if **complementarity** (the value of the Complem-ity column in the table produced when you specify **PRINTLEVEL2=1** or **PRINTLEVEL2=2**) is  $> s$ , *and* the conditions related to other **AND\_KEEPPGOING** parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_KEEPPGOING\_DG=s**

is used to determine whether optimization should stop. If a stopping condition is met, if the **duality gap** (the value of the Duality\_gap column in the table produced when you specify **PRINTLEVEL2=1** or **PRINTLEVEL2=2**) is  $> s$ , *and* the conditions related to other **AND\_KEEPPGOING** parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_KEEPPGOING\_IB=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total bound infeasibility  $\sum_{i=1}^n infeas_{bi}$  (see the *infeas<sub>b</sub>* array in the section “Interior Point: Upper Bounds” on page 443; this value appears in the Tot\_infeasb column in the table produced when you specify **PRINTLEVEL2=2**) is  $> s$ , *and* the conditions related to other **AND\_KEEPPGOING** parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_KEEPPGOING\_IC=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the *infeas<sub>c</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeas<sub>c</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , and the conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

**AND\_KEEPPGOING\_ID=s**

is used to determine whether optimization should stop. If a stopping condition is met, if total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the *infeas<sub>d</sub>* array in the section “Interior Point Algorithmic Details” on page 436; this value appears in the Tot\_infeas<sub>d</sub> column in the table produced when you specify PRINTLEVEL2=2) is  $> s$ , and the conditions related to other AND\_KEEPPGOING parameters are also satisfied, optimization will continue. This option is discussed in the section “Stopping Criteria” on page 440.

---

## RHS Statement

**RHS variable ;**

The RHS variable list is used when the *dense* format of the CONDATA= data set is used. The values of the SAS variable specified in the RHS list are constraint right-hand-side values. If the RHS list is not specified, the CONDATA= data set is searched and a SAS variable with the name \_RHS\_ is used. If there is no RHS list and no SAS variable named \_RHS\_, all constraints are assumed to have zero right-hand-side values. The RHS list variable must have numeric values.

---

## ROW Statement

**ROW variables ;**

The ROW list is used when either the *sparse* or the *dense* format of side constraints is being used. SAS variables in the ROW list have values that are constraint or special row names. The SAS variables in the ROW list must have character values.

If the *dense* data format is used, there must be only one SAS variable in this list. In this case, if a ROW list is not specified, the CONDATA= data set is searched and the SAS variable with the name \_ROW\_ or \_CON\_ is used.

If the *sparse* data format is used and the ROW statement is not specified, the CONDATA= data set is searched and SAS variables with names beginning with \_ROW\_ or \_CON\_ are used. The number of SAS variables in the ROW list must not be less than the number of SAS variables in the COEF list. The *i*th ROW list variable is paired with the *i*th COEF list variable. If the number of ROW list variables is greater than the number of COEF list variables, the last ROW list variables have no COEF partner. These ROW list variables that have no corresponding COEF list variable are used in observations that have a TYPE list variable value. All ROW list variable values are tagged as having the type indicated. If there is no TYPE list variable, all ROW list variable values are constraint names.

---

## RUN Statement

**RUN ;**

The RUN statement causes optimization to be started or resumed. The RUN statement has no options. If PROC NETFLOW is called and is not terminated because of an error or a **QUIT** statement, and you have not used a RUN statement, a RUN statement is assumed implicitly as the last statement of PROC NETFLOW. Therefore, PROC NETFLOW always performs optimization and saves the obtained (optimal) solution in the current output data sets.

---

## SAVE Statement

**SAVE options ;**

The options available with the SAVE statement of PROC NETFLOW are summarized by purpose in the following table.

**Table 7.5** Functional Summary, SAVE Statement

| Description                            | Statement | Option   |
|--|-----------|----------|
| <b>Output Data Set Options:</b>        |           |          |
| Unconstrained primal solution data set | SAVE      | ARCOUT=  |
| Unconstrained dual solution data set   | SAVE      | NODEOUT= |
| Constrained primal solution data set   | SAVE      | CONOUT=  |
| Constrained dual solution data set     | SAVE      | DUALOUT= |

The SAVE statement can be used to specify output data sets and create observations in these data sets. Use the SAVE statement if no optimization is to be performed before these output data sets are created.

The SAVE statement must be used to save solutions in data sets if there is no more optimization to do. If more optimization is to be performed, after which you want to save the solution, then do one of the following:

- Submit a **RUN** statement followed by a SAVE statement.
- Use the PROC NETFLOW or **RESET** statement to specify current output data sets. After optimization, output data sets are created and observations are automatically sent to the current output data sets.

Consider the following example:

```
proc netflow options; lists;
  reset maxit1=10 maxit2=25
    arcout=arcout0    nodeout=nodeout0
    conout=conout0    dualout=dualout0;
run;
/* Stage 1 optimization stops after iteration 10. */
```

```

/* No output data sets are created yet.          */
save arcout=arcout1 nodeout=nodeout1;
/* arcout1 and nodeout1 are created.            */
reset arcout=arcout2 maxit1=999999;
run;
/* The stage 1 optimum is reached.              */
/* Arcout2 and nodeout0 are created.            */
/* Arcout0 is not created as arcout=arcout2 over- */
/* rides the arcout=arcout0 specified earlier.   */
/* Stage 2 optimization stops after 25 iterations */
/* as MAXIT2=25 was specified.                  */
save conout=conout1;
/* Conout1 is created.                          */
reset maxit2=999999 dualout=null;
run;
/* The stage 2 optimum is reached.              */
/* Conout0 is created.                          */
/* No dualout is created as the last NETFLOW or  */
/* reset statements dualout=data set specification*/
/* was dualout=null.                           */

```

The data sets specified in the PROC NETFLOW and [RESET](#) statements are created when an optimal solution is found. The data sets specified in SAVE statements are created immediately.

The data sets in the preceding example are all distinct, but this need not be the case. The only exception to this is that the [ARCOU=](#) data set and the [NODEOUT=](#) data set (or the [CONOUT=](#) data set and the [DUALOUT=](#) data set) that are being created at the same time must be distinct. Use the [SHOW DATASETS](#) statement to examine what data sets are current and when they were created.

The following options can appear in the SAVE statement:

**ARCOU=SAS-data-set** (or **AOUT=SAS-data-set**)

**NODEOUT=SAS-data-set** (or **NOUT=SAS-data-set**)

**CONOUT=SAS-data-set** (or **COUT=SAS-data-set**)

**DUALOUT=SAS-data-set** (or **DOUT=SAS-data-set**)

## SHOW Statement

**SHOW** *options / qualifiers* ;

The options available with the SHOW statement of PROC NETFLOW are summarized by purpose in the following table.

**Table 7.6** Functional Summary, SHOW Statement

| Description                                      | Statement | Option     |
|--|-----------|------------|
| <b>SHOW Statement Options:</b>                   |           |            |
| Show problem, optimization status                | SHOW      | STATUS     |
| Show network model parameters                    | SHOW      | NETSTMT    |
| Show data sets that have been or will be created | SHOW      | DATASETS   |
| Show options that pause optimization             | SHOW      | PAUSE      |
| Show simplex algorithm options                   | SHOW      | SIMPLEX    |
| Show pricing strategy options                    | SHOW      | PRICING    |
| Show miscellaneous options                       | SHOW      | MISC       |
| <b>SHOW Statement Qualifiers:</b>                |           |            |
| Display information only on relevant options     | SHOW      | / RELEVANT |
| Display options for current stage only           | SHOW      | / STAGE    |

The SHOW statement enables you to examine the status of the problem and values of the **RESET** statement options. All output of the SHOW statement appears on the SAS log. The amount of information displayed when a SHOW statement is processed can be limited if some of the options of the SHOW statement are specified. These options indicate whether the problem status or a specific category of the **RESET** options is of interest. If no options are specified, the problem status and information on all **RESET** statement options in every category is displayed. The amount of displayed information can be limited further by following any SHOW statement options with a slash (/) and one or both qualifiers, RELEVANT and STAGE.

### STATUS

produces one of the following optimization status reports, whichever is applicable. The warning messages are issued only if the network or entire problem is infeasible.

```
NOTE: Optimization Status.
      Optimization has not started yet.
```

```
NOTE: Optimization Status.
      Optimizing network (ignoring any side constraints).
      Number of iterations=17
      Of these, 3 were degenerate
```

```
WARNING: This optimization has detected that the network is
         infeasible.
```

```
NOTE: Optimization Status.
      Found network optimum (ignoring side constraints)
```

Number of iterations=23  
Of these, 8 were degenerate

NOTE: Optimization Status.  
Optimizing side constrained network.  
Number of iterations=27  
Of these, 9 were degenerate

WARNING: This optimization has detected that the problem is  
infeasible.

NOTE: Optimization Status.  
Found side constrained network optimum  
Number of iterations=6  
Of these, 0 were degenerate

## DATASETS

produces a report on output data sets.

NOTE: Current output SAS data sets  
No output data sets have been specified

NOTE: Current output SAS data sets  
ARCOUT=libname.memname  
NODEOUT=libname.memname  
CONOUT=libname.memname  
DUALOUT=libname.memname

NOTE: Other SAS data sets specified in previous ARCOUT=, NODEOUT=,  
CONOUT=, or DUALOUT=.  
libname.memname  
.  
.  
.

NOTE: Current output SAS data sets (SHOW DATASETS)  
libname.memname  
.  
.  
.

NOTE: SAS data sets specified as ARCOUT= NODEOUT= CONOUT= or  
DUALOUT= data sets in previous PROC NETFLOW, SET, RESET  
and SAVE statements.

The number following the data set specification was the  
iteration number when observations were placed into the  
data set.

| libname.memname | iteration_number |
|-----------------|------------------|
| .               | .                |
| .               | .                |
| .               | .                |

**PAUSE**

produces a report on the current settings of options used to make optimization pause.

NOTE: Options and parameters that stop optimization for reasons other than infeasibility or optimality (SHOW PAUSE)

```
FEASIBLEPAUSE1=FALSE
ENDPAUSE1=FALSE
PAUSE1=999999
MAXIT1=1000
FEASIBLEPAUSE2=FALSE
PAUSE2=999999
MAXIT2=999999
```

**SIMPLEX**

produces the following:

NOTE: Options and parameters that control the primal simplex network algorithm (excluding those that affect the pricing strategies) (SHOW SIMPLEX)

```
LRATIO1=FALSE
BIGM1=NOTWOPHASE1=TRUE, TWOPHASE1=NOBIGM1=FALSE
CYCLEMULT1=0.15
PERTURB1=FALSE
MINBLOCK1=2
INTFIRST=TRUE
LRATIO2=FALSE
BIGM2=NOTWOPHASE2=TRUE, TWOPHASE2=NOBIGM2=FALSE
REFACTFREQ=50
U=0.1
MAXLUUPDATES=6
MAXL=40
```

**PRICING**

produces the following:

NOTE: Options and parameters that control the primal simplex network algorithm pricing strategies (SHOW PRICING)

```
PRICETYPE1=Q
P1SCAN=FIRST
P1NPARTIAL=10
Q1FILLSCAN=FIRST
QSIZE1=24
REFRESHQ1=0.75
REDUCEQSIZE1=1
Q1FILLNPARTIAL=10
PRICETYPE2=Q
P2SCAN=FIRST
P2NPARTIAL=10
DUALFREQ=4
Q2FILLSCAN=FIRST
QSIZE2=24
REFRESHQ2=0.75
```



```
REDUCEQSIZE2=1
Q2FILLNPARTIAL=10
```

## MISC

produces the following:

```
NOTE: Miscellaneous options and parameters (SHOW MISC)
VERBOSE=12
ZTOL1=TRUE
ZERO1=1E-6
FUTURE1=FALSE
ZTOL2=TRUE
ZERO2=1E-6
FUTURE2=FALSE
```

Following a slash (/), the qualifiers below can appear in any SHOW statement.

## RELEVANT

indicates that you want information only on relevant options of the **RESET** statement. The following will *not* be displayed if / RELEVANT is specified:

- information on noncurrent data sets
- the options that control the reasons why stage 1 optimization should be halted and the options that control the simplex algorithm during stage 1 optimization, if the unconstrained optimum has been reached or constrained optimization has been performed
- if **P1SCAN=BEST** or **P1SCAN=FIRST**, the **P1NPARTIAL=** option is irrelevant
- if **PRICETYPE1=BLAND** or **PRICETYPE1=NOQ**, the options **QSIZE1=**, **Q1FILLSCAN=**, **REFRESHQ1=**, and **REDUCEQSIZE1=** are irrelevant
- if **Q1FILLSCAN=BEST** or **Q1FILLSCAN=FIRST**, the **Q1FILLNPARTIAL=** option is irrelevant
- the options that control the reasons stage 2 optimization should be halted, the options that control the simplex algorithm during stage 2 optimization, if the constrained optimum has been reached
- if **P2SCAN=BEST** or **P2SCAN=FIRST**, the **P2NPARTIAL=** option is irrelevant
- if **PRICETYPE2=BLAND** or **PRICETYPE2=NOQ**, the options **QSIZE2=**, **Q2FILLSCAN=**, **REFRESHQ2=**, and **REDUCEQSIZE2=** are irrelevant
- if **Q2FILLSCAN=BEST** or **Q2FILLSCAN=FIRST**, the **Q2FILLNPARTIAL=** option is irrelevant

## STAGE

indicates that you want to examine only the options that affect the optimization that is performed if a **RUN** statement is executed next. Before any optimization has been done, only stage 2 options are displayed if the problem has side constraints and the **SCRATCH** option is used, or if the **CONOPT** statement is specified. Otherwise, stage 1 options are displayed. If still optimizing neglecting constraints, only stage 1 options will be displayed. If the unconstrained optimum has been reached and optimization that considers constraints has not been performed, stage 1 options are displayed. If the problem has constraints, stage 2 options are displayed. If any optimization that considers constraints has been performed, only stage 2 options are displayed.

---

## SUPDEM Statement

**SUPDEM** *variable* ;

The SAS variable in this list, which must be present in the **NODEDATA=** data set, contains supply and demand information for the nodes in the **NODE** list. A positive SUPDEM list variable value  $s$  ( $s > 0$ ) denotes that the node named in the **NODE** list variable can supply  $s$  units of flow. A negative SUPDEM list variable value  $-d$  ( $d > 0$ ) means that this node demands  $d$  units of flow. If a SAS variable is not explicitly specified, a SAS variable with the name **\_SUPDEM\_** or **\_SD\_** in the **NODEDATA=** data set is used as the SUPDEM variable. If a node is a transshipment node (neither a supply nor a demand node), an observation associated with this node need not be present in the **NODEDATA=** data set. If present, the SUPDEM list variable value must be zero or a missing value.

---

## SUPPLY Statement

**SUPPLY** *variable* ;

The SUPPLY statement identifies the SAS variable in the **ARCDATA=** data set that contains the supply at the node named in that observation's **TAILNODE** list variable. If a tail node does not supply flow, use zero or a missing value for the observation's SUPPLY list variable value. If a tail node has supply capability, a missing value indicates that the supply quantity is given in another observation. It is not necessary to have a SUPPLY statement if the name of this SAS variable is **\_SUPPLY\_**.

---

## TAILNODE Statement

**TAILNODE** *variable* ;

**TAIL** *variable* ;

**FROMNODE** *variable* ;

**FROM** *variable* ;

The TAILNODE statement specifies the SAS variable that must be present in the **ARCDATA=** data set that has as values the names of tail nodes of arcs. The TAILNODE variable must have character values. It is not necessary to have a TAILNODE statement if the name of the SAS variable is **\_TAIL\_** or **\_FROM\_**. If the TAILNODE list variable value is missing, it is assumed that the observation of **ARCDATA=** data set contains information concerning a nonarc variable.

---

## TYPE Statement

**TYPE** *variable* ;

**CONTYPE** *variable* ;

The TYPE list, which is optional, names the variable that has as values keywords that indicate either the constraint type for each constraint or the type of special rows in the **CONDATA=** data set. The values of

the TYPE list variable also indicate, in each observation of the **CONDATA=** data set, how values of the **VAR** or **COEF** list variables are to be interpreted and how the type of each constraint or special row name is determined. If the TYPE list is not specified, the **CONDATA=** data set is searched and a SAS variable with the name **\_TYPE\_** is used. Valid keywords for the TYPE variable are given below. If there is no TYPE statement and no other method is used to furnish type information (see the **DEFCONTYPE=** option), all constraints are assumed to be of the type “less than or equal to” and no special rows are used. The TYPE list variable must have character values and can be used when the data in the **CONDATA=** data set is in either the **sparse** or the **dense** format. If the TYPE list variable value has a \* as its first character, the observation is ignored because it is a comment observation.

### TYPE List Variable Values

The following are valid TYPE list variable values. The letters in boldface denote the characters that PROC NETFLOW uses to determine what type the value suggests. You need to have at least these characters. In the following list, the minimal TYPE list variable values have additional characters to aid you in remembering these values.

|                  |  |
|------------------|--|
| <                | less than or equal to ( $\leq$ )   |
| =                | equal to (=)   |
| >                | greater than or equal to ( $\geq$ )  |
| <b>CAPAC</b>     | capacity   |
| <b>COST</b>      | cost   |
| <b>EQ</b>        | equal to   |
| <b>FREE</b>      | free row (used only for linear programs solved by interior point)              |
| <b>GAIN</b>      | gain in arc flow (generalized networks)  |
| <b>GE</b>        | greater than or equal to   |
| <b>LE</b>        | less than or equal to  |
| <b>LOSS</b>      | loss in arc flow (generalized networks)  |
| <b>LOWERBD</b>   | lower flow or value bound  |
| <b>LOWblank</b>  | lower flow or value bound  |
| <b>MAXIMIZE</b>  | maximize (opposite of cost)  |
| <b>MINIMIZE</b>  | minimize (same as cost)  |
| <b>MULT</b>      | value of arc multiplier (generalized networks)                                 |
| <b>OBJECTIVE</b> | objective function (same as cost)  |
| <b>RHS</b>       | rhs of constraint  |
| <b>TYPE</b>      | type of constraint   |
| <b>UPPCOST</b>   | reserved for future use  |
| <b>UNREST</b>    | unrestricted variable (used only for linear programs solved by interior point) |
| <b>UPPER</b>     | upper value bound or capacity; second letter must not be N                     |

The valid TYPE list variable values in function order are

- **LE** less than or equal to ( $\leq$ )
- **EQ** equal to (=)
- **GE** greater than or equal to ( $\geq$ )

- **COST**  
**MINIMIZE**  
**MAXIMIZE**  
**OBJECTIVE**  
cost or objective function coefficient
- **CAPAC**  
**UPPER**  
capacity or upper value bound
- **LOWERBD**  
**LOWblank**  
lower flow or value bound
- **RHS** rhs of constraint
- **TYPE** type of constraint
- **MULT**  
**GAIN**  
**LOSS**  
value of arc multiplier in a generalized network

A TYPE list variable value that has the first character \* causes the observation to be treated as a comment. If the first character is a negative sign, then  $\leq$  is the type. If the first character is a zero, then  $=$  is the type. If the first character is a positive number, then  $\geq$  is the type.

---

## VAR Statement

**VAR** *variables* ;

The VAR variable list is used when the **dense** data format is used. The names of these SAS variables are also names of the arc and nonarc variables that have data in the **CONDATA=** data set. If no explicit VAR list is specified, all numeric variables not on other lists are put onto the VAR list. The VAR list variables must have numeric values. The values of the VAR list variables in some observations can be interpreted differently than in other observations. The values can be coefficients in the side constraints, costs and objective function coefficients, or bound data. How these numeric values are interpreted depends on the value of each observation's **TYPE** or **ROW** list variable value. If there are no **TYPE** list variables, the VAR list variable values are all assumed to be side constraint coefficients.

## Details: NETFLOW Procedure

### Input Data Sets

PROC NETFLOW is designed so that there are as few rules as possible that you must obey when inputting a problem's data. Raw data are acceptable. This should cut the amount of processing required to groom the data before it is input to PROC NETFLOW. Data formats are so flexible that, due to space restrictions, all possible forms for a problem's data are not shown here. Try any reasonable form for your problem's data; it should be acceptable. PROC NETFLOW will outline its objections.

There are several ways to supply the same piece of data. You do not have to restrict yourself to using any particular one. If you use several ways, PROC NETFLOW checks that the data are consistent each time the data are encountered. After all input data sets have been read, data are merged so that the problem is described completely. The order of the observations is not important in any of the input data sets.

### ARC DATA= Data Set

See the section “[Getting Started: NETFLOW Procedure](#)” on page 320 and the section “[Introductory Example](#)” on page 321 for a description of this input data set.

**NOTE:** Information for an arc or nonarc variable can be specified in more than one observation. For example, consider an arc directed from node A toward node B that has a cost of 50, capacity of 100, and lower flow bound of 10 flow units. Some possible observations in the `ARC DATA=` data set may be

| <code>_TAIL_</code> | <code>_HEAD_</code> | <code>_COST_</code> | <code>_CAPAC_</code> | <code>_LO_</code> |
|---------------------|---------------------|---------------------|----------------------|-------------------|
| A                   | B                   | 50                  | .                    | .                 |
| A                   | B                   | .                   | 100                  | .                 |
| A                   | B                   | .                   | .                    | 10                |
| A                   | B                   | 50                  | 100                  | .                 |
| A                   | B                   | .                   | 100                  | 10                |
| A                   | B                   | 50                  | .                    | 10                |
| A                   | B                   | 50                  | 100                  | 10                |

Similarly, for a nonarc variable with `upperbd=100`, `lowerbd=10`, and objective function coefficient=50, the `_TAIL_` and `_HEAD_` values are missing.

### CON DATA= Data Set

Regardless of whether the data in the `CON DATA=` data set is in the `sparse` or `dense` format, you will receive a warning if PROC NETFLOW finds a constraint row that has no coefficients. You will also be warned if any nonarc variable has no constraint coefficients.

#### Dense Input Format

If the dense format is used, most SAS variables in the `CON DATA=` data set belong to the `VAR` list and have names of arc and nonarc variables. These names can be values of the `NAME` list SAS variables in the `ARC DATA=` data set, or names of nonarc variables, or names in the form `tail_head`, or any combination of these three forms. Names in the form `tail_head` are default arc names, and if you use them, you must specify

node names in the `ARCDATA=` data set (values of the `TAILNODE` and `HEADNODE` list SAS variables) using no lowercase letters.

There can be three other variables in the `CONDATA=` data set, belonging, respectively, to the `ROW`, `TYPE`, and `RHS` lists. the section “[Introductory Example](#)” on page 321 uses the dense data format.

Consider the SAS code that creates a dense format `CONDATA=` data set that has data for three constraints. This data set was used in the section “[Introductory Example](#)” on page 321.

```
data cond1;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
-2 . 1 . . . >= -15
. -2 . . 1 . GE -15
. . -3 4 . . EQ 0
. . . . -3 4 = 0
;
```

You can use nonconstraint type values to furnish data on costs, capacities, lower flow bounds (and, if there are nonarc variables, objective function coefficients and upper and lower bounds). You need not have such (or as much) data in the `ARCDATA=` data set. The first three observations in the following data set are examples of observations that provide cost, capacity and lower bound data.

```
data cond1b;
  input m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
63 81 200 . 220 . cost .
95 80 175 140 100 100 capac .
20 10 50 . 35 . lo .
-2 . 1 . . . >= -15
. -2 . . 1 . GE -15
. . -3 4 . . EQ 0
. . . . -3 4 = 0
;
```

If a `ROW` list variable is used, the data for a constraint can be spread over more than one observation. To illustrate, the data for the first constraint, (which is called `con1`), and the cost and capacity data (in special rows called `costrow` and `caprow`, respectively) are spread over more than one observation in the following data set.

```
data cond1c;
  input _row_ $
        m_e_ref1 m_e_ref2 thrupt1 r1_gas thrupt2 r2_gas
        _type_ $ _rhs_;
  datalines;
costrow 63 . . . . .
costrow . 81 200 . . . cost .
. . . . 220 . cost .
caprow . . . . . capac .
caprow 95 . 175 . 100 100 .
caprow . 80 175 140 . . .
lorow 20 10 50 . 35 . lo .
```

```

con1    -2    .    1    .    .    .    .
con1    .    .    .    .    .    .    . >= -15
con2    . -2    .    .    1    .    . GE -15
con3    .    . -3    4    .    .    . EQ  0
con4    .    .    .    . -3    4    . =  0
;

```

Using both **ROW** and **TYPE** lists, you can use special row names. Examples of these are “costrow” and “caprow” in the last data set. It should be restated that in any of the input data sets of PROC NETFLOW, the order of the observations does not matter. However, the **CONDATA=** data set can be read more quickly if PROC NETFLOW knows what type of constraint or special row a **ROW** list variable value is. For example, when the first observation is read, PROC NETFLOW does not know whether costrow is a constraint or special row and how to interpret the value 63 for the arc with the name m\_e\_ref1. When PROC NETFLOW reads the second observation, it learns that costrow has type cost and that the values 81 and 200 are costs. When the entire **CONDATA=** data set has been read, PROC NETFLOW knows the type of all special rows and constraints. Data that PROC NETFLOW had to set aside (such as the first observation 63 value and the costrow **ROW** list variable value, which at the time had unknown type, but is then known to be a cost special row) is reprocessed. During this second pass, if a **ROW** list variable value has unassigned constraint or special row type, it is treated as a constraint with **DEFCONTYPE=** (or **DEFCONTYPE=** default) type. Associated **VAR** list variable values as coefficients of that constraint.

### Sparse Input Format

The side constraints usually become sparse as the problem size increases. When the sparse data format of the **CONDATA=** data set is used, only nonzero constraint coefficients must be specified. Remember to specify the **SPARSECONDATA** option in the **PROC NETFLOW** statement. With the sparse method of specifying constraint information, the names of arc and nonarc variables do not have to be valid SAS variable names.

A sparse format **CONDATA=** data set for the oil industry example in the section “**Introductory Example**” on page 321 is displayed in the following code.

```

title 'Setting Up Condata = Cond2 for PROC NETFLOW';
data cond2;
    input _column_ $ _row1 $ _coef1 _row2 $ _coef2 ;
    datalines;
m_e_ref1  con1  -2    .    .
m_e_ref2  con2  -2    .    .
thruput1  con1   1  con3  -3
r1_gas    .    .  con3   4
thruput2  con2   1  con4  -3
r2_gas    .    .  con4   4
_type_    con1   1  con2   1
_type_    con3   0  con4   0
_rhs_     con1 -15  con2 -15
;

```

Recall that the **COLUMN** list variable values “\_type\_” and “\_rhs\_” are the default values of the **TYPEOBS=** and **RHSOBS=** options. Also, the default rhs value of constraints (con3 and con4) is zero. The third to last observation has the value “\_type\_” for the **COLUMN** list variable. The **\_ROW1** variable value is con1, and the **\_COEF1\_** variable has the value 1. This indicates that the constraint con1 is *greater than* or equal to type (because the value 1 is *greater than* zero). Similarly, the data in the second to last observation’s **\_ROW2** and **\_COEF2** variables indicate that con2 is an *equality* constraint (0 *equals* zero).

An alternative, using a **TYPE** list variable is as follows:

```

title 'Setting Up Condata = Cond3 for PROC NETFLOW';
data cond3;
    input _column_ $ _row1 $ _coef1 _row2 $ _coef2 _type_ $ ;
    datalines;
m_e_ref1  con1  -2      .      .  >=
m_e_ref2  con2  -2      .      .  .
thruput1  con1   1  con3  -3  .
r1_gas    .      .  con3   4  .
thruput2  con2   1  con4  -3  .
r2_gas    .      .  con4   4  .
.          con3   .  con4   .  eq
.          con1 -15  con2 -15  ge
;

```

If the **COLUMN** list variable is missing in a particular observation (the last two observations in the data set cond3, for instance), the constraints named in the **ROW** list variables all have the constraint type indicated by the value in the **TYPE** list variable. It is for this type of observation that you are allowed more **ROW** list variables than **COEF** list variables. If corresponding **COEF** list variables are not missing (for example, the last observation in the data set cond3), these values are the rhs values of those constraints. Therefore, you can specify both constraint type and rhs in the same observation.

As in the previous CONDATA= data set, if the **COLUMN** list variable is an arc or nonarc variable, the **COEF** list variable values are coefficient values for that arc or nonarc variable in the constraints indicated in the corresponding **ROW** list variables. If in this same observation, the **TYPE** list variable contains a constraint type, all constraints named in the **ROW** list variables in that observation have this constraint type (for example, the first observation in the data set cond3). Therefore, you can specify both constraint type and coefficient information in the same observation.

Also note that DEFCONTYPE=EQ could have been specified, saving you from having to include in the data that CON3 and CON4 are of this type.

In the oil industry example, arc costs, capacities, and lower flow bounds are presented in the **ARCDATA=** data set. Alternatively, you could have used the following input data sets.

```

title3 'Setting Up Arcdata = Arcd2 for PROC NETFLOW';
data arcd2;
    input __from_&$11. __to_&$15. ;
    datalines;
middle east  refinery 1
middle east  refinery 2
u.s.a.       refinery 1
u.s.a.       refinery 2
refinery 1   r1
refinery 2   r2
r1           ref1 gas
r1           ref1 diesel
r2           ref2 gas
r2           ref2 diesel
ref1 gas     servstn1 gas
ref1 gas     servstn2 gas
ref1 diesel  servstn1 diesel
ref1 diesel  servstn2 diesel

```



```

ref2 gas      servstn1 gas
ref2 gas      servstn2 gas
ref2 diesel   servstn1 diesel
ref2 diesel   servstn2 diesel
;
title 'Setting Up Condata = Cond4 for PROC NETFLOW';
data cond4;
    input _column_&$27. _row1 $ _coef1 _row2 $ _coef2 _type_ $ ;
    datalines;
.                con1 -15    con2 -15    ge
.                costrow .      .      cost
.                .      . caprow .      capac
middle east_refinery 1    con1 -2      .      .
middle east_refinery 2    con2 -2      .      .
refinery 1_r1            con1 1      con3 -3      .
r1_ref1 gas              .      .      con3 4      =
refinery 2_r2            con2 1      con4 -3      .
r2_ref2 gas              .      .      con4 4      eq
middle east_refinery 1    costrow 63 caprow 95      .
middle east_refinery 2    costrow 81 caprow 80      .
u.s.a._refinery 1        costrow 55      .      .
u.s.a._refinery 2        costrow 49      .      .
refinery 1_r1            costrow 200 caprow 175      .
refinery 2_r2            costrow 220 caprow 100      .
r1_ref1 gas              .      .      caprow 140      .
r1_ref1 diesel           .      .      caprow 75      .
r2_ref2 gas              .      .      caprow 100      .
r2_ref2 diesel           .      .      caprow 75      .
ref1 gas_servstn1 gas     costrow 15 caprow 70      .
ref1 gas_servstn2 gas     costrow 22 caprow 60      .
ref1 diesel_servstn1 diesel costrow 18      .      .
ref1 diesel_servstn2 diesel costrow 17      .      .
ref2 gas_servstn1 gas     costrow 17 caprow 35      .
ref2 gas_servstn2 gas     costrow 31      .      .
ref2 diesel_servstn1 diesel costrow 36      .      .
ref2 diesel_servstn2 diesel costrow 23      .      .
middle east_refinery 1    .      20      .      .      lo
middle east_refinery 2    .      10      .      .      lo
refinery 1_r1            .      50      .      .      lo
refinery 2_r2            .      35      .      .      lo
ref2 gas_servstn1 gas     .      5      .      .      lo
;

```

The first observation in the cond4 data set defines con1 and con2 as *greater than or equal to* ( $\geq$ ) constraints that both (by coincidence) have rhs values of -15. The second observation defines the special row costrow as a cost row. When costrow is a **ROW** list variable value, the associated **COEF** list variable value is interpreted as a cost or objective function coefficient. PROC NETFLOW has to do less work if constraint names and special rows are defined in observations near the top of a data set, but this is not a strict requirement. The fourth to ninth observations contain constraint coefficient data. Observations 7 and 9 have **TYPE** list variable values that indicate that constraints con3 and con4 are equality constraints. The last five observations contain lower flow bound data. Observations that have an arc or nonarc variable name in the **COLUMN** list variable, a nonconstraint type **TYPE** list variable value, and a value in (one of) the **COEF** list variables are valid.

The following data set is equivalent to the cond4 data set.

```

title 'Setting Up Condata = Cond5 for PROC NETFLOW';
data cond5;
  input _column_&$27. _row1 $ _coef1 _row2 $ _coef2 _type_ $ ;
  datalines;
middle east_refinery 1          con1  -2 costrow  63      .
middle east_refinery 2          con2  -2  lorow   10      .
refinery 1_r1                   .      .   con3   -3      =
r1_ref1 gas                     caprow 140   con3    4      .
refinery 2_r2                   con2    1   con4   -3      .
r2_ref2 gas                     .      .   con4    4      eq
.                                CON1 -15   CON2 -15      GE
ref2 diesel_servstn1 diesel     .    36 costrow .   cost
.                                .      .   caprow .   capac
.                                lorow .      .      lo
middle east_refinery 1          caprow 95   lorow  20      .
middle east_refinery 2          caprow 80 costrow 81      .
u.s.a._refinery 1               .      .      .   55      cost
u.s.a._refinery 2               costrow 49   .      .      .
refinery 1_r1                   con1    1   caprow 175      .
refinery 1_r1                   lorow  50 costrow 200      .
refinery 2_r2                   costrow 220 caprow 100      .
refinery 2_r2                   .    35      .      .      lo
r1_ref1 diesel                 caprow2 75      .      .   capac
r2_ref2 gas                     .      .   caprow 100      .
r2_ref2 diesel                 caprow2 75      .      .      .
ref1 gas_servstn1 gas           costrow 15   caprow  70      .
ref1 gas_servstn2 gas           caprow2 60 costrow 22      .
ref1 diesel_servstn1 diesel     .      .   costrow 18      .
ref1 diesel_servstn2 diesel     costrow 17      .      .      .
ref2 gas_servstn1 gas           costrow 17   lorow   5      .
ref2 gas_servstn1 gas           .      .   caprow2 35      .
ref2 gas_servstn2 gas           .    31      .      .   cost
ref2 diesel_servstn2 diesel     .      .   costrow 23      .
;

```

If you have data for a linear programming program that has an embedded network, the steps required to change that data into a form that is acceptable by PROC NETFLOW are

1. Identify the nodal flow conservation constraints. The coefficient matrix of these constraints (a submatrix of the LP's constraint coefficient matrix) has only two nonzero elements in each column, -1 and 1.
2. Assign a node to each nodal flow conservation constraint.
3. The rhs values of conservation constraints are the corresponding node's supplies and demands. Use this information to create a **NODEDATA=** data set.
4. Assign an arc to each column of the flow conservation constraint coefficient matrix. The arc is directed from the node associated with the row that has the 1 element in it and directed toward to the node associated with the row that has the -1 element in it. Set up an **ARCDATA=** data set that has two SAS variables. This data set could resemble **ARCDATA=arcd2**. These will eventually be the **TAILNODE** and **HEADNODE** list variables when PROC NETFLOW is used. Each observation consists of the tail and head node of each arc.

5. Remove from the data of the linear program all data concerning the nodal flow conservation constraints.
6. Put the remaining data into a CONDATA= data set. This data set will probably resemble CONDATA=cond4 or CONDATA=cond5.

### The Sparse Format Summary

The following list illustrates possible CONDATA= data set observation sparse formats. a1, b1, b2, b3 and c1 have as a `_COLUMN_` variable value either the name of an arc (possibly in the form *tail\_head*) or the name of a nonarc variable.

- If there is no `TYPE` list variable in the CONDATA= data set, the problem must be constrained and there is no nonconstraint data in the CONDATA= data set.

|    | <code>_COLUMN_</code>                          | <code>_ROWx_</code> | <code>_COEFx_</code> | <code>_ROWy_</code><br>(no <code>_COEFy_</code> )<br>(may not be<br>in CONDATA) |
|----|--|---------------------|----------------------|---|
| a1 | variable                                       | constraint          | lhs coef             | +-----+   |
| a2 | <code>_TYPE_</code> or<br>TYPEOBS=             | constraint          | -1 0 1               |   |
| a3 | <code>_RHS_</code> or<br>RHSOBS= or<br>missing | constraint          | rhs value            | constraint  |
|    |  |                     |                      | or  |
|    |  |                     |                      | missing   |
| a4 | <code>_TYPE_</code> or<br>TYPEOBS=             | constraint          | missing              |   |
| a5 | <code>_RHS_</code> or<br>RHSOBS= or<br>missing | constraint          | missing              |   |
|    |  |                     |                      | +-----+   |

Observations of the form a4 and a5 serve no useful purpose but are still allowed to make problem generation easier.

- If there are no `ROW` list variables in the data set, the problem has no constraints and the information is nonconstraint data. There must be a `TYPE` list variable and only one `COEF` list variable in this case. The `COLUMN` list variable has as values the names of arcs or nonarc variables and must not have missing values or special row names as values.

|    | <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_COEFx_</code> |
|----|-----------------------|---------------------|----------------------|
| b1 | variable              | UPPERBD             | capacity             |
| b2 | variable              | LOWERBD             | lower flow           |
| b3 | variable              | COST                | cost                 |

- Using a `TYPE` list variable for constraint data implies the following:

|    | <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_ROWx_</code> | <code>_COEFx_</code> | <code>_ROWy_</code><br>(no <code>_COEFy_</code> )<br>(may not be<br>in CONDATA) |
|----|-----------------------|---------------------|---------------------|----------------------|---|
| c1 | variable              | missing             | +-----+             | lhs coef             | +-----+   |

|    |                                   |          |                     |           |            |  |                   |
|----|-----------------------------------|----------|---------------------|-----------|------------|--|-------------------|
| c2 | _TYPE_ or<br>TYPEOBS=             | missing  | c                   | -1 0 1    |            |  |                   |
| c3 | _RHS_ or<br>missing<br>or RHSOBS= | missing  | n  <br>  s  <br>  t | rhs value | constraint |  | <br>or<br>missing |
| c4 | variable                          | con type | r                   | lhs coef  |            |  |                   |
| c5 | _RHS_ or<br>missing<br>or RHSOBS= | con type | a  <br>  i  <br>  n | rhs value |            |  |                   |
| c6 | missing                           | TYPE     | t                   | -1 0 1    |            |  |                   |
| c7 | missing                           | RHS      | +-----+             | rhs value | +-----+    |  |                   |

If the observation is of the form c4 or c5, and the `_COEFx_` values are missing, the constraint is assigned the type data specified in the `_TYPE_` variable.

- Using a `TYPE` list variable for arc and nonarc variable data implies the following:

| <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_ROWx_</code> | <code>_COEFx_</code> | <code>_ROWy_</code><br>(no <code>_COEFy_</code> )<br>(may not be<br>in CONDATA) |
|-----------------------|---------------------|---------------------|----------------------|---|
| d1                    | variable            | UPPERBD             | missing              | capacity  |
| d2                    | variable            | LOWERBD             | or                   | lowerflow   |
| d3                    | variable            | COST                | special              | cost  |
|                       |                     |                     | row                  | row   |
|                       |                     |                     | name                 | name  |
| d4                    | missing             |                     | special              |   |
|                       |                     |                     | row                  |   |
|                       |                     |                     | name                 |   |
| d5                    | variable            | missing             |                      | value that  |
|                       |                     |                     |                      | is interpreted  |
|                       |                     |                     |                      | according to  |
|                       |                     |                     |                      | <code>_ROWx_</code>   |

Observations with form d1 to d5 can have `ROW` list variable values. Observation d4 must have `ROW` list variable values. The `ROW` value is put into the `ROW` name tree so that when dealing with observation d4 or d5, the `COEF` list variable value is interpreted according to the type of `ROW` list variable value. For example, the following three observations define the `_ROWx_` variable values `up_row`, `lo_row` and `co_row` as being an upper value bound row, lower value bound row, and cost row, respectively.

| <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_ROWx_</code> | <code>_COEFx_</code> |
|-----------------------|---------------------|---------------------|----------------------|
| .                     | UPPERBD             | up_row              | .                    |
| variable_a            | LOWERBD             | lo_row              | lower flow           |
| variable_b            | COST                | co_row              | cost                 |

PROC NETFLOW is now able to correctly interpret the following observation:

| <code>_COLUMN_</code> | <code>_TYPE_</code> | <code>_ROW1_</code> | <code>_COEF1_</code> | <code>_ROW2_</code> | <code>_COEF2_</code> | <code>_ROW3_</code> | <code>_COEF3_</code> |
|-----------------------|---------------------|---------------------|----------------------|---------------------|----------------------|---------------------|----------------------|
| var_c                 | .                   | up_row              | upval                | lo_row              | loval                | co_row              | cost                 |

If the `TYPE` list variable value is a constraint type and the value of the `COLUMN` list variable equals the value of the `TYPEOBS=` option or the default value `_TYPE_`, the `TYPE` list variable value is ignored.

## NODEDATA= Data Set

See the section “Getting Started: NETFLOW Procedure” on page 320 and the section “Introductory Example” on page 321 for a description of this input data set.

---

## Output Data Sets

The procedure determines the flow that should pass through each arc as well as the value assigned to each nonarc variable. The goal is that the minimum flow bounds, capacities, lower and upper value bounds, and side constraints are not violated. This goal is reached when total cost incurred by such a flow pattern and value assignment is feasible and optimal. The solution found must also conserve flow at each node.

The `ARCOUT=` data set contains a solution obtained when performing optimization that does not consider any constraints. The `NODEOUT=` data set contains nodal dual variable information for this type of solution. You can choose to have PROC NETFLOW create the `ARCOUT=` data set and the `NODEOUT=` data set and save the optimum of the network or the nodal dual variable values before any optimization that considers the side constraints is performed.

If there are side constraints, the `CONOUT=` data set can be produced and contains a solution obtained after performing optimization that considers constraints. The `DUALOUT=` data set contains dual variable information for nodes and side constraints from the solution obtained after optimization that considers the constraints. The `CONOUT=` data set and `DUALOUT=` data set can be used to save the constrained optimal solution.

## ARCOUT= and CONOUT= Data Sets

The `ARCOUT=` and `CONOUT=` data sets contain the same variables. Furthermore, the variables in the output data sets depend on whether or not the problem has a network component.

If the problem has a network component, the variables and their possible values in an observation are as follows:

|                       |   |
|-----------------------|---|
| <code>_FROM_</code>   | a tail node of an arc. This is a missing value if an observation has information about a nonarc variable.                                     |
| <code>_TO_</code>     | a head node of an arc. This is a missing value if an observation has information about a nonarc variable.                                     |
| <code>_COST_</code>   | the cost of an arc or the objective function coefficient of a nonarc variable   |
| <code>_CAPAC_</code>  | the capacity of an arc or upper value bound of a nonarc variable  |
| <code>_LO_</code>     | the lower flow bound of an arc or lower value bound of a nonarc variable  |
| <code>_NAME_</code>   | a name of an arc or nonarc variable   |
| <code>_SUPPLY_</code> | the supply of the tail node of the arc in the observation. This is a missing value if an observation has information about a nonarc variable. |
| <code>_DEMAND_</code> | the demand of the head node of the arc in the observation. This is a missing value if an observation has information about a nonarc variable. |
| <code>_FLOW_</code>   | the flow through the arc or value of the nonarc variable  |
| <code>_FCOST_</code>  | flow cost, the product of <code>_COST_</code> and <code>_FLOW_</code>   |
| <code>_RCOST_</code>  | the reduced cost of the arc or nonarc variable  |
| <code>_ANUMB_</code>  | the number of the arc (positive) or nonarc variable (nonpositive); used for warm starting PROC NETFLOW  |
| <code>_TNUMB_</code>  | the number of the tail node in the network basis spanning tree; used for warm starting PROC NETFLOW   |
| <code>_STATUS_</code> | the status of the arc or nonarc variable  |

If the problem does not have a network component, the variables and their possible values in an observation are as follows:

|                       |  |
|-----------------------|--|
| <code>_OBJFN_</code>  | the objective function coefficient of a variable   |
| <code>_UPPERBD</code> | the upper value bound of a variable  |
| <code>_LOWERBD</code> | the lower value bound of a variable  |
| <code>_NAME_</code>   | the name of a variable   |
| <code>_VALUE_</code>  | the value of the variable  |
| <code>_FCOST_</code>  | objective function value for that variable; the product of <code>_OBJFN_</code> and <code>_VALUE_</code> |

The variables present in the `ARC DATA=` data set are present in an `ARC OUT=` data set or a `CON OUT=` data set. For example, if there is a variable called `tail` in the `ARC DATA=` data set and you specified the SAS variable list

```
from tail;
```

then `tail` is a variable in the `ARC OUT=` and `CON OUT=` data sets instead of `_FROM_`. Any `ID` list variables also appear in the `ARC OUT=` and `CON OUT=` data sets.

## NODEOUT= and DUALOUT= Data Sets

There are two types of observations in the **NODEOUT=** and **DUALOUT=** data sets. One type of observation contains information about a node. These are called *type N* observations. There is one such observation of this type for each node. The **\_NODE\_** variable has a name of a node, and the **\_CON\_** variable values in these observations are missing values.

The other type of observation contains information about constraints. These are called the *type C* observations. There is one such observation for each constraint. The **\_CON\_** variable has a name of a constraint, and the **\_NODE\_** variable values in these observations are missing values.

Many of the variables in the **NODEOUT=** and **DUALOUT=** data sets contain information used to warm start PROC NETFLOW. The variables **\_NODE\_**, **\_SD\_**, **\_DUAL\_**, **\_VALUE\_**, **\_RHS\_**, **\_TYPE\_**, and **\_CON\_** contain information that might be of interest to you.

The **NODEOUT=** and **DUALOUT=** data sets look similar, as the same variables are in both. These variables and their values in an observation of each type are

|                |  |
|----------------|--|
| <b>_NODE_</b>  | Type N: the node name<br>Type C: a missing value   |
| <b>_SD_</b>    | Type N: the supply (positive) or demand (negative) of the node<br>Type C: a missing value  |
| <b>_DUAL_</b>  | Type N: the dual variable value of the node in <b>_NODE_</b><br>Type C: the dual variable value of the constraint named in <b>_CON_</b>  |
| <b>_NNUMB_</b> | Type N: the number of the node named in <b>_NODE_</b><br>Type C: the number of the constraint named in <b>_CON_</b>  |
| <b>_PRED_</b>  | Type N: the predecessor in the network basis spanning tree of the node named in <b>_NODE_</b><br>Type C: the number of the node toward which the arc with number in <b>_ARCID_</b> is directed, or the constraint number associated with the slack, surplus, or artificial variable basic in this row  |
| <b>_TRAV_</b>  | Type N: the traversal thread label of the node named in <b>_NODE_</b><br>Type C: a missing value   |
| <b>_SCESS_</b> | Type N: the number of successors (including itself) in the network basis spanning tree of the node named in <b>_NODE_</b><br>Type C: a missing value   |
| <b>_ARCID_</b> | Type N: if <b>_ARCID_</b> is nonnegative, <b>_ARCID_</b> is the number of the network basis spanning tree arc directed from the node with number <b>_PRED_</b> to the node named in <b>_NODE_</b> . If <b>_ARCID_</b> is negative, minus <b>_ARCID_</b> is the number of the network basis spanning tree arc directed from the node named in <b>_NODE_</b> to the node with number <b>_PRED_</b> .<br>Type C: if <b>_ARCID_</b> is positive, <b>_ARCID_</b> is the number of the arc basic in a constraint row. If nonpositive, minus <b>_ARCID_</b> is the number of the nonarc variable basic in a constraint row. |
| <b>_FLOW_</b>  | Type N: the flow minus the lower flow bound of the arc <b>_ARCID_</b><br>Type C: the flow minus lower flow bound of the arc <b>_ARCID_</b> or value lower bound of the nonarc variable value minus <b>_ARCID_</b>  |

|                      |   |
|----------------------|---|
| <code>_FBQ_</code>   | Type N: If <code>_FBQ_</code> is positive, then <code>_FBQ_</code> is the subscript in arc length arrays of the first arc directed toward the node named in <code>_NODE_</code> . PROC NETFLOW's arc length arrays are sorted so that data of arcs directed toward the same head node are together. If <code>_FBQ_</code> is negative, no arcs are directed toward the node named in <code>_NODE_</code> . Arcs directed toward node $i$ have subscripts in the arc length arrays between observations $\text{FBQ}(i)$ and $(\text{FBQ}(i + 1)) - 1$ , inclusive. |
| <code>_VALUE_</code> | Type C: a missing value<br>Type N: a missing value<br>Type C: the lhs value (the sum of the products of coefficient and flows or values) of the constraint named in <code>_CON_</code>  |
| <code>_RHS_</code>   | Type N: a missing value<br>Type C: the rhs value of the constraint named in <code>_CON_</code>  |
| <code>_TYPE_</code>  | Type N: a missing value<br>Type C: the type of the constraint named in <code>_CON_</code>   |
| <code>_CON_</code>   | Type N: a missing value<br>Type C: the name of the constraint   |

If specified in variable lists, the variables in the input data sets are used instead of some of the previous variables. These variables are specified in the **NODE**, **SUPDEM**, **RHS**, **TYPE**, and **ROW** (if there is only one variable in the **ROW** list) lists and are used instead of `_NODE_`, `_SD_`, `_RHS_`, `_TYPE_`, and `_CON_`, respectively.

### MPSOUT= Data Set

The **MPSOUT=** data set contains problem data converted from a PROC NETFLOW format into an MPS-format SAS data set. The six fields, FIELD1 to FIELD6, in the **MPSOUT=** data set correspond to the six columns in MPS standard. For more information about the MPS-format SAS data set, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User's Guide: Mathematical Programming*).

---

## Converting Any PROC NETFLOW Format to an MPS-Format SAS Data Set

The **MPSOUT=** option enables you to convert an input data set for the NETFLOW procedure into an MPS-format SAS data set. The converted data set is readable by the OPTLP procedure.

The conversion can handle linear programs and network flow formulations. If you specify a network flow formulation, it will be converted into an equivalent linear program. When multiple objective row names are present, rows with the name encountered first are combined into the objective row. The remaining rows are marked as free rows.

For information about how the contents of the MPS-format SAS data set are interpreted, see Chapter 15, “The MPS-Format SAS Data Set” (*SAS/OR User's Guide: Mathematical Programming*).

For an example demonstrating the use of the **MPSOUT=** option, see [Example 7.15](#). For examples that demonstrate how to migrate to the OPTMODEL procedure, see the section “[Examples: NETFLOW Procedure](#)” on page 474.



---

## Case Sensitivity

Whenever the NETFLOW procedure has to compare character strings, whether they are node names, arc names, nonarc names, or constraint names, if the two strings have different lengths, or on a character by character basis the character is different *or has different cases*, PROC NETFLOW judges the character strings to be different.

Not only is this rule enforced when one or both character strings are obtained as values of SAS variables in PROC NETFLOW's input data sets, it also should be obeyed if one or both character strings were originally SAS variable names, or were obtained as the values of options or statements parsed to PROC NETFLOW. For example, if the network has only one node that has supply capability, or if you are solving a **MAXFLOW** or **SHORTPATH** problem, you can indicate that node using the **SOURCE=** option.

If you specify

```
proc netflow source=NotableNode
```

then PROC NETFLOW looks for a value of the **TAILNODE** list variable that is `NotableNode`.

Version 6 of the SAS System converts text that makes up statements into uppercase. The name of the node searched for would be `NOTABLENODE`, even if this was your SAS code:

```
proc netflow source=NotableNode
```

If you want PROC NETFLOW to behave as it did in Version 6, specify

```
options validvarname=v6;
```

If the **SPARSECONDATA** option is not specified, and you are running SAS software Version 6 or have specified options `validvarname=v6`; using a later version, all **NAME** list variable values in the **ARC DATA=** data set are uppercased. This is because the SAS System has uppercased all SAS variable names, particularly those in the **VAR** list of the **CON DATA=** data set.

Entities that contain blanks must be enclosed in single or double quotes.

See the section “**Cautions**” on page 356 for additional discussion of case sensitivity.

---

## Loop Arcs

When using the primal simplex network algorithm, loop arcs (arcs directed toward nodes from which they originate) are prohibited. Rather, introduce a dummy intermediate node in loop arcs. For example, replace arc (A,A) with (A,B) and (B,A). B is the name of a new node, and it must be distinct for each loop arc.

---

## Multiple Arcs

Multiple arcs with the same tail and head nodes are prohibited. PROC NETFLOW checks to ensure there are no such arcs before proceeding with the optimization. Introduce a new dummy intermediate node in multiple

arcs. This node must be distinct for each multiple arc. For example, if some network has three arcs directed from node A toward node B, then replace one of these three with arcs (A,C) and (C,B) and replace another one with (A,D) and (D,B). C and D are new nodes added to the network.

## Pricing Strategies

The pricing strategy is the part of the simplex iteration that selects the nonbasic arc, constraint slack, surplus, or nonarc variable that should have a flow or value change, and perhaps enter the basis so that the total cost incurred is improved.

The pricing mechanism takes a large amount of computational effort, so it is important to use the appropriate pricing strategy for the problem under study. As in other large scale mathematical programming software, network codes can spend more than half of their execution time performing simplex iterations in the pricing step. Some compromise must be made between using a fast strategy and improving the quality of the flow or value change candidate selection, although more simplex iterations may need to be executed.

The configuration of the problem to be optimized has a great effect on the choice of strategy. If a problem is to be run repeatedly, experimentation on that problem to determine which scheme is best may prove worthwhile. The best pricing strategy to use when there is a large amount of work to do (for example, when a cold start is used) may not be appropriate when there is little work required to reach the optimum (such as when a warm start is used). If paging is necessary, then a pricing strategy that reduces the number of simplex iterations performed might have the advantage. The proportion of time spent doing the pricing step during stage 1 optimization is usually less than the same proportion when doing stage 2 optimization. Therefore, it is more important to choose a stage 2 pricing strategy that causes fewer, but not necessarily the fewest, iterations to be executed.

There are many similarities between the pricing strategies for optimizing an unconstrained problem (or when constraints are temporarily ignored) and the pricing mechanisms for optimizing considering constraints. To prevent repetition, options have a suffix or embedded  $x$ . Replace  $x$  with 1 for optimization without constraint consideration and 2 for optimization with constraint consideration.

There are three main types of pricing strategies:

- $\text{PRICETYPE}_x=\text{NOQ}$
- $\text{PRICETYPE}_x=\text{BLAND}$
- $\text{PRICETYPE}_x=\text{Q}$

The pricing strategy that usually performs better than the others is  $\text{PRICETYPE}_x=\text{Q}$ . For this reason,  $\text{PRICETYPE}_x=\text{Q}$  is the default.

### $\text{PRICETYPE}_x=\text{NOQ}$

$\text{PRICETYPE}_x=\text{NOQ}$  is the least complex pricing strategy, but it is nevertheless quite efficient. In contrast to the specification of  $\text{PRICETYPE}_x=\text{Q}$ , a candidate queue is not set up.

The  $\text{PxSCAN=}$  option controls the amount of additional candidate selection work done to find a better candidate after an eligible candidate has been found.

If  $PxSCAN=FIRST$  is specified, the search for candidates finishes when the first eligible candidate is found, with this exception: if a node has more than one eligible arc directed toward it, the best such arc is chosen.

If  $PxSCAN=BEST$  is specified, everything that is nonbasic is examined, and the best candidate of all is chosen.

If  $PxSCAN=PARTIAL$  is specified, once an eligible candidate is found, the scan continues for another  $PxNPARTIAL=$  cycles in the hope that during the additional scan, a better candidate is found. Examining all nonbasic arcs directed toward a single node is counted as only one cycle.

If  $PxSCAN=FIRST$  or  $PxSCAN=PARTIAL$  is specified, the scan for entering candidates starts where the last iteration's search left off. For example, if the last iteration's scan terminated after examining arcs that are directed toward the node with internal number  $i$ , the next iteration's scan starts by examining arcs directed toward the node with internal number  $i + 1$ . If  $i$  is the largest node number, next iterations scan begins by scanning arcs directed toward node 1 (during stage 1) or scanning constraint slack or surplus variables, if any, or nonarc variables, if any, (during stage 2). During stage 2, if the scan terminated after examining the slack or surplus of constraint  $i$ , next iterations scan starts by examining the slack or surplus of the constraint with the internal number greater than  $i$  that has such a logical variable. If the scan terminated after examining the nonarc variable  $i$ , the next iterations scan starts by examining the nonarc variable with internal number  $i + 1$ , (or arcs directed to the node with the smallest internal number if the nonarc variable with the greatest number has been examined). This is termed a *wraparound search*.

## PRICETYPE $x=Q$

If  $PRICETYPEx=Q$ , a queue is set up. Candidates currently on the queue are tested at each iteration and either enter the basis or are removed from the queue. The size of the queue can be specified by using the  $QSIZEx=$  option. The default value for  $QSIZE1=$  is

```
QSIZE1=number of arcs/200
if (QSIZE1<24) QSIZE1=24
else if (QSIZE1>100) QSIZE1=100
```

The default value for  $QSIZE2=$  is

```
QSIZE2=(number of arcs+number of nonarc variables)/200
if (QSIZE2<24) QSIZE2=24
else if (QSIZE2>100) QSIZE2=100
```

controls the amount of additional candidate selection work done to find a better candidate after an eligible candidate has been found *in the queue*.

If you specify  $PxSCAN=BEST$ , the best eligible candidate found is removed from the queue. It can sustain a flow or value change and possibly enter the basis.

If you specify  $PxSCAN=FIRST$ , the first eligible candidate found is removed from the queue, and possibly sustains a flow or value change and enters the basis.

If you specify  $PxSCAN=PARTIAL$ ,  $PxNPARTIAL=$  can then be also specified. After an eligible candidate has been found,  $PxNPARTIAL=$  more queue members are examined and the best of the eligible candidates found is chosen.

When  $P_xSCAN=FIRST$  or  $P_xSCAN=PARTIAL$ , the scan of the queue is wraparound. When the member last added to the queue has been examined, the scan continues from the member that was first added to the queue.

When the queue is empty, or after  $QSIZE_x =$  times  $REFRESHQ_x =$  iterations have been executed since the queue was last refreshed, new candidates are found and put onto the queue. Valid values for the  $REFRESHQ_x =$  options are greater than 0.0 and less than or equal to 1.0. The default for  $REFRESHQ_x$  is 0.75. If the scan cannot find enough candidates to fill the queue, the procedure reduces the value of  $QSIZE_x =$ . If  $qfound$  is the number of candidates found, the new  $QSIZE_x =$  value is  $qfound + ((old\ QSIZE_x - qfound) \times REDUCEQSIZE_x)$ . Valid values of the  $REDUCEQSIZE_x =$  option are between 0.0 and 1.0, inclusive. The default for  $REDUCEQSIZE_x =$  is 1.0.

The  $Q_xFILLSCAN =$  option controls the amount of additional candidate selection work performed to find better candidates to put into the queue after the queue has been filled.

If you specify  $Q_xFILLSCAN=FIRST$ , the nonbasic arcs, and during stage 2 optimization, nonbasic constraint slack and surplus variables, and nonbasic nonarc variables are scanned; the scan stops when the queue is filled. If a node has more than one eligible arc directed toward it, the best such arc is put onto the queue.  $Q_xFILLSCAN=FIRST$  is the default.

If  $Q_xFILLSCAN=BEST$  is specified, everything that is nonbasic is scanned and the best eligible candidates are used to fill the queue.

If  $Q_xFILLSCAN=PARTIAL$  is specified, after the queue is full, the scan continues for another  $Q_xFILLNPARTIAL =$  cycles in the hope that during the additional scan, better candidates are found to replace other candidates previously put onto the queue.  $Q_xFILLNPARTIAL=10$  is the default. If  $Q_xFILLSCAN=FIRST$  or  $Q_xFILLSCAN=PARTIAL$ , the scan starts where the previous iteration ended; that is, it is wraparound.

In the following section, dual variables and reduced costs are explained. These help PROC NETFLOW determine whether an arc, constraint slack, surplus, or nonarc variable should have a flow or value change.  $P2SCAN=ANY$  and the  $DUALFREQ =$  option can be specified to control stage 2 pricing, and how often dual variables and reduced costs are calculated.

What usually happens when  $PRICETYPE2=Q$  is specified is that before the first iteration, the queue is filled with nonbasic variables that are eligible to enter the basis. At the start of each iteration, a candidate on the queue is examined and its reduced cost is calculated to ensure that it is still eligible to enter the basis. If it is ineligible to enter the basis, it is removed from the queue and another candidate on the queue is examined, until a candidate on the queue is found that can enter the basis. When this happens, a *minor* iteration occurs. If there are no candidates left on the queue, or several iterations have been performed since the queue was refreshed, new nonbasic variables that are eligible to enter the basis are found and are placed on the queue. When this occurs, the iteration is termed a *major* iteration. Dual variables are calculated or maintained every iteration.

During most optimizations, if a variable is put onto the queue during a major iteration, it usually remains eligible to enter the basis in later minor iterations. Specifying  $P2SCAN=ANY$  indicates that PROC NETFLOW should choose *any* candidate on the queue and use that as the entering variable. Reduced costs are not calculated. It is simply hoped that the chosen candidate is eligible. Sometimes, a candidate on the queue is chosen that has become ineligible and the optimization takes “a step backward” rather than “a step forward” toward the optimum. However, the disadvantages of incurring an occasional step backwards and the possible danger of never converging to the optimum are offset by not having to calculate reduced costs and, more

importantly, not having to maintain dual variable values. The calculation of dual variables is one of two large linear equation systems that must be solved each iteration in the simplex iteration.

If P2SCAN=ANY is specified, dual variables are calculated after DUALFREQ= iterations have been performed since they were last calculated. These are used to calculate the reduced costs of all the candidates currently on the queue. Any candidate found to be ineligible to enter the basis is removed from the queue. DUALFREQ=4 is the default.

Once again, the practice of not maintaining correct dual variable values is dangerous because backward steps are allowed, so the optimization is not guaranteed to converge to the optimum. However, if PROC NETFLOW does not run forever, it can find the optimum much more quickly than when the P2SCAN= option is not ANY. Before concluding that any solution is optimal, PROC NETFLOW calculates true dual variable values and reduced costs and uses these to verify that the optimum is really at hand.

Whether P2SCAN=ANY is specified or not, dual variables are always calculated at the start of major iterations.

### PRICETYPE<sub>x</sub>=BLAND

PRICETYPE<sub>x</sub>=BLAND is equivalent to specifying in the PROC NETFLOW or RESET statement all three options PRICETYPE<sub>x</sub>=NOQ, PxSCAN=FIRST, and LRATIO<sub>x</sub>, and the scans are not wraparound. Bland (1977) proved that this pivot rule prevents the simplex algorithm from cycling. However, because the pivots concentrate on the lower indexed arcs, constraint slack, surplus, and nonarc variables, optimization with PRICETYPE<sub>x</sub>=BLAND can make the optimization execute slowly.

---

## Dual Variables, Reduced Costs, and Status

During optimization, dual variables and reduced costs are used to determine whether an arc, constraint slack, surplus, or nonarc variable should have a flow or value change. The ARCOUT= and CONOUT= data sets each have a variable called \_RCOST\_ that contains reduced cost values. In the CONOUT= data set, this variable also has the reduced costs of nonarc variables. For an arc, the reduced cost is the amount that would be added to the total cost if that arc were made to convey one more unit of flow. For a nonarc variable, the reduced cost is the amount that would be added to the total cost if the value currently assigned to that nonarc variable were increased by one.

During the optimization of a minimization problem, if an arc has a positive reduced cost, PROC NETFLOW takes steps to decrease the flow through it. If an arc has a negative reduced cost, PROC NETFLOW takes steps to increase the flow through it. At optimality, the reduced costs of arcs with flow at their respective lower bounds are nonnegative; otherwise, the optimizer would have tried to increase the flow, thereby decreasing the total cost. The \_STATUS\_ of each such nonbasic arc is LOWERBD NONBASIC. The reduced costs of arcs with flow at capacity are nonpositive. The \_STATUS\_ of each such nonbasic arc is UPPERBD NONBASIC. Even though it would decrease total cost, the optimizer cannot increase the flows through such arcs because of the capacity bound. Similar arguments apply for nonarc variables.

The reduced cost is also the amount that would be subtracted from the total cost if that arc was made to convey one less unit of flow. Similarly, a reduced cost is the amount subtracted from the total cost if the value currently assigned to that nonarc variable is decreased by one.

The dual variables and reduced costs can be used to detect whether multiple optimal solutions exist. A zero reduced cost of a nonbasic arc indicates the existence of multiple optimal solutions. A zero reduced cost

indicates, by definition, that the flow through such arcs can be changed with zero change to the total cost. (Basic arcs and basic nonarc variables technically have zero reduced costs. A missing value is used for these so that reduced costs of nonbasic arcs and nonbasic nonarc variables that are zero are highlighted.)

The range over which costs can vary before the present solution becomes nonoptimal can be determined through examination of the reduced costs. For any nonbasic arc with assigned flow equal to its lower bound, the amount by which the cost must be decreased before it becomes profitable for this arc to convey additional flow is the value of its reduced cost. The cost reduction necessary for a nonbasic arc currently assigned capacity flow to undergo a worthwhile flow decrease is the absolute value of its reduced cost. In both cases, this minimum cost reduction changes the reduced cost to zero. Any further reduction promotes a possible basis change.

The reduced cost of an arc  $(t, h)$  is  $rc_{t,h} = c_{t,h} - \pi_t + \pi_h$  where  $\pi_i$  is the dual value for node  $i$  and  $c_{t,h}$  is the cost of the arc with tail node  $t$  and head node  $h$ .

If the problem has side constraints and arc  $(t, h)$  has nonzero lhs coefficients, then the following term must be subtracted from  $rc_{t,h}$  :

$$\sum_i \text{condual}_i H_{i,(t,h)}$$

where  $\text{condual}_i$  is the dual variable of constraint  $i$ , and  $H_{i,(t,h)}$  is the coefficient of arc  $(t, h)$  in constraint  $i$ .

If  $d_n$  is the objective function coefficient of nonarc variable  $n$ , the reduced cost is  $rc_n = d_n - \sum_i \text{condual}_i Q_{i,n}$ , where  $Q_{i,n}$  is the coefficient of nonarc variable  $n$  in constraint  $i$ .

---

## The Working Basis Matrix

Let **T** be the basis matrix of NPSC. The following partitioning is done:

$$\mathbf{T} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix}$$

where

- $n$  is the number of nodes.
- $k$  is the number of side constraints.
- **A** ( $n \times n$ ) is the network component of the basis. Most of the columns of this matrix are columns of the problem's node-arc incidence matrix. The arcs associated with columns of **A**, called key basic variables or key arcs, form a spanning tree. The data structures of the spanning tree of this submatrix of the basis **T** enable the computations involving **T** and the manner in which **T** is updated to be very efficient, especially those dealing with **A** (or  $\mathbf{A}^{-1}$ ).
- **C** ( $k \times n$ ) are the key arcs' side constraint coefficient columns.
- **B** ( $n \times k$ ) are the node-arc incidence matrix columns of the nontree arcs. The columns of **B** having nonzero elements are associated with basic nonspanning tree arcs.

- $D$  ( $k \times k$ ) are the constraint coefficient columns of nonkey basic variables. Nonkey basic variables not only include nontree basic arcs but also basic slack, surplus, artificial, or nonarc variables.

It is more convenient to factor  $T$  by block triangular matrices  $P$  and  $M$ , such that  $P = TM$ . The matrices  $P$  and  $M$  are used instead of  $T$  because they are less burdensome to work with. You can perform block substitution when solving the simplex iteration linear systems of equations

$$P = \begin{bmatrix} A & 0 \\ C & D_w \end{bmatrix}$$

$$M = \begin{bmatrix} I & -A^{-1}B \\ 0 & I \end{bmatrix}$$

where  $D_w = D - CA^{-1}B$  and is called the working basis matrix.

To perform block substitution, you need the tree data structure of the  $A$  matrix, and also the  $C$ ,  $B$ , and  $D_w$  matrices. Because the  $C$  matrix consists of columns of the constraint coefficient matrix, the maintenance of  $C$  from iteration to iteration simply entails changing information specifying which columns of the constraint coefficient matrix compose  $C$ .

The  $A^{-1}B$  matrix is usually very sparse. Fortunately, the information in  $A^{-1}B$  can be initialized easily using the tree structures. In most iterations, only one column is replaced by a new one. The values of the elements of the new column may already be known from preceding steps of the simplex iteration.

The working basis matrix is the submatrix that presents the most computational complexity. However, PROC NETFLOW usually can use classical simplex pivot techniques. In many iterations, only one column of  $D_w$  changes. Sometimes it is not necessary to update  $D_w$  or its inverse at all.

If **INVD\_2D** is specified in the **PROC NETFLOW** statement, only one row and one column may need to be changed in the  $D_w^{-1}$  before the next simplex iteration can begin. The new contents of the changed column are already known. The new elements of the row that changes are influenced by the contents of a row of  $A^{-1}B$  that is very sparse.

If **INVD\_2D** is not specified in the **PROC NETFLOW** statement, the Bartels-Golub update can be used to update the **LU** factors of  $D_w$ . The choice must be made whether to perform a series of updates (how many depends on the number of nonzeros in a row of  $A^{-1}B$ ), or refactorization.

---

## Flow and Value Bounds

The capacity and lower flow bound of an arc can be equal. Negative arc capacities and lower flow bounds are permitted. If both arc capacities and lower flow bounds are negative, the lower flow bound must be at least as negative as the capacity. An arc (A,B) that has a negative flow of  $-f$  units can be interpreted as an arc that conveys  $f$  units of flow from node B to node A.

The upper and lower value bounds of a nonarc variable can be equal. Negative upper and lower bounds are permitted. If both are negative, the lower bound must be at least as negative as the upper bound.

---

## Tightening Bounds and Side Constraints

If any piece of data is furnished to PROC NETFLOW more than once, PROC NETFLOW checks for consistency so that no conflict exists concerning the data values. For example, if the cost of some arc is seen to be one value and as more data are read, the cost of the same arc is seen to be another value, PROC NETFLOW issues an error message on the SAS log and stops. There are two exceptions:

- The bounds of arcs and nonarc variables are made as tight as possible. If several different values are given for the lower flow bound of an arc, the greatest value is used. If several different values are given for the lower bound of a nonarc variable, the greatest value is used. If several different values are given for the capacity of an arc, the smallest value is used. If several different values are given for the upper bound of a nonarc variable, the smallest value is used.
- Several values can be given for inequality constraint right-hand sides. For a particular constraint, the lowest rhs value is used for the rhs if the constraint is of *less than or equal to* type. For a particular constraint, the greatest rhs value is used for the rhs if the constraint is of *greater than or equal to* type.

---

## Reasons for Infeasibility

Before optimization commences, PROC NETFLOW tests to ensure that the problem is not infeasible by ensuring that, with respect to supplies, demands, and arc flow bounds, flow conservation can be obeyed at each node.

- Let  $IN$  be the sum of lower flow bounds of arcs directed toward a node plus the node's supply. Let  $OUT$  be the sum of capacities of arcs directed from that node plus the node's demand. If  $IN$  exceeds  $OUT$ , not enough flow can leave the node.
- Let  $OUT$  be the sum of lower flow bounds of arcs directed from a node plus the node's demand. Let  $IN$  be the total capacity of arcs directed toward the node plus the node's supply. If  $OUT$  exceeds  $IN$ , not enough flow can arrive at the node.

Reasons why a network problem can be infeasible are similar to those previously mentioned but apply to a set of nodes rather than for an individual node. Consider the network illustrated in [Figure 7.13](#).





east” is a supply node, but you do not want to stipulate that it supplies 100 units, as before. The node “u.s.a.” should also remain a supply node, but you do not want to stipulate that it supplies 80 units. You must specify that these nodes have missing S supply capabilities.

```

title 'Oil Industry Example';
title3 'Crude Oil can come from anywhere';
data miss_s;
  missing S;
  input  _node_&$15. _sd_;
  datalines;
middle east      S
u.s.a.           S
servstn1 gas     -95
servstn1 diesel -30
servstn2 gas     -40
servstn2 diesel -15
;

```

The following PROC NETFLOW run uses the same ARCDATA= and CONDATA= data sets used in the section “[Introductory Example](#)” on page 321.

```

proc netflow
  nodedata=miss_s      /* the supply (missing S) and */
                      /* demand data          */
  arcdata=arcd1        /* the arc descriptions    */
  condata=cond1        /* the side constraints    */
  conout=solution;     /* the solution data set   */
run;
print some_arcs('middle east' 'u.s.a.',_all_)/short;
proc print;
  sum _fcost_;
run;

```

The following messages appear on the SAS log:

```
NOTE: Number of nodes= 14 .
NOTE: All supply nodes have unspecified (.S) supply capability. Number of these
      nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 0 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of iterations performed (neglecting any constraints)= 15 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= 50040 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of arc and nonarc variable side constraint coefficients= 8 .
NOTE: Number of iterations, optimizing with constraints= 3 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum reached.
NOTE: Minimal total cost= 50075 .
NOTE: The data set WORK.SOLUTION has 18 observations and 14 variables.
```

The PRINT statement reports the arcs directed away from the supply nodes, shown in [Figure 7.14](#). The amount of crude obtained from the Middle East and U.S.A. is 30 and 150 units, respectively.

**Figure 7.14** Print Statement, Oil Example, Missing S Supplies

| Oil Industry Example             |             |            |        |          |      |          |
|----------------------------------|-------------|------------|--------|----------|------|----------|
| Crude Oil can come from anywhere |             |            |        |          |      |          |
| The NETFLOW Procedure            |             |            |        |          |      |          |
| _N_                              | _from_      | _to_       | _cost_ | _capac_  | _lo_ | _name_   |
| 1                                | middle east | refinery 1 | 63     | 95       | 20   | m_e_ref1 |
| 2                                | u.s.a.      | refinery 1 | 55     | 99999999 | 0    |          |
| 3                                | middle east | refinery 2 | 81     | 80       | 10   | m_e_ref2 |
| 4                                | u.s.a.      | refinery 2 | 49     | 99999999 | 0    |          |
|                                  |             |            |        |          |      |          |
|                                  | _N_         | _FLOW_     |        |          |      |          |
|                                  | 1           | 20         |        |          |      |          |
|                                  | 2           | 125        |        |          |      |          |
|                                  | 3           | 10         |        |          |      |          |
|                                  | 4           | 25         |        |          |      |          |

The CONOUT= data set is shown in Figure 7.15.

**Figure 7.15** Missing S SUPDEM Values in NODEDATA

| Oil Industry Example             |             |                 |        |          |      |          |          |
|----------------------------------|-------------|-----------------|--------|----------|------|----------|----------|
| Crude Oil can come from anywhere |             |                 |        |          |      |          |          |
| Obs                              | _from_      | _to_            | _cost_ | _capac_  | _lo_ | _name_   | _SUPPLY_ |
| 1                                | refinery 1  | r1              | 200    | 175      | 50   | thruput1 | .        |
| 2                                | refinery 2  | r2              | 220    | 100      | 35   | thruput2 | .        |
| 3                                | r1          | ref1 diesel     | 0      | 75       | 0    |          | .        |
| 4                                | r1          | ref1 gas        | 0      | 140      | 0    | r1_gas   | .        |
| 5                                | r2          | ref2 diesel     | 0      | 75       | 0    |          | .        |
| 6                                | r2          | ref2 gas        | 0      | 100      | 0    | r2_gas   | .        |
| 7                                | middle east | refinery 1      | 63     | 95       | 20   | m_e_ref1 | S        |
| 8                                | u.s.a.      | refinery 1      | 55     | 99999999 | 0    |          | S        |
| 9                                | middle east | refinery 2      | 81     | 80       | 10   | m_e_ref2 | S        |
| 10                               | u.s.a.      | refinery 2      | 49     | 99999999 | 0    |          | S        |
| 11                               | ref1 diesel | servstn1 diesel | 18     | 99999999 | 0    |          | .        |
| 12                               | ref2 diesel | servstn1 diesel | 36     | 99999999 | 0    |          | .        |
| 13                               | ref1 gas    | servstn1 gas    | 15     | 70       | 0    |          | .        |
| 14                               | ref2 gas    | servstn1 gas    | 17     | 35       | 5    |          | .        |
| 15                               | ref1 diesel | servstn2 diesel | 17     | 99999999 | 0    |          | .        |
| 16                               | ref2 diesel | servstn2 diesel | 23     | 99999999 | 0    |          | .        |
| 17                               | ref1 gas    | servstn2 gas    | 22     | 60       | 0    |          | .        |
| 18                               | ref2 gas    | servstn2 gas    | 31     | 99999999 | 0    |          | .        |

| Obs      | _DEMAND_ | _FLOW_ | _FCOST_  | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_   |          |
|----------|----------|--------|----------|---------|---------|---------|------------|----------|
| 1        | .        | 145.00 | 29000.00 | .       | 7       | 2       | KEY_ARC    | BASIC    |
| 2        | .        | 35.00  | 7700.00  | 17      | 8       | 3       | LOWERBD    | NONBASIC |
| 3        | .        | 36.25  | 0.00     | .       | 10      | 5       | KEY_ARC    | BASIC    |
| 4        | .        | 108.75 | 0.00     | .       | 9       | 5       | KEY_ARC    | BASIC    |
| 5        | .        | 8.75   | 0.00     | .       | 12      | 6       | KEY_ARC    | BASIC    |
| 6        | .        | 26.25  | 0.00     | .       | 11      | 6       | KEY_ARC    | BASIC    |
| 7        | .        | 20.00  | 1260.00  | 8       | 2       | 1       | LOWERBD    | NONBASIC |
| 8        | .        | 125.00 | 6875.00  | .       | 3       | 4       | KEY_ARC    | BASIC    |
| 9        | .        | 10.00  | 810.00   | 32      | 4       | 1       | LOWERBD    | NONBASIC |
| 10       | .        | 25.00  | 1225.00  | .       | 5       | 4       | KEY_ARC    | BASIC    |
| 11       | 30       | 30.00  | 540.00   | .       | 17      | 8       | KEY_ARC    | BASIC    |
| 12       | 30       | 0.00   | 0.00     | 12      | 18      | 10      | LOWERBD    | NONBASIC |
| 13       | 95       | 68.75  | 1031.25  | .       | 13      | 7       | KEY_ARC    | BASIC    |
| 14       | 95       | 26.25  | 446.25   | .       | 14      | 9       | NONKEY_ARC | BASIC    |
| 15       | 15       | 6.25   | 106.25   | .       | 19      | 8       | KEY_ARC    | BASIC    |
| 16       | 15       | 8.75   | 201.25   | .       | 20      | 10      | KEY_ARC    | BASIC    |
| 17       | 40       | 40.00  | 880.00   | .       | 15      | 7       | KEY_ARC    | BASIC    |
| 18       | 40       | 0.00   | 0.00     | 7       | 16      | 9       | LOWERBD    | NONBASIC |
| =====    |          |        |          |         |         |         |            |          |
| 50075.00 |          |        |          |         |         |         |            |          |

The optimal supplies of nodes “middle east” and “u.s.a.” are 30 and 150 units, respectively. For this example, the same optimal solution is obtained if these nodes had supplies less than these values (each supplies 1

unit, for example) and the **THRUNET** option was specified in the **PROC NETFLOW** statement. With the **THRUNET** option active, when total supply exceeds total demand, the specified nonmissing demand values are the lowest number of flow units that must be absorbed by the corresponding node. This is demonstrated in the following PROC NETFLOW run. The missing S is most useful when nodes are to supply optimal numbers of flow units and it turns out that for some nodes, the optimal supply is 0.

```
data miss_s_x;
    missing S;
    input  _node_&$15. _sd_;
    datalines;
middle east      1
u.s.a.           1
servstn1 gas     -95
servstn1 diesel  -30
servstn2 gas     -40
servstn2 diesel  -15
;

proc netflow
    thrunet
    nodedata=miss_s_x      /* No supply (missing S)      */
    arcdata=arccl          /* the arc descriptions      */
    condata=condl          /* the side constraints      */
    conout=solution;       /* the solution data set    */
run;
print some_arcs('middle east' 'u.s.a.',_all_)/short;

proc print;
    sum _fcost_;
run;
```

The following messages appear on the SAS log. Note that the Total supply= 2, not 0 as in the last run.

```
NOTE: Number of nodes= 14 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 2 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of iterations performed (neglecting any constraints)= 20 .
NOTE: Of these, 1 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= 50040 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of arc and nonarc variable side constraint coefficients= 8 .
NOTE: Number of iterations, optimizing with constraints= 3 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum reached.
NOTE: Minimal total cost= 50075 .
NOTE: The data set WORK.SOLUTION has 18 observations and 14 variables.
```

The PRINT statement and the CONDATA= data set are very similar; the supplies of the supply nodes are 1,

not missing S. Otherwise, the solutions are identical.

If total supply exceeds total demand, any missing S values are ignored. If total demand exceeds total supply, any missing D values are ignored.

---

## Balancing Total Supply and Total Demand

### When Total Supply Exceeds Total Demand

When total supply of a network problem exceeds total demand, PROC NETFLOW can add an extra node (called the *excess node*) to the problem and set the demand at that node equal to the difference between total supply and total demand. There are three ways that this excess node can be joined to the network. All three ways entail PROC NETFLOW generating a set of arcs (henceforth referred to as the *generated arcs*) that are directed toward the excess node. The total amount of flow in generated arcs equals the demand of the excess node. The generated arcs originate from one of three sets of nodes.

When you specify the **THRUNET** option, the set of nodes that generated arcs originate from are all demand nodes, even those demand nodes with unspecified demand capability. You indicate that a node has unspecified demand capability by using a missing D value instead of an actual value for demand data (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 407). The value specified as the demand of a demand node is in effect a lower bound of the number of flow units that node can actually demand. For missing D demand nodes, this lower bound is zero.

If you do not specify the **THRUNET** option, the way in which the excess node is joined to the network depends on whether there are demand nodes with unspecified demand capability (nodes with missing D demand).

If there are missing D demand nodes, these nodes are the set of nodes that generated arcs originate from. The value specified as the demand of a demand node, if not missing D, is the number of flow units that node actually demands. For a missing D demand node, the actual demand of that node may be zero or greater.

If there are no missing D demand nodes, the set of nodes that generated arcs originate from are the set of supply nodes. The value specified as the supply of a supply node is in effect an upper bound of the number of flow units that node can actually supply. For missing S supply nodes (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 407), this upper bound is zero, so missing S nodes when total supply exceeds total demand are transshipment nodes, nodes that neither supply nor demand flow.

### When Total Supply Is Less Than Total Demand

When total supply of a network problem is less than total demand, PROC NETFLOW can add an extra node (called the *excess node*) to the problem and set the supply at that node equal to the difference between total demand and total supply. There are three ways that this excess node can be joined to the network. All three ways entail PROC NETFLOW generating a set of arcs (henceforth referred to as the *generated arcs*) that originate from the excess node. The total amount of flow in generated arcs equals the supply of the excess node. The generated arcs are directed toward one of three sets of nodes.

When you specify the **THRUNET** option, the set of nodes that generated arcs are directed toward are all supply nodes, even those supply nodes with unspecified supply capability. You indicate that a node has unspecified supply capability by using a missing S value instead of an actual value for supply data (discussed in the section “[Missing S Supply and Missing D Demand Values](#)” on page 407). The value specified as the

supply of a supply node is in effect a lower bound of the number of flow units that node can actually supply. For missing S supply nodes, this lower bound is zero.

If you do not specify the **THRUNET** option, the way in which the excess node is joined to the network depends on whether there are supply nodes with unspecified supply capability (nodes with missing S supply).

If there are missing S supply nodes, these nodes are the set of nodes that generated arcs are directed toward. The value specified as the supply of a supply node, if not missing S, is the number of flow units that node actually supplies. For a missing S supply node, the actual supply of that node may be zero or greater.

If there are no missing S supply nodes, the set of nodes that generated arcs are directed toward are the set of demand nodes. The value specified as the demand of a demand node is in effect an upper bound of the number of flow units that node can actually demand. For missing D demand nodes, (discussed in the section “Missing S Supply and Missing D Demand Values” on page 407), this upper bound is zero, so missing D nodes when total supply is less than total demand are transshipment nodes, nodes that neither supply nor demand flow.

---

## Warm Starts

Using a warm start can increase the overall speed of PROC NETFLOW when it is used repetitively on problems with similar structure. It is most beneficial when a solution of a previous optimization is close to the optimum of the same network with some of its parameters, for example, arc costs, changed. Whether a problem is changed or not, a nonoptimal solution resulting from a previous optimization can be used to restart optimization, thereby saving PROC NETFLOW from having to repeat work to reach the warm start already available.

Time also is saved in the data structure initialization part of the NETFLOW procedure’s execution. Information about the previous optimal solution, particularly concerning the size of the problem, a description of the basis spanning tree structure, and what is basic in constraint rows, is known. Information about which nonbasic arcs have capacity flow and which nonbasic nonarc variables are at their respective upper bounds also makes up part of the warm start. The procedure can place arc data into the internal arc length arrays in precisely defined locations, in order of ascending head node internal number. It is not necessary to have multiple passes through the data because literals such as node, nonarc variable, arc, constraint, and special row names are defined and meaning is attached to each. This also saves a considerable amount of memory. None of the pre-optimization feasibility checks need be repeated.

Warm starts also are useful if you want to determine the effect of arcs being closed to carrying flow. The costs of these arcs are set high enough to ensure that the next optimal solution never has flow through them. Similarly, the effect of opening arcs can be determined by changing the cost of such arcs from an extreme to a reasonable value.

Specify the **FUTURE1** or **FUTURE2** option to ensure that additional data about a solution to be used as a warm start are output to output data sets. If the **FUTURE1** option is specified, extra observations with information on what is to be the warm start are set up for the **NODEOUT=** and **ARCOUT=** data sets. The warm start solution in these data sets is a solution obtained after optimization neglecting side constraints. Any cost list variable value in the **ARCOUT=** data set (and, if there are side constraints, any constraint data in the **CONDATA=** data set) can be changed before the solution is used as a warm start in a subsequent PROC NETFLOW run. Any nonarc variable data in the **CONDATA=** data set can be changed at this time as well. New nonarc variables not present in the original problem when the warm start was generated can also be added to the **CONDATA=** data set before the problem is warm started.

If the **FUTURE2** option is specified, extra variables containing information on what will be the warm start solution are set up for the **DUALOUT=** and **CONOUT=** data sets. The warm start solution in these data sets is obtained after optimization that considers side constraints has been performed. Part of the warm start is concerned with the constraint part of the basis. Only cost list variable values in the **CONOUT=** data set can be changed before the solution is used as a warm start in a subsequent PROC NETFLOW run.

If a primal simplex optimization is to use a warm start, the **WARM** option must be specified in the PROC NETFLOW statement. Otherwise, the primal simplex network algorithm processes the data for a cold start and the extra information is not used.

The **ARCDATA=** data set is either the **ARCOUT=** data set from a previous run of PROC NETFLOW with the **FUTURE1** option specified (if an unconstrained warm start is used) or the **CONOUT=** data set from a previous run of PROC NETFLOW with the **FUTURE2** option specified (if the warm start was obtained after optimization that considers side constraints was used).

The **NODEDATA=** data set is the **NODEOUT=** data set from a previous run of PROC NETFLOW with **FUTURE1** specified if an unconstrained warm start is being used. Otherwise, the **DUALIN=** is the **DUALOUT=** data sets from a previous run of PROC NETFLOW with **FUTURE2** specified, if the warm start was obtained after optimization that considers side constraints was used.

You never need to alter the **NODEOUT=** data set or the **DUALOUT=** data set between the time they are generated and when they are used as a warm start. The results would be unpredictable if incorrect changes were made to these data sets, or if a **NODEDATA=** or a **DUALIN=** data set were used with an **ARCDATA=** data set of a different solution.

It is possible, and often useful, to specify **WARM** and either **FUTURE1** or **FUTURE2**, or both, in the same PROC NETFLOW statement if a new warm start is to be generated from the present warm start.

The extent of the changes allowed to a primal simplex warm start between the time it is generated and when it is used depends on whether the warm start describes an unconstrained or constrained solution. The following list describes parts of a constrained or an unconstrained warm start that can be altered:

- **COST** list variable values
- the value of an arc's capacity, as long as the new capacity value is not less than the lower flow bound or the flow through the arc
- any nonarc variable information, in an unconstrained warm start
- for an unconstrained warm start, any side constraint data

The changes that can be made in constraint data for a constrained warm start are more restrictive than those for an unconstrained warm start. The lhs coefficients, type, and rhs value of a constraint can be changed as long as that constraint's slack, surplus, or artificial variable is basic. The constraint name cannot be changed.

### Example of a Warm Start

The following sample SAS session demonstrates how the warm start facilities are used to obtain optimal solutions to an unconstrained network where some arc cost changes occur or optimization is halted before the optimum is found.



```

                /* data already in data sets node0 and arc0 */
proc netflow
  nodedata=node0 /* if supply_demand information */
                /* is in this SAS data set */
  arcdata=arc0;
                /* variable list specifications go here */
                /* assume that they are not necessary here */
                /* if they are, they must be included in */
                /* all the PROC NETFLOW calls that follow */
  reset
    future1
    nodeout=node2 /* nodeout and arcout are necessary */
                /* when FUTURE1 is used */
    arcout=arc1;
proc print
  data=arc1; /* display the optimal solution */
proc fsedit
  data=arc1; /* change some arc costs */
data arc2;
  reset arc1;
  oldflow=_flow_;
  oldfc=_fcost_;
                /* make duplicates of the flow and flowcost*/
                /* variables. If a id list was explicitly */
                /* specified, add oldflow and oldfc to this*/
                /* list so that they appear in subsequently*/
                /* created arcout= data sets */

```

The following PROC NETFLOW uses the warm start created previously, performs 250 stage 2 iterations and saves that solution, which (as `FUTURE1`, `ARCOUT=`, and `NODEOUT=` are specified) can be used as a warm start in another PROC NETFLOW run.

```

proc netflow
  warm
  nodedata=node2
  arcdata=arc2;
  reset
    maxit1=250
    future1;
  run;
  save
    nodeout=savelib.node3
    arcout=savelib.arc3;
                /* optimization halted because 250 iterations */
                /* were performed to resume optimization, */
                /* possibly in another session (the output */
                /* data sets were saved in a SAS library */
                /* called savelib) */

```

Using the latest warm start, PROC NETFLOW is re-invoked to find the optimal solution.

```

proc netflow
  warm
  nodedata=savelib.node3

```

```

    arcdata=savelib.arc3;
reset
    future1
    nodeout=node4
    arcout=arc4;
run;

```

If this problem has constraints with data in a data set called CON0, then in each of the previous PROC NETFLOW statements, specify **CONDATA=CON0**. Between PROC NETFLOW runs, you can change constraint data. In each of the **RESET** statements, you could specify the **CONOUT=** data set to save the last (possibly optimal) solution reached by the optimizer if it reaches stage 2. You could specify **FUTURE2** and the **DUALOUT=** data set to generate a constrained warm start.

```

proc netflow
    warm
    nodedata=node4
    arcdata=arc4
    condata=con0;
reset
    maxit2=125 /* optional, here as a reason why          */
                /* optimum will not be obtained          */
    scratch    /* optional, but warm start might be good */
                /* enough to start stage 2 optimization   */
    future2
run;
    /* optimization halted after 125 stage 2 iterations */
save dualout=dual1 conout=conout1;

```

Stage 2 optimization halted before optimum was reached. Now you can make cost and nonarc variable objective function coefficient changes. Then to restart optimization, use

```

proc netflow
    warm
    condata=con0
                /* NB. NETFLOW reads constraint data only */
    dualin=dual1
    arcdata=con1;
reset
    future2
    dualout=dual2
    conout=con2;
run;

```

---

## How to Make the Data Read of PROC NETFLOW More Efficient

This section contains information useful when you want to solve large constrained network problems. However, much of this information is also useful if you have a large linear programming problem. All of the options described in this section that are not directly applicable to networks (options such as **ARCS\_ONLY\_ARCDATA**, **ARC\_SINGLE\_OBS**, **NNODES=**, and **NARCS=**) can be specified to improve the speed at which LP data are read.

## Large Constrained Network Problems

Many of the models presented to PROC NETFLOW are enormous. They can be considered large by linear programming standards; problems with thousands of variables and constraints. When dealing with side constrained network programming problems, models can have not only a linear programming component of that magnitude, but also a larger, possibly *much* larger, network component.

The majority of a network problem's decision variables are arcs. Like an LP decision variable, an arc has an objective function coefficient, upper and lower value bounds, and a name. Arcs can have coefficients in constraints. Therefore, an arc is quite similar to an LP variable and places the same memory demands on optimization software as an LP variable. But a typical network model has many more arcs and nonarc variables than the typical LP model has variables. And arcs have tail and head nodes. Storing and processing node names require huge amounts of memory. To make matters worse, node names occupy memory at times when a large amount of other data should also reside in memory.

While memory requirements are lower for a model with embedded network component compared with the equivalent LP *once optimization starts*, the same is usually not true *during the data read*. Even though nodal flow conservation constraints in the LP should not be specified in the constrained network formulation, the memory requirements to read the latter are greater because each arc (unlike an LP variable) originates at one node, and is directed toward another.

## Paging

PROC NETFLOW has facilities to read data when the available memory is insufficient to store all the data at once. PROC NETFLOW does this by allocating memory for different purposes, for example, to store an array or receive data read from an input SAS data set. After that memory has filled, the information is sent to disk and PROC NETFLOW can resume filling that memory with new information. Often, information must be retrieved from disk so that data previously read can be examined or checked for consistency. Sometimes, to prevent any data from being lost, or to retain any changes made to the information in memory, the contents of the memory must be sent to disk before other information can take its place. This process of swapping information to and from disk is called paging. Paging can be very time-consuming, so it is crucial to minimize the amount of paging performed.

There are several steps you can take to make PROC NETFLOW read the data of network and linear programming models more efficiently, particularly when memory is scarce and the amount of paging must be reduced. PROC NETFLOW will then be able to tackle large problems in what can be considered reasonable amounts of time.

## The Order of Observations

PROC NETFLOW is quite flexible in the ways data can be supplied to it. Data can be given by any reasonable means. PROC NETFLOW has convenient defaults that can save you work when generating the data. There can be several ways to supply the same piece of data, and some pieces of data can be given more than once. PROC NETFLOW reads everything, then merges it all together. However, this flexibility and convenience come at a price; PROC NETFLOW may not assume the data has a characteristic that, if possessed by the data, could save time and memory during the data read. There are several options that indicate the data has some exploitable characteristic.

For example, an arc cost can be specified once or several times in the `ARCDATA=` or `CONDATA=` data set, or both. Every time it is given in `ARCDATA`, a check is made to ensure that the new value is the same as any corresponding value read in a previous observation of `ARCDATA`. Every time it is given in `CONDATA`,

a check is made to ensure that the new value is the same as the value read in a previous observation of **CONDATA**, or previously in **ARCDATA**. It would save PROC NETFLOW time if it knew that arc cost data would be encountered only once while reading **ARCDATA**, so performing the time-consuming check for consistency would not be necessary. Also, if you indicate that **CONDATA** contains data for constraints only, PROC NETFLOW will not expect any arc information, so memory will not be allocated to receive such data while reading **CONDATA**. This memory is used for other purposes and this might lead to a reduction in paging. If applicable, use the **ARC\_SINGLE\_OBS** or the **CON\_SINGLE\_OBS** option, or both, and the **NON\_REPLIC=COEFS** specification to improve how **ARCDATA** and **CONDATA** are read.

PROC NETFLOW allows the observations in input data sets to be in any order. However, major time savings can result if you are prepared to order observations in particular ways. Time spent by the SORT procedure to sort the input data sets, particularly the **CONDATA=** data set, may be more than made up for when PROC NETFLOW reads them, because PROC NETFLOW has in memory information possibly used when the previous observation was read. PROC NETFLOW can assume a piece of data is either similar to that of the last observation read or is new. In the first case, valuable information such as an arc or a nonarc variable number or a constraint number is retained from the previous observation. In the last case, checking the data with what has been read previously is not necessary.

Even if you do not sort the **CONDATA=** data set, grouping observations that contain data for the same arc or nonarc variable or the same row pays off. PROC NETFLOW establishes whether an observation being read is similar to the observation just read.

Practically, several input data sets for PROC NETFLOW might have this characteristic, because it is natural for data for each constraint to be grouped together ( **dense** format of **CONDATA**) or data for each column to be grouped together ( **sparse** format of **CONDATA**). If data for each arc or nonarc is spread over more than one observation of the **ARCDATA=** data set, it is natural to group these observations together.

Use the **GROUPED=** option to indicate whether observations of the **ARCDATA=** data set, **CONDATA=** data set, or both are grouped in a way that can be exploited during data read.

Time is saved if the type data for each row appears near the top of the **CONDATA=** data set, especially if it has the **sparse** format. Otherwise, when reading an observation, if PROC NETFLOW does not know if a row is a constraint or special row, the data are set aside. Once the data set has been completely read, PROC NETFLOW must reprocess the data it set aside. By then, it knows the type of each constraint or row or, if its type was not provided, it is assumed to have a default type.

## Better Memory Utilization

In order for PROC NETFLOW to make better utilization of available memory, you can now specify options that indicate the approximate size of the model. PROC NETFLOW then knows what to expect. For example, if you indicate that the problem has no nonarc variables, PROC NETFLOW will not allocate memory to store nonarc data. That memory is utilized better for other purposes. Memory is often allocated to receive or store data of some type. If you indicate that the model does not have much data of a particular type, the memory that would otherwise have been allocated to receive or store that data can be used to receive or store data of another type.

- **NNODES=** approximate number of nodes
- **NARCS=** approximate number of arcs
- **NNAS=** approximate number of nonarc variables or LP variables

- **NCONS=** approximate number of constraints
- **NCOEFS=** approximate number of constraint coefficients

These options will sometimes be referred to as Nxxxx= options.

You do not need to specify all these options for the model, but the more you do, the better. If you do not specify some or all of these options, PROC NETFLOW guesses the size of the problem by using what it already knows about the model. Sometimes PROC NETFLOW guesses the size of the model by looking at the number of observations in the **ARCDATA=** and **CONDATA=** data sets. However, PROC NETFLOW uses rough rules of thumb; that typical models are proportioned in certain ways (for example, if there are constraints, then arcs and nonarcs usually have 5 constraint coefficients). If your model has an unusual shape or structure, you are encouraged to use these options.

If you do use the options and you do not know the exact values to specify, *overestimate* the values. For example, if you specify **NARCS=10000** but the model has 10100 arcs, when dealing with the last 100 arcs, PROC NETFLOW might have to page out data for 10000 arcs each time one of the last arcs must be dealt with. Memory could have been allocated for all 10100 arcs without affecting (much) the rest of the data read, so **NARCS=10000** could be more of a hindrance than a help.

The point of these Nxxxx= options is to indicate the model size when PROC NETFLOW does not know it. When PROC NETFLOW knows the “real” value, that value is used instead of Nxxxx=.

When PROC NETFLOW is given a constrained solution warm start, PROC NETFLOW knows from the warm start information all model size parameters, so Nxxxx= options are not used. When an unconstrained warm start is used and the **SAME\_NONARC\_DATA** is specified, PROC NETFLOW knows the number of nonarc variables, so that is used instead of the value of the **NNAS=** option.

**ARCS\_ONLY\_ARCDATA** indicates that data for only arcs are in the **ARCDATA=** data set. Memory would not be wasted to receive data for nonarc and LP variables.

Use the memory usage parameters:

- The **BYTES=** option specifies the size of PROC NETFLOW main working memory in number of bytes.
- The **MAXARRAYBYTES=** option specifies the maximum number of bytes that an array can occupy.
- The **MEMREP** option indicates that memory usage report is to be displayed on the SAS log.

Specifying the **BYTES=** parameter is particularly important. Specify as large a number as possible, but not such a large number of bytes that will cause PROC NETFLOW (rather, the SAS System running underneath PROC NETFLOW) to run out of memory. Use the **MAXARRAYBYTES=** option if the model is very large or “disproportionate.” Try increasing or decreasing the **MAXARRAYBYTES=** option. Limiting the amount of memory for use by big arrays is good if they would take up too much memory to the detriment of smaller arrays, buffers, and other things that require memory. However, too small a value of the **MAXARRAYBYTES=** option might cause PROC NETFLOW to page a big array excessively. Never specify a value for the **MAXARRAYBYTES=** option that is smaller than the main node length array. PROC NETFLOW reports the size of this array on the SAS log if you specify the **MEMREP** option. The **MAXARRAYBYTES=** option influences paging not only in the data read, but also during optimization. It is often better if optimization is performed as fast as possible, even if the read is made slower as a consequence.

## Use Defaults to Reduce the Amount of Data

Use as much as possible the parameters that specify default values. For example, if there are several arcs with the same cost value *c*, use **DEFCOST=*c*** for arcs that have that cost. Use missing values in the **COST** variable in **ARCDATA** instead of *c*. PROC NETFLOW ignores missing values, but must read, store, and process nonmissing values, even if they are equal to a default option or could have been equal to a default parameter had it been specified. Sometimes, using default parameters makes the need for some SAS variables in the **ARCDATA=** and **CONDATA=** data sets no longer necessary, or reduces the quantity of data that must be read. The default options are

- **DEFCOST=** default cost of arcs, objective function of nonarc variables or LP variables
- **DEFMINFLOW=** default lower flow bound of arcs, lower bound of nonarc variables or LP variables
- **DEFCAPACITY=** default capacity of arcs, upper bound of nonarc variables or LP variables
- **DEFCONTYPE=LE** **DEFCONTYPE= <=**  
**DEFCONTYPE=EQ** **DEFCONTYPE= =**  
**DEFCONTYPE=GE** **DEFCONTYPE= >=** (default constraint type)

The default options themselves have defaults. For example, you do not need to specify **DEFCOST=0** in the **PROC NETFLOW** statement. You should still have missing values in the **COST** variable in **ARCDATA** for arcs that have zero costs.

If the network has only one supply node, one demand node, or both, use

- **SOURCE=** name of single node that has supply capability
- **SUPPLY=** the amount of supply at **SOURCE**
- **SINK=** name of single node that demands flow
- **DEMAND=** the amount of flow **SINK** demands

Do not specify that a constraint has zero right-hand-side values. That is the default. The only time it might be practical to specify a zero rhs is in observations of **CONDATA** read early so that PROC NETFLOW can infer that a row is a constraint. This could prevent coefficient data from being put aside because PROC NETFLOW did not know the row was a constraint.

## Names of Things

To cut data read time and memory requirements, reduce the number of bytes in the longest node name, longest arc name, and longest constraint name to 8 bytes or less. The longer a name, the more bytes must be stored and compared with other names.

If an arc has no constraint coefficients, do not give it a name in the **NAME** list variable in the **ARCDATA=** data set. Names for such arcs serve no purpose.

PROC NETFLOW can have a default name for each arc. If an arc is directed from node *tailname* toward node *headname*, the default name for that arc is *tailname\_headname*. If you do not want PROC NETFLOW to use these default arc names, specify **NAMECTRL=1**. Otherwise, PROC NETFLOW must use memory for storing node names and these node names must be searched often.

If you want to use the default *tailname\_headname name*, that is, `NAMECTRL=2` or `NAMECTRL=3`, do not use underscores in node names. If a `CONDATA` has a `dense` format and has a variable in the `VAR` list `A_B_C_D`, or if the value `A_B_C_D` is encountered as a value of the `COLUMN` list variable when reading `CONDATA` that has the `sparse` format, PROC NETFLOW first looks for a node named A. If it finds it, it looks for a node called `B_C_D`. It then looks for a node with the name `A_B` and possibly a node with name `C_D`. A search for a node named `A_B_C` and possibly a node named D is done. Underscores could have caused PROC NETFLOW to look unnecessarily for nonexistent nodes. Searching for node names can be expensive, and the amount of memory to store node names large. It might be better to assign the arc name `A_B_C_D` directly to an arc by having that value as a `NAME` list variable value for that arc in `ARCDATA` and specify `NAMECTRL=1`.

## Other Ways to Speed Up Data Reads

Use warm starts as much as possible.

- `WARM` indicates that the input SAS data sets contain a warm start.

The data read of a warm start is much faster than a cold start data read. The model size is known before the read starts. The observations of the `NODEDATA=` or `DUALIN=` data sets have observations ordered by node name and constraint name. Information is stored directly in the data structures used by PROC NETFLOW. For a cold start, much of preprocessing must be performed before the information can be stored in the same way. And using a warm start can greatly reduce the time PROC NETFLOW spends doing optimization.

- `SAME_NONARC_DATA` is an option that excludes data from processing.

This option indicates that the warm start nonarc variable data in `ARCDATA` is read and any nonarc variable data in `CONDATA` is to be ignored. Use this option if it is applicable, or when `CONDATA` has no nonarc variable data, or such data are duplicated in `ARCDATA`. `ARCDATA` is always read before `CONDATA`.

Arcs and nonarc variables can have associated with them values or quantities that have no bearing with the optimization. This information is given in `ARCDATA` in the `ID` list variables. For example, in a distribution problem, information such as truck number and driver's name can be associated with each arc. This is useful when a solution is saved in an output SAS data set. However, PROC NETFLOW needs to reserve memory to process this information when data are being read. For large problems when memory is scarce, it might be better to remove ancillary data from `ARCDATA`. After PROC NETFLOW runs, use SAS software to merge this information into the output data sets that contain the optimal solution.

---

## Macro Variable `_ORNETFL`

The NETFLOW procedure creates and initializes a SAS macro variable called `_ORNETFL`. After exiting the procedure, you can use `%put &_ORNETFL;` to view details about the optimization.

When the network simplex method is used, the value of `_ORNETFL` consists of the following parts:

- `ERROR_STATUS`, indicating the existence or absence of any errors
- `OPT_STATUS`, the stage of the optimization, or what solution has been found



Ideally, at the end of a PROC NETFLOW run in which the network simplex method is used, \_ORNETFL has the following value:

```
ERROR_STATUS=OK OPT_STATUS=OPTIMAL OBJECTIVE=x  
SOLUTION=OPTIMAL
```

At the end of a PROC NETFLOW run in which the interior point algorithm is used, \_ORNETFL should have the following value:

```
ERROR_STATUS=OK SOLUTION=OPTIMAL OBJECTIVE=x  
ITERATIONS=x ITERATING_TIME=x SOLUTION_TIME=x
```

Nontrailing blank characters that are unnecessary are removed.

If the preprocessor detects that a problem with a network component is infeasible, and you specify that the interior point algorithm should be used, \_ORNETFL has the following value:

```
ERROR_STATUS=OK SOLUTION=INFEASIBLE  
ITERATIONS=0 ITERATING_TIME=0 SOLUTION_TIME=0
```

The same value is assigned to the \_ORNETFL macro variable if the preprocessor detects that an LP problem is infeasible.



Table 7.11 lists alternate values for the \_ORNETFL value parts.

**Table 7.11** PROC NETFLOW \_ORNETFL Macro Values

| Keyword       | Value                                | Meaning  |
|---------------|--------------------------------------|--|
| ERROR_STATUS  | OK                                   | No errors  |
|               | MEMORY                               | Memory request failed  |
|               | IO                                   | Input/output error   |
|               | DATA                                 | Error in the data  |
|               | BUG                                  | Error with PROC NETFLOW  |
|               | SEMANTIC                             | Semantic error   |
|               | SYNTAX                               | Syntax error   |
|               | UNKNOWN                              | Unknown error  |
| OPT_STATUS    | START                                | No optimization has been done  |
|               | STAGE_1                              | Performing stage 1 optimization  |
|               | UNCON_OPT                            | Reached unconstrained optimum, but there are side constraints                    |
|               | STAGE_2                              | Performing stage 2 optimization  |
|               | OPTIMAL                              | Reached the optimum  |
| OBJECTIVE     | <i>objective</i>                     | Total cost or profit   |
| MINFLOW       | <i>minflow</i>                       | If <b>MAXFLOW</b> and <b>MAXIMIZE</b> are specified at the same time             |
| MAXFLOW       | <i>maxflow</i>                       | If <b>MAXFLOW</b> is specified   |
| SHORTEST_PATH | <i>shortpath</i>                     | If <b>SHORTPATH</b> is specified   |
| LONGEST_PATH  | <i>longpath</i>                      | If <b>SHORTPATH</b> and <b>MAXIMIZE</b> are specified at the same time           |
| SOLUTION      | NONOPTIMAL                           | More optimization is required  |
|               | STAGE_2_REQUIRED                     | Reached unconstrained optimum, stage 2 optimization is required                  |
|               | OPTIMAL                              | Have determined the optimum  |
|               | INFEASIBLE                           | Infeasible; no solution exists   |
|               | UNRESOLVED_OPTIMALITY_OR_FEASIBILITY | The optimization process stops before optimality or infeasibility can be proven. |
|               | MAXITERB_OPTION                      | The interior point algorithm stops after performing maximal                      |
|               | _STOPPED_OPTIMIZATION                | number of iterations specified by the <b>MAXITERB=</b> option                    |
|               |                                      |  |

## Memory Limit

The system option MEMSIZE sets a limit on the amount of memory used by the SAS System. If you do not specify a value for this option, then the SAS System sets a default memory limit. Your operating environment determines the actual size of the default memory limit, which is sufficient for many applications.

However, to solve most realistic optimization problems, the NETFLOW procedure might require more memory. Increasing the memory limit can reduce the chance of an out-of-memory condition.

**NOTE:** The MEMSIZE system option is not available in some operating environments. See the documentation for your operating environment for more information.

You can specify -MEMSIZE 0 to indicate all available memory should be used, but this setting should be used with caution. In most operating environments, it is better to specify an adequate amount of memory than to specify -MEMSIZE 0. For example, if you are running PROC OPTLP to solve LP problems with only a few hundred thousand variables and constraints, -MEMSIZE 500M might be sufficient to enable the procedure to run without an out-of-memory condition. When problems have millions of variables, -MEMSIZE 1000M or higher might be needed. These are “rules of thumb”—problems with atypical structure, density, or other characteristics can increase the optimizer’s memory requirements.

The MEMSIZE option can be specified at system invocation, on the SAS command line, or in a configuration file. The syntax is described in the SAS Companion for your operating environment.

To report a procedure’s memory consumption, you can use the FULLSTIMER option. The syntax is described in the SAS Companion for your operating environment.

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## The Interior Point Algorithm: NETFLOW Procedure

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### Introduction

The simplex algorithm, developed shortly after World War II, was the main method used to solve linear programming problems. Over the last fifteen years, the interior point algorithm has been developed to also solve linear programming problems. From the start it showed great theoretical promise, and considerable research in the area resulted in practical implementations that performed competitively with the simplex algorithm. More recently, interior point algorithms have evolved to become superior to the simplex algorithm, in general, especially when the problems are large.

The interior point algorithm has been implemented in PROC NETFLOW. This algorithm can be used to solve linear programs as well as network problems. When PROC NETFLOW detects that the problem has no network component, it automatically invokes the interior point algorithm to solve the problem. The data required by PROC NETFLOW for a linear program resembles the data for nonarc variables and constraints for constrained network problems.

If PROC NETFLOW does detect a network component to the problem (the problem has arcs), you must specify the option **INTPOINT** in the **PROC NETFLOW** statement if you want to use the interior point algorithm. PROC NETFLOW first converts the constrained network model into an equivalent linear programming formulation, solves that, then converts the LP back to the network model. These models remain conceptually easy since they are based on network diagrams that represent the problem pictorially. This procedure accepts the network specification in a format that is particularly suited to networks. This not only simplifies problem description but also aids in the interpretation of the solution. The conversions to and from the equivalent LP are done “behind the scenes.”

There are many variations of interior point algorithms. PROC NETFLOW uses the Primal-Dual with Predictor-Corrector algorithm. This algorithm and related theory can be found in the texts by Roos, Terlaky,

and Vial (1997), Wright (1996), and Ye (1996).

The remainder of this section is split into two parts. In the first part, how you use PROC NETFLOW's interior point algorithm to solve network problems is described. In the second part, using PROC NETFLOW to solve linear programming problems (its interior point algorithm must be used) is described. Both parts are organized similarly:

- The way data are supplied to PROC NETFLOW is outlined in a "Getting Started" subsection.
- An "Introductory Example" is solved to demonstrate how the data are set up, how PROC NETFLOW is used to compute the solution, and how the optimum is saved.
- More sophisticated ways to use PROC NETFLOW interactively are detailed in an "Interactivity" subsection.
- A "Functional Summary" lists the statements and options that can be used to control PROC NETFLOW. Of particular interest are the options used to control the optimizer, and the way the solution is saved into output data sets or is displayed.

The Linear Programs section has additional subsections:

- "Mathematical Description of LP"
- "Interior Point Algorithmic Details," a brief theory of the algorithm containing information about the options that can be specified to control the interior point algorithm.
- "Syntax" subsection, which is a subset of the syntax when the simplex algorithm is used. Gone are the statements and lists relevant only when the simplex algorithm is used.

---

## Network Models: Interior Point Algorithm

The data required by PROC NETFLOW for a network problem is identical whether the simplex algorithm or the interior point algorithm is used as the optimizer. By default, the simplex algorithm is used for problems with a network component. To use the interior point algorithm, all you need to do is specify the **INTPOINT** option in the **PROC NETFLOW** statement. You can optionally specify some options that control the interior point algorithm, of which there are only a few. The interior point algorithm is remarkably robust when reasonable choices are made during the design and implementation, so it does not need to be tuned to the same extent as the simplex algorithm.

### When to Use INTPOINT: Network Models: Interior Point Algorithm

PROC NETFLOW uses the primal simplex network algorithm and the primal partitioning algorithm to solve constrained network problems. These algorithms are fast, since they take advantage of algebraic properties of the network component of the problem.

If the network component of the model is large compared to the side constraint component, PROC NETFLOW's optimizer can store what would otherwise be a large matrix as a spanning tree computer data structure. Computations involving the spanning tree data structure can be performed much faster than those

using matrices. Only the nonnetwork part of the problem, hopefully quite small, needs to be manipulated by PROC NETFLOW as matrices.

In contrast, LP optimizers must contend with matrices that can be large for large problems. Arithmetic operations on matrices often accumulate rounding errors that cause difficulties for the algorithm. So in addition to the performance improvements, network optimization is generally more numerically stable than LP optimization.

The nodal flow conservation constraints do not need to be specified in the network model. They are implied by the network structure. However, flow conservation constraints do make up the data for the equivalent LP model. If you have an LP that is small after the flow conservation constraints are removed, that problem is a definite candidate for solution by PROC NETFLOW's specialized simplex method.

However, some constrained network problems are solved more quickly by the interior point algorithm than the network optimizer in PROC NETFLOW. Usually, they have a large number of side constraints or nonarc variables. These models are more like LPs than network problems. The network component of the problem is so small that PROC NETFLOW's network simplex method cannot recoup the effort to exploit that component rather than treat the whole problem as an LP. If this is the case, it is worthwhile to get PROC NETFLOW to convert a constrained network problem to the equivalent LP and use its interior point algorithm. This conversion must be done before any optimization has been performed (specify the **INTPOINT** option in the **PROC NETFLOW** statement).

Even though some network problems are better solved by converting them to an LP, the input data and the output solution are more conveniently maintained as networks. You retain the advantages of casting problems as networks: ease of problem generation and expansion when more detail is required. The model and optimal solutions are easy to understand, as a network can be drawn.

### Getting Started: Network Models: Interior Point Algorithm

To solve network programming problems with side constraints using PROC NETFLOW, you save a representation of the network and the side constraints in three SAS data sets. These data sets are then passed to PROC NETFLOW for solution. There are various forms that a problem's data can take. You can use any one or a combination of several of these forms.

The **NODEDATA=** data set contains the names of the supply and demand nodes and the supply or demand associated with each. These are the elements in the column vector  $b$  in problem (NPSC).

The **ARCDATA=** data set contains information about the variables of the problem. Usually these are arcs, but there can also be data related to nonarc variables in the **ARCDATA=** data set. If there are no arcs, this is a linear programming problem.

An arc is identified by the names of its tail node (where it originates) and head node (where it is directed). Each observation can be used to identify an arc in the network and, optionally, the cost per flow unit across the arc, the arc's lower flow bound, capacity, and name. These data are associated with the matrix  $F$  and the vectors  $c$ ,  $l$ , and  $u$  in problem (NPSC).

**NOTE:** Although  $F$  is a node-arc incidence matrix, it is specified in the **ARCDATA=** data set by arc definitions. Do not explicitly specify these flow conservation constraints as constraints of the problem.

In addition, the **ARCDATA=** data set can be used to specify information about nonarc variables, including objective function coefficients, lower and upper value bounds, and names. These data are the elements of the vectors  $d$ ,  $m$ , and  $v$  in problem (NPSC). Data for an arc or nonarc variable can be given in more than one observation.

Supply and demand data also can be specified in the **ARCDATA=** data set. In such a case, the **NODEDATA=** data set may not be needed.

The **CONDATA=** data set describes the side constraints and their right-hand sides. These data are elements of the matrices  $H$  and  $Q$  and the vector  $r$ . Constraint types are also specified in the **CONDATA=** data set. You can include in this data set upper bound values or capacities, lower flow or value bounds, and costs or objective function coefficients. It is possible to give all information about some or all nonarc variables in the **CONDATA=** data set.

An arc or nonarc variable is identified in this data set by its name. If you specify an arc's name in the **ARCDATA=** data set, then this name is used to associate data in the **CONDATA=** data set with that arc. Each arc also has a default name that is the name of the tail and head node of the arc concatenated together and separated by an underscore character; *tail\_head*, for example.

If you use the **dense** side constraint input format and want to use the default arc names, these arc names are names of SAS variables in the **VAR** list of the **CONDATA=** data set.

If you use the **sparse** side constraint input format (also described later) and want to use the default arc names, these arc names are values of the **COLUMN** list SAS variable of the **CONDATA=** data set.

When using the interior point algorithm, the execution of PROC NETFLOW has two stages. In the preliminary (zeroth) stage, the data are read from the **NODEDATA=** data set, the **ARCDATA=** data set, and the **CONDATA=** data set. Error checking is performed. The model is converted into an equivalent linear program.

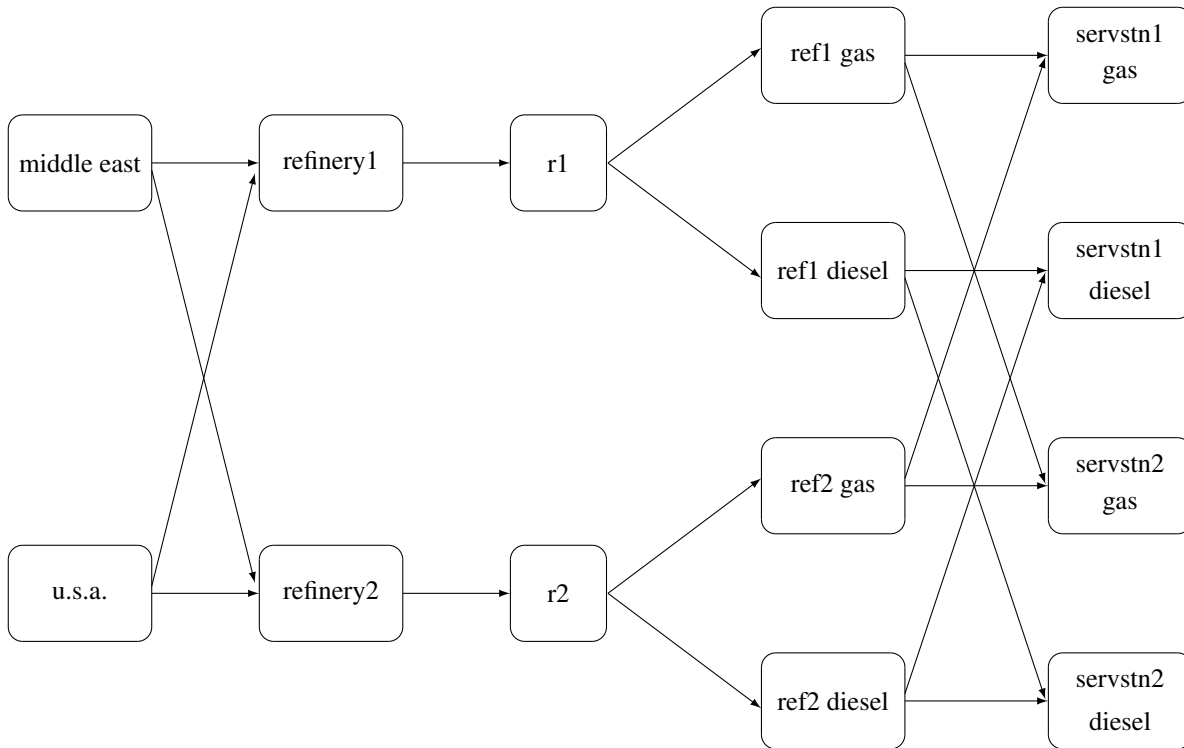
In the next stage, the linear program is preprocessed. This is optional but highly recommended. Preprocessing analyzes the model and tries to determine before optimization whether variables can be “fixed” to their optimal values. Knowing that, the model can be modified and these variables dropped out. It can be determined that some constraints are redundant. Sometimes, preprocessing succeeds in reducing the size of the problem, thereby making the subsequent optimization easier and faster.

The optimal solution to the linear program is then found. The linear program is converted back to the original constrained network problem, and the optimum for this is derived from the optimum of the equivalent linear program. If the problem was preprocessed, the model is now post-processed, where fixed variables are reintroduced. The solution can be saved in the **CONOUT=** data set. This data set is also named in the **PROC NETFLOW**, **RESET**, and **SAVE** statements.

The interior point algorithm cannot efficiently be warm started, so options such as **FUTURE1** and **FUTURE2** options are irrelevant.

### Introductory Example: Network Models: Interior Point Algorithm

Consider the following transshipment problem for an oil company in the section “Introductory Example” on page 321. Recall that crude oil is shipped to refineries where it is processed into gasoline and diesel fuel. The gasoline and diesel fuel are then distributed to service stations. At each stage there are shipping, processing, and distribution costs. Also, there are lower flow bounds and capacities. In addition, there are side constraints to model crude mix stipulations, and model the limitations on the amount of Middle Eastern crude that can be processed by each refinery and the conversion proportions of crude to gasoline and diesel fuel. The network diagram is reproduced in Figure 7.16.

**Figure 7.16** Oil Industry Example

To solve this problem with PROC NETFLOW, a representation of the model is saved in three SAS data sets that are identical to the data sets supplied to PROC NETFLOW when the simplex algorithm was used.

To find the minimum cost flow through the network that satisfies the supplies, demands, and side constraints, invoke PROC NETFLOW as follows:

```

proc netflow
  intpoint          /* <<<--- Interior Point used */
  nodedata=noded    /* the supply and demand data */
  arcdata=arc1       /* the arc descriptions      */
  condata=con1       /* the side constraints      */
  conout=solution;   /* the solution data set    */
run;

```

The following messages, which appear on the SAS log, summarize the model as read by PROC NETFLOW and note the progress toward a solution:

```
NOTE: Number of nodes= 14 .
NOTE: Number of supply nodes= 2 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 180 , total demand= 180 .
NOTE: Number of arcs= 18 .
NOTE: Number of <= side constraints= 0 .
NOTE: Number of == side constraints= 2 .
NOTE: Number of >= side constraints= 2 .
NOTE: Number of side constraint coefficients= 8 .
NOTE: The following messages relate to the equivalent Linear Programming
      problem solved by the Interior Point algorithm.
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 16 .
NOTE: Number of >= constraints= 2 .
NOTE: Number of constraint coefficients= 44 .
NOTE: Number of variables= 18 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 3.
NOTE: After preprocessing, number of >= constraints= 2.
NOTE: The preprocessor eliminated 13 constraints from the problem.
NOTE: The preprocessor eliminated 33 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 5.
NOTE: The preprocessor eliminated 13 variables from the problem.
NOTE: 4 columns, 0 rows and 4 coefficients were added to the problem to handle
      unrestricted variables, variables that are split, and constraint slack or
      surplus variables.
NOTE: There are 10 sub-diagonal nonzeros in the unfactored A Atranspose matrix.
NOTE: The 5 factor nodes make up 1 supernodes
NOTE: There are 0 nonzero sub-rows or sub-columns outside the supernodal
      triangular regions along the factors leading diagonal.
NOTE: Bound feasibility attained by iteration 1.
NOTE: Dual feasibility attained by iteration 1.
NOTE: Constraint feasibility attained by iteration 1.
NOTE: The Primal-Dual Predictor-Corrector Interior Point algorithm performed 6
      iterations.
NOTE: Optimum reached.
NOTE: Objective= 50875.
NOTE: The data set WORK.SOLUTION has 18 observations and 10 variables.
```

The first set of messages provide statistics on the size of the equivalent linear programming problem. The number of variables may not equal the number of arcs if the problem has nonarc variables. This example has none. To convert a network to an equivalent LP problem, a flow conservation constraint must be created for each node (including an excess or bypass node, if required). This explains why the number of equality side constraints and the number of constraint coefficients change when the interior point algorithm is used.

If the preprocessor was successful in decreasing the problem size, some messages will report how well it did. In this example, the model size was cut in half!

The following set of messages describe aspects of the interior point algorithm. Of particular interest are those concerned with the Cholesky factorization of  $AA^T$  where  $A$  is the coefficient matrix of the final LP. It is crucial to preorder the rows and columns of this matrix to prevent *fill-in* and reduce the number of row

operations to undertake the factorization. See the section “Interior Point Algorithmic Details” on page 436 for more explanation.

Unlike PROC LP, which displays the solution and other information as output, PROC NETFLOW saves the optimum in output SAS data sets you specify. For this example, the solution is saved in the SOLUTION data set. It can be displayed with PROC PRINT as

```
proc print data=solution;
  var _from_ _to_ _cost_ _capac_ _lo_ _name_
      _supply_ _demand_ _flow_ _fcost_ ;
  sum _fcost_;
  title3 'Constrained Optimum';
run;
```

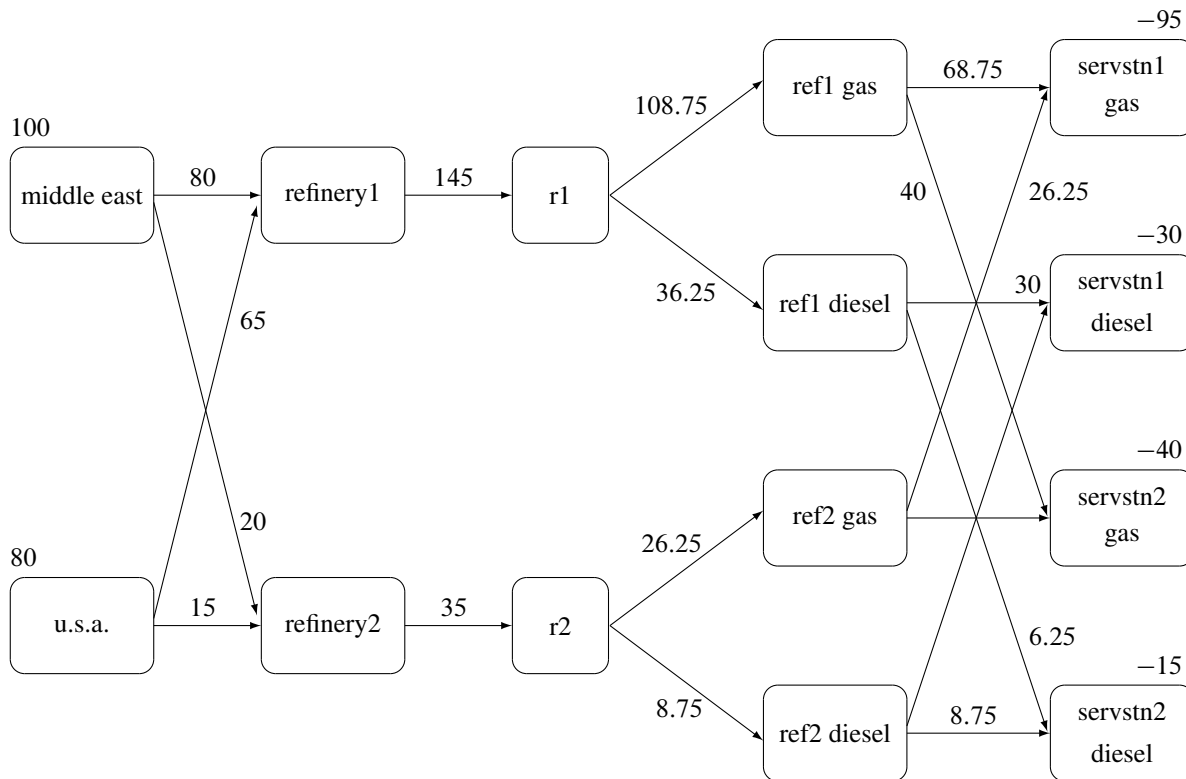
Figure 7.17 CONOUT=SOLUTION

| Oil Industry Example |  |  |  |  |  |   |  |   |  |  |  |
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| Constrained Optimum  |  |  |  |  |  |   |  |   |  |  |  |
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total cost of the solution found by the simplex algorithm. In this example, the solutions are the same (within several significant digits), but sometimes the solutions can be different.

**Figure 7.18** Oil Industry Solution



### Interactivity: Network Models: Interior Point Algorithm

PROC NETFLOW can be used interactively. You begin by giving the **PROC NETFLOW** statement with **INTPOINT** specified, and you must specify the **ARC DATA=** data set. The **CON DATA=** data set must also be specified if the problem has side constraints. If necessary, specify the **NODE DATA=** data set.

The variable lists should be given next. If you have variables in the input data sets that have special names (for example, a variable in the **ARC DATA=** data set named **\_TAIL\_** that has tail nodes of arcs as values), it may not be necessary to have many or any variable lists.

So far, this is the same as when the simplex algorithm is used, except the **INTPOINT** option is specified in the **PROC NETFLOW** statement. The **PRINT**, **QUIT**, **SAVE**, **SHOW**, **RESET**, and **RUN** statements follow and can be listed in any order. The **QUIT** statements can be used only once. The others can be used as many times as needed.

The **CONOPT** and **PIVOT** statements are not relevant to the interior point algorithm and should not be used.

Use the **RESET** or **SAVE** statement to change the name of the output data set. There is only one output data set, the **CONOUT=** data set. With the **RESET** statement, you can also indicate the reasons why optimization should stop (for example, you can indicate the maximum number of iterations that can be performed). PROC NETFLOW then has a chance to either execute the next statement, or, if the next statement is one that PROC NETFLOW does not recognize (the next PROC or DATA step in the SAS session), do any allowed

optimization and finish. If no new statement has been submitted, you are prompted for one. Some options of the **RESET** statement enable you to control aspects of the interior point algorithm. Specifying certain values for these options can reduce the time it takes to solve a problem. Note that any of the **RESET** options can be specified in the **PROC NETFLOW** statement.

The **RUN** statement starts optimization. Once the optimization has started, it runs until the optimum is reached. The **RUN** statement should be specified at most once.

The **QUIT** statement immediately stops **PROC NETFLOW**. The **SAVE** statement has options that enable you to name the output data set; information about the current solution is put in this output data set. Use the **SHOW** statement if you want to examine the values of options of other statements. Information about the amount of optimization that has been done and the **STATUS** of the current solution can also be displayed using the **SHOW** statement.

The **PRINT** statement makes **PROC NETFLOW** display parts of the problem. The way the **PRINT** statements are specified are identical whether the interior point algorithm or the simplex algorithm is used, however there are minor differences in what is displayed for each arc, nonarc variable or constraint coefficient.

**PRINT ARCS** produces information on all arcs. **PRINT SOME\_ARCS** limits this output to a subset of arcs. There are similar **PRINT** statements for nonarc variables and constraints:

```
PRINT NONARCS;
PRINT SOME_NONARCS;
PRINT CONSTRAINTS;
PRINT SOME_CONS;
```

**PRINT CON\_ARCS** enables you to limit constraint information that is obtained to members of a set of arcs and that have nonzero constraint coefficients in a set of constraints. **PRINT CON\_NONARCS** is the corresponding statement for nonarc variables.

For example, an interactive **PROC NETFLOW** run might look something like this:

```
proc netflow
    intpoint      /* use the Interior Point algorithm */
    arcdata=data set
    other options;
    variable list specifications; /* if necessary      */
    reset options;
    print options;                /* look at problem */
run;                             /* do the optimization */
    print options; /* look at the optimal solution */
    save options;  /* keep optimal solution        */
```

If you are interested only in finding the optimal solution, have used SAS variables that have special names in the input data sets, and want to use default settings for everything, then the following statement is all you need.

```
proc netflow intpoint arcdata= data set ;
```

## Functional Summary: Network Models, Interior Point Algorithm

The following table outlines the options available for the NETFLOW procedure when the interior point algorithm is being used, classified by function.

**Table 7.12** Functional Summary, Network Models

| Description                                     | Statement    | Option            |
|---|--------------|-------------------|
| <b>Input Data Set Options:</b>                  |              |                   |
| Arcs input data set                             | PROC NETFLOW | ARCDATA=          |
| Nodes input data set                            | PROC NETFLOW | NODEDATA=         |
| Constraint input data set                       | PROC NETFLOW | CONDATA=          |
| <b>Output Data Set Option:</b>                  |              |                   |
| Constrained solution data set                   | PROC NETFLOW | CONOUT=           |
| <b>Data Set Read Options:</b>                   |              |                   |
| CONDATA has sparse data format                  | PROC NETFLOW | SPARSECONDATA     |
| Default constraint type                         | PROC NETFLOW | DEFCONTYPE=       |
| Special COLUMN variable value                   | PROC NETFLOW | TYPEOBS=          |
| Special COLUMN variable value                   | PROC NETFLOW | RHSOBS=           |
| Used to interpret arc and nonarc variable names | PROC NETFLOW | NAMECTRL=         |
| No new nonarc variables                         | PROC NETFLOW | SAME_NONARC_DATA  |
| No nonarc data in ARCDATA                       | PROC NETFLOW | ARCS_ONLY_ARCDATA |
| Data for an arc found once in ARCDATA           | PROC NETFLOW | ARC_SINGLE_OBS    |
| Data for a constraint found once in CONDATA     | PROC NETFLOW | CON_SINGLE_OBS    |
| Data for a coefficient found once in CONDATA    | PROC NETFLOW | NON_REPLIC=       |
| Data are grouped, exploited during data read    | PROC NETFLOW | GROUPED=          |
| <b>Problem Size Specification Options:</b>      |              |                   |
| Approximate number of nodes                     | PROC NETFLOW | NNODES=           |
| Approximate number of arcs                      | PROC NETFLOW | NARCS=            |
| Approximate number of nonarc variables          | PROC NETFLOW | NNAS=             |
| Approximate number of coefficients              | PROC NETFLOW | NCOEFS=           |
| Approximate number of constraints               | PROC NETFLOW | NCONS=            |
| <b>Network Options:</b>                         |              |                   |
| Default arc cost                                | PROC NETFLOW | DEFCOST=          |
| Default arc capacity                            | PROC NETFLOW | DEFCAPACITY=      |
| Default arc lower flow bound                    | PROC NETFLOW | DEFMINFLOW=       |
| Network's only supply node                      | PROC NETFLOW | SOURCE=           |
| SOURCE's supply capability                      | PROC NETFLOW | SUPPLY=           |
| Network's only demand node                      | PROC NETFLOW | SINK=             |
| SINK's demand                                   | PROC NETFLOW | DEMAND=           |
| Convey excess supply/demand through network     | PROC NETFLOW | THRUNET           |
| Find maximal flow between SOURCE and SINK       | PROC NETFLOW | MAXFLOW           |
| Cost of bypass arc for MAXFLOW problem          | PROC NETFLOW | BYPASSDIVIDE=     |

| Description  | Statement    | Option             |
|--|--------------|--------------------|
| Find shortest path from <b>SOURCE</b> to <b>SINK</b> | PROC NETFLOW | SHORTPATH          |
| <b>Memory Control Options:</b>                       |              |                    |
| Issue memory usage messages to SAS log               | PROC NETFLOW | MEMREP             |
| Number of bytes to use for main memory               | PROC NETFLOW | BYTES=             |
| Proportion of memory for arrays                      | PROC NETFLOW | COREFACTOR=        |
| Maximum bytes for a single array                     | PROC NETFLOW | MAXARRAYBYTES=     |
| <b>Interior Point Algorithm Options:</b>             |              |                    |
| Use interior point algorithm                         | PROC NETFLOW | INTPOINT           |
| Factorization method                                 | RESET        | FACT_METHOD=       |
| Allowed amount of dual infeasibility                 | RESET        | TOLDINF=           |
| Allowed amount of primal infeasibility               | RESET        | TOLPINF=           |
| Allowed total amount of dual infeasibility           | RESET        | TOLTOTDINF=        |
| Allowed total amount of primal infeasibility         | RESET        | TOLTOTPINF=        |
| Cut-off tolerance for Cholesky factorization         | RESET        | CHOLTINYTOL=       |
| Density threshold for Cholesky processing            | RESET        | DENSETHR=          |
| Step-length multiplier                               | RESET        | PDSTEPMULT=        |
| Preprocessing type                                   | RESET        | PRSLTYPE=          |
| Print optimization progress on SAS log               | RESET        | PRINTLEVEL2=       |
| Write optimization time to SAS log                   | RESET        | OPTIM_TIMER        |
| <b>Interior Point Stopping Criteria Options:</b>     |              |                    |
| Maximum number of interior point iterations          | RESET        | MAXITERB=          |
| Primal-dual (duality) gap tolerance                  | RESET        | PDGAPTOL=          |
| Stop because of complementarity                      | RESET        | STOP_C=            |
| Stop because of duality gap                          | RESET        | STOP_DG=           |
| Stop because of <i>infeas<sub>b</sub></i>            | RESET        | STOP_IB=           |
| Stop because of <i>infeas<sub>c</sub></i>            | RESET        | STOP_IC=           |
| Stop because of <i>infeas<sub>d</sub></i>            | RESET        | STOP_ID=           |
| Stop because of complementarity                      | RESET        | AND_STOP_C=        |
| Stop because of duality gap                          | RESET        | AND_STOP_DG=       |
| Stop because of <i>infeas<sub>b</sub></i>            | RESET        | AND_STOP_IB=       |
| Stop because of <i>infeas<sub>c</sub></i>            | RESET        | AND_STOP_IC=       |
| Stop because of <i>infeas<sub>d</sub></i>            | RESET        | AND_STOP_ID=       |
| Stop because of complementarity                      | RESET        | KEEPGOING_C=       |
| Stop because of duality gap                          | RESET        | KEEPGOING_DG=      |
| Stop because of <i>infeas<sub>b</sub></i>            | RESET        | KEEPGOING_IB=      |
| Stop because of <i>infeas<sub>c</sub></i>            | RESET        | KEEPGOING_IC=      |
| Stop because of <i>infeas<sub>d</sub></i>            | RESET        | KEEPGOING_ID=      |
| Stop because of complementarity                      | RESET        | AND_KEEPPGOING_C=  |
| Stop because of duality gap                          | RESET        | AND_KEEPPGOING_DG= |
| Stop because of <i>infeas<sub>b</sub></i>            | RESET        | AND_KEEPPGOING_IB= |
| Stop because of <i>infeas<sub>c</sub></i>            | RESET        | AND_KEEPPGOING_IC= |
| Stop because of <i>infeas<sub>d</sub></i>            | RESET        | AND_KEEPPGOING_ID= |

| Description  | Statement    | Option         |
|--|--------------|----------------|
| <b>PRINT Statement Options:</b>  |              |                |
| Display everything   | PRINT        | PROBLEM        |
| Display arc information  | PRINT        | ARCS           |
| Display nonarc variable information  | PRINT        | NONARCS        |
| Display variable information   | PRINT        | VARIABLES      |
| Display constraint information   | PRINT        | CONSTRAINTS    |
| Display information for some arcs  | PRINT        | SOME_ARCS      |
| Display information for some nonarc variables                                  | PRINT        | SOME_NONARCS   |
| Display information for some variables   | PRINT        | SOME_VARIABLES |
| Display information for some constraints                                       | PRINT        | SOME_CONS      |
| Display information for some constraints associated with some arcs             | PRINT        | CON_ARCS       |
| Display information for some constraints associated with some nonarc variables | PRINT        | CON_NONARCS    |
| Display information for some constraints associated with some variables        | PRINT        | CON_VARIABLES  |
| <b>PRINT Statement Qualifiers:</b>   |              |                |
| Produce a short report   | PRINT        | / SHORT        |
| Produce a long report  | PRINT        | / LONG         |
| Display arcs/variables with zero flow/value                                    | PRINT        | / ZERO         |
| Display arcs/variables with nonzero flow/value                                 | PRINT        | / NONZERO      |
| <b>SHOW Statement Options:</b>   |              |                |
| Show problem, optimization status  | SHOW         | STATUS         |
| Show network model parameters  | SHOW         | NETSTMT        |
| Show data sets that have been or will be created                               | SHOW         | DATASETS       |
| <b>Miscellaneous Options:</b>  |              |                |
| Infinity value   | PROC NETFLOW | INFINITY=      |
| Scale constraint row, nonarc variable column coefficients, or both             | PROC NETFLOW | SCALE=         |
| Maximization instead of minimization   | PROC NETFLOW | MAXIMIZE       |

## Linear Programming Models: Interior Point Algorithm

By default, the interior point algorithm is used for problems without a network component, that is, a linear programming problem. You do not need to specify the `INTPOINT` option in the `PROC NETFLOW` statement (although you will do no harm if you do).

Data for a linear programming problem resembles the data for side constraints and nonarc variables supplied to `PROC NETFLOW` when solving a constrained network problem. It is also very similar to the data required by the LP procedure.

## Mathematical Description of LP

If the network component of NPSC is removed, the result is the mathematical description of the linear programming problem. If an LP has  $g$  variables, and  $k$  constraints, then the formal statement of the problem solved by PROC NETFLOW is

$$\begin{array}{ll} \text{minimize} & d^T z \\ \text{subject to} & Qz \{ \geq, =, \leq \} r \\ & m \leq z \leq v \end{array}$$

where

- $d$  is the  $g \times 1$  objective function coefficient vector
- $z$  is the  $g \times 1$  variable value vector
- $Q$  is the  $k \times g$  constraint coefficient matrix for variables, where  $Q_{i,j}$  is the coefficient of variable  $j$  in the  $i$ th constraint
- $r$  is the  $k \times 1$  side constraint right-hand-side vector
- $m$  is the  $g \times 1$  variable value lower bound vector
- $v$  is the  $g \times 1$  variable value upper bound vector

## Interior Point Algorithmic Details

After preprocessing, the linear program to be solved is

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0 \end{array}$$

This is the *primal* problem. The matrices  $d$ ,  $z$ , and  $Q$  of NPSC have been renamed  $c$ ,  $x$ , and  $A$  respectively, as these symbols are by convention used more, the problem to be solved is different from the original because of preprocessing, and there has been a change of primal variable to transform the LP into one whose variables have zero lower bounds. To simplify the algebra here, assume that variables have infinite bounds, and constraints are equalities. (Interior point algorithms do efficiently handle finite bounds, and it is easy to introduce primal slack variables to change inequalities into equalities.) The problem has  $n$  variables;  $i$  is a variable number,  $k$  is an iteration number, and if used as a subscript or superscript it denotes “of iteration  $k$ ”.

There exists an equivalent problem, the *dual* problem, stated as

$$\begin{array}{ll} \text{maximize} & b^T y \\ \text{subject to} & A^T y + s = c \\ & s \geq 0 \end{array}$$

where  $y$  are dual variables, and  $s$  are dual constraint slacks.

The interior point algorithm solves the system of equations to satisfy the Karush-Kuhn-Tucker (KKT) conditions for optimality:

$$\begin{aligned} Ax &= b \\ A^T y + s &= c \\ x^T s &= 0 \\ x &\geq 0 \\ s &\geq 0 \end{aligned}$$

These are the conditions for feasibility, with the *complementarity* condition  $x^T s = 0$  added. Complementarity forces the optimal objectives of the primal and dual to be equal,  $c^T x_{opt} = b^T y_{opt}$ , as

$$\begin{aligned} 0 &= x_{opt}^T s_{opt} = s_{opt}^T x_{opt} = (c - A^T y_{opt})^T x_{opt} \\ &= c^T x_{opt} - y_{opt}^T (Ax_{opt}) = c^T x_{opt} - b^T y_{opt} \end{aligned}$$

Before the optimum is reached, a solution  $(x, y, s)$  may not satisfy the KKT conditions:

- Primal constraints may be violated,  $infeas_c = b - Ax \neq 0$ .
- Dual constraints may be violated,  $infeas_d = c - A^T y - s \neq 0$ .
- Complementarity may not be satisfied,  $x^T s = c^T x - b^T y \neq 0$ .

This is called the *duality gap*.

The interior point algorithm works by using Newton's method to find a direction to move  $(\Delta x^k, \Delta y^k, \Delta s^k)$  from the current solution  $(x^k, y^k, s^k)$  toward a better solution:

$$(x^{k+1}, y^{k+1}, s^{k+1}) = (x^k, y^k, s^k) + \alpha(\Delta x^k, \Delta y^k, \Delta s^k)$$

where  $\alpha$  is the *step length* and is assigned a value as large as possible but  $\leq 1.0$  and not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  is “too close” to zero. The direction in which to move is found using the following:

$$\begin{aligned} A\Delta x^k &= -infeas_c \\ A^T \Delta y^k + \Delta s^k &= -infeas_d \\ S^k \Delta x^k + X^k \Delta s^k &= -X^k S^k e \end{aligned}$$

where  $S = \text{diag}(s)$ ,  $X = \text{diag}(x)$ , and  $e$  is a vector with all elements equal to 1.

To greatly improve performance, the third equation is changed to

$$S^k \Delta x^k + X^k \Delta s^k = -X^k S^k e + \sigma_k \mu_k e$$

where  $\mu_k = 1/n X^k S^k e$ , the average complementarity, and  $0 \leq \sigma_k \leq 1$ .

The effect now is to find a direction in which to move to reduce infeasibilities and to reduce the complementarity toward zero, but if any  $x_i^k s_i^k$  is too close to zero, it is “nudged out” to  $\mu$ , and any  $x_i^k s_i^k$  that is larger than  $\mu$  is “nudged into”  $\mu$ . A  $\sigma_k$  close to or equal to 0.0 biases a direction toward the optimum, and a value for  $\sigma_k$  close to or equal to 1.0 “centers” the direction toward a point where all pairwise products  $x_i^k s_i^k = \mu$ . Such points make up the *central path* in the interior. Although centering directions make little, if any, progress in reducing  $\mu$  and moving the solution closer to the optimum, substantial progress toward the optimum can usually be made in the next iteration.

The central path is crucial to why the interior point algorithm is so efficient. This path “guides” the algorithm to the optimum through the interior of feasible space. Without centering, the algorithm would find a series of solutions near each other close to the boundary of feasible space. Step lengths along the direction would be small and many more iterations would probably be required to reach the optimum.

The calculation of the direction is the most time-consuming step of the interior point algorithm. Assume the  $k$ th iteration is being performed, so the subscript and superscript  $k$  can be dropped from the algebra:

$$\begin{aligned} A \Delta x &= -infeas_c \\ A^T \Delta y + \Delta s &= -infeas_d \\ S \Delta x + X \Delta s &= -X S e + \sigma \mu e \end{aligned}$$

Rearranging the second equation,

$$\Delta s = -infeas_d - A^T \Delta y$$

Rearranging the third equation,

$$\begin{aligned} \Delta s &= X^{-1}(-S \Delta x - X S e + \sigma \mu e) \\ \Delta s &= -\Theta \Delta x - S e + X^{-1} \sigma \mu e \end{aligned}$$

where  $\Theta = S X^{-1}$ .

Equating these two expressions for  $\Delta s$  and rearranging,

$$\begin{aligned} -\Theta \Delta x - S e + X^{-1} \sigma \mu e &= -infeas_d - A^T \Delta y \\ -\Theta \Delta x &= S e - X^{-1} \sigma \mu e - infeas_d - A^T \Delta y \\ \Delta x &= \Theta^{-1}(-S e + X^{-1} \sigma \mu e + infeas_d + A^T \Delta y) \\ \Delta x &= \rho + \Theta^{-1} A^T \Delta y \end{aligned}$$

where  $\rho = \Theta^{-1}(-S e + X^{-1} \sigma \mu e + infeas_d)$ .



Substituting into the first direction equation,

$$\begin{aligned}
 A\Delta x &= -infeas_c \\
 A(\rho + \Theta^{-1}A^T\Delta y) &= -infeas_c \\
 A\Theta^{-1}A^T\Delta y &= -infeas_c - A\rho \\
 \Delta y &= (A\Theta^{-1}A^T)^{-1}(-infeas_c - A\rho)
 \end{aligned}$$

$\Theta$ ,  $\rho$ ,  $\Delta y$ ,  $\Delta x$  and  $\Delta s$  are calculated in that order. The hardest term is the factorization of the  $(A\Theta^{-1}A^T)$  matrix to determine  $\Delta y$ . Fortunately, although the *values* of  $(A\Theta^{-1}A^T)$  are different for each iteration, the *locations* of the nonzeros in this matrix remain fixed; the nonzero locations are the same as those in the matrix  $(AA^T)$ . This is due to  $\Theta^{-1} = XS^{-1}$  being a diagonal matrix, which has the effect of merely scaling the columns of  $(AA^T)$ .

The fact that the nonzeros in  $A\Theta^{-1}A^T$  have a constant pattern is exploited by all interior point algorithms, and is a major reason for their excellent performance. Before iterations begin,  $AA^T$  is examined and its rows and columns are permuted so that during Cholesky Factorization, the number of *fill-ins* created is smaller. A list of arithmetic operations to perform the factorization is saved in concise computer data structures (working with memory locations rather than actual numerical values). This is called *symbolic factorization*. During iterations, when memory has been initialized with numerical values, the operations list is performed sequentially. Determining how the factorization should be performed again and again is unnecessary.

### The Primal-Dual Predictor-Corrector Interior Point Algorithm

The variant of the interior point algorithm implemented in PROC NETFLOW is a Primal-Dual Predictor-Corrector interior point algorithm. At first, Newton's method is used to find a direction to move  $(\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k)$ , but calculated as if  $\mu$  is zero, that is, a step with no centering, known as an *affine* step:

$$\begin{aligned}
 A\Delta x_{aff}^k &= -infeas_c \\
 A^T\Delta y_{aff}^k + \Delta s_{aff}^k &= -infeas_d \\
 S^k\Delta x_{aff}^k + X^k\Delta s_{aff}^k &= -X^kS^ke \\
 (x_{aff}^k, y_{aff}^k, s_{aff}^k) &= (x^k, y^k, s^k) + \alpha(\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k)
 \end{aligned}$$

where  $\alpha$  is the *step length* as before.

Complementarity  $x^Ts$  is calculated at  $(x_{aff}^k, y_{aff}^k, s_{aff}^k)$  and compared with the complementarity at the starting point  $(x^k, y^k, s^k)$ , and the success of the affine step is gauged. If the affine step was successful in reducing the complementarity by a substantial amount, the need for centering is not great, and the value of  $\sigma_k$  in the following linear system is assigned a value close to zero. If, however, the affine step was unsuccessful, centering would be beneficial, and the value of  $\sigma_k$  in the following linear system is assigned a value closer to 1.0. The value of  $\sigma_k$  is therefore adaptively altered depending on the progress made toward the optimum.

A second linear system is solved to determine a centering vector  $(\Delta x_c^k, \Delta y_c^k, \Delta s_c^k)$  from  $(x_{aff}^k, y_{aff}^k, s_{aff}^k)$  :

$$\begin{aligned} A \Delta x_c^k &= 0 \\ A^T \Delta y_c^k + \Delta s_c^k &= 0 \\ S^k \Delta x_c^k + X^k \Delta s_c^k &= -X^k S^k e \\ S^k \Delta x_c^k + X^k \Delta s_c^k &= -X_{aff}^k S_{aff}^k e + \sigma_k \mu_k e \end{aligned}$$

Then

$$\begin{aligned} (\Delta x^k, \Delta y^k, \Delta s^k) &= (\Delta x_{aff}^k, \Delta y_{aff}^k, \Delta s_{aff}^k) + (\Delta x_c^k, \Delta y_c^k, \Delta s_c^k) \\ (x^{k+1}, y^{k+1}, s^{k+1}) &= (x^k, y^k, s^k) + \alpha (\Delta x^k, \Delta y^k, \Delta s^k) \end{aligned}$$

where, as before,  $\alpha$  is the *step length* assigned a value as large as possible but not so large that an  $x_i^{k+1}$  or  $s_i^{k+1}$  is “too close” to zero.

Although the Predictor-Corrector variant entails solving two linear system instead of one, fewer iterations are usually required to reach the optimum. The additional overhead of calculating the second linear system is small, as the factorization of the  $(A\Theta^{-1}A^T)$  matrix has already been performed to solve the first linear system.

## Stopping Criteria

There are several reasons why PROC NETFLOW stops interior point optimization. Optimization stops when

- the number of iteration equals `MAXITERB=m`
- the relative gap ( $duality\ gap / (c^T x)$ ) between the primal and dual objectives is smaller than the value of the `PDGAPTOL=` option, and both the primal and dual problems are feasible. **Duality gap** is defined in the section “[Interior Point Algorithmic Details](#)” on page 436.

PROC NETFLOW may stop optimization when it detects that the rate at which the **complementarity** or **dualitygap** is being reduced is too slow, that is, there are consecutive iterations when the **complementarity** or **duality gap** has stopped getting smaller and the infeasibilities, if nonzero, have also stalled. Sometimes, this indicates the problem is infeasible.

The reasons to stop optimization outlined in the previous paragraph will be termed the *usual* stopping conditions in the following explanation.

However, when solving some problems, especially if the problems are large, the usual stopping criteria are inappropriate. PROC NETFLOW might stop prematurely. If it were allowed to perform additional optimization, a better solution would be found. On other occasions, PROC NETFLOW might do too much work. A sufficiently good solution might be reached several iterations before PROC NETFLOW eventually stops.

You can see PROC NETFLOW’s progress to the optimum by specifying `PRINTLEVEL2=2`. PROC NETFLOW will produce a table on the SAS log. A row of the table is generated during each iteration and consists of values of the **affine step** complementarity, the **complementarity** of the solution for the next iteration, the

total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi}$  (see the  $\text{infeas}_b$  array in the section “Interior Point: Upper Bounds” on page 443), the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci}$  (see the  $\text{infeas}_c$  array in the section “Interior Point Algorithmic Details” on page 436), and the total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di}$  (see the  $\text{infeas}_d$  array in the section “Interior Point Algorithmic Details” on page 436). As optimization progresses, the values in all columns should converge to zero.

To tailor stopping criteria to your problem, you can use two sets of parameters: the STOP\_x and the KEEPGOING\_x parameters. The STOP\_x parameters (STOP\_C, STOP\_DG, STOP\_IB, STOP\_IC, and STOP\_ID) are used to test for some condition at the beginning of each iteration and if met, to stop immediately. The KEEPGOING\_x parameters (KEEPGOING\_C, KEEPGOING\_DG, KEEPGOING\_IB, KEEPGOING\_IC, and KEEPGOING\_ID) are used when PROC NETFLOW would ordinarily stop but does not if some conditions are not met.

For the sake of conciseness, a set of options will be referred to as the part of the option name they have in common followed by the suffix x. For example, STOP\_C, STOP\_DG, STOP\_IB, STOP\_IC, and STOP\_ID will collectively be referred to as STOP\_x.

At the beginning of each iteration, PROC NETFLOW will test whether *complementarity* is  $\leq$  STOP\_C (provided you have specified a STOP\_C parameter) and if it is, PROC NETFLOW will stop. If the *duality gap* is  $\leq$  STOP\_DG (provided you have specified a STOP\_DG parameter), PROC NETFLOW will stop immediately. This is also true for the other STOP\_x parameters that are related to infeasibilities, STOP\_IB, STOP\_IC, and STOP\_ID.

For example, if you want PROC NETFLOW to stop optimizing for the usual stopping conditions, plus the additional condition, *complementarity*  $\leq$  100 or *duality gap*  $\leq$  0.001, then use

```
proc netflow stop_c=100 stop_dg=0.001
```

If you want PROC NETFLOW to stop optimizing for the usual stopping conditions, plus the additional condition, *complementarity*  $\leq$  1000 and *duality gap*  $\leq$  0.001 and constraint infeasibility  $\leq$  0.0001, then use

```
proc netflow
  and_stop_c=1000 and_stop_dg=0.01 and_stop_ic=0.0001
```

Unlike the STOP\_x parameters that cause PROC NETFLOW to stop when any one of them is satisfied, the corresponding AND\_STOP\_x parameters (AND\_STOP\_C, AND\_STOP\_DG, AND\_STOP\_IB, AND\_STOP\_IC, and AND\_STOP\_ID) cause PROC NETFLOW to stop only if all (more precisely, all that are specified) options are satisfied. For example, if PROC NETFLOW should stop when

- *complementarity*  $\leq$  100 or *duality gap*  $\leq$  0.001 or
- *complementarity*  $\leq$  1000 and *duality gap*  $\leq$  0.001 and constraint infeasibility  $\leq$  0.000

then use

```
proc netflow
  stop_c=100 stop_dg=0.001
  and_stop_c=1000 and_stop_dg=0.01 and_stop_ic=0.0001
```

Just as the STOP\_x parameters have AND\_STOP\_x partners, the KEEPGOING\_x parameters have AND\_KEEPPGOING\_x partners. The role of the KEEPGOING\_x and AND\_KEEPPGOING\_x parameters is to prevent optimization from stopping too early, even though a usual stopping criterion is met.

When PROC NETFLOW detects that it should stop for a usual stopping condition, it performs the following tests:

- It will test whether *complementarity* is  $> \text{KEEPGOING\_C}$  (provided you have specified a *KEEPGOING\_C* parameter), and if it is, PROC NETFLOW will perform more optimization.
- Otherwise, PROC NETFLOW will then test whether the primal-dual gap is  $> \text{KEEPGOING\_DG}$  (provided you have specified a *KEEPGOING\_DG* parameter), and if it is, PROC NETFLOW will perform more optimization.
- Otherwise, PROC NETFLOW will then test whether the total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi} > \text{KEEPGOING\_IB}$  (provided you have specified a *KEEPGOING\_IB* parameter), and if it is, PROC NETFLOW will perform more optimization.
- Otherwise, PROC NETFLOW will then test whether the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci} > \text{KEEPGOING\_IC}$  (provided you have specified a *KEEPGOING\_IC* parameter), and if it is, PROC NETFLOW will perform more optimization.
- Otherwise, PROC NETFLOW will then test whether the total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di} > \text{KEEPGOING\_ID}$  (provided you have specified a *KEEPGOING\_ID* parameter), and if it is, PROC NETFLOW will perform more optimization.
- Otherwise it will test whether *complementarity* is  $> \text{AND\_KEEPGOING\_C}$  (provided you have specified an *AND\_KEEPPGOING\_C* parameter), *and* the primal-dual gap is  $> \text{AND\_KEEPGOING\_DG}$  (provided you have specified an *AND\_KEEPPGOING\_DG* parameter), *and* the total bound infeasibility  $\sum_{i=1}^n \text{infeas}_{bi} > \text{AND\_KEEPGOING\_IB}$  (provided you have specified an *AND\_KEEPPGOING\_IB* parameter), *and* the total constraint infeasibility  $\sum_{i=1}^m \text{infeas}_{ci} > \text{AND\_KEEPGOING\_IC}$  (provided you have specified an *AND\_KEEPPGOING\_IC* parameter) *and* the total dual infeasibility  $\sum_{i=1}^n \text{infeas}_{di} > \text{AND\_KEEPGOING\_ID}$  (provided you have specified an *AND\_KEEPPGOING\_ID* parameter), and if it is, PROC NETFLOW will perform more optimization.

If all these tests to decide whether more optimization should be performed are false, optimization is stopped.

For example,

```
proc netflow
  stop_c=1000
  and_stop_c=2000 and_stop_dg=0.01
  and_stop_ib=1 and_stop_ic=1 and_stop_id=1
  keepgoing_c=1500
  and_keepgoing_c=2500 and_keepgoing_dg=0.05
  and_keepgoing_ib=1 and_keepgoing_ic=1 and_keepgoing_id=1
```

At the beginning of each iteration, PROC NETFLOW will stop if

- *complementarity*  $\leq 1000$  or

- **complementarity**  $\leq 2000$  and **duality gap**  $\leq 0.01$  and the total bound, constraint, and dual infeasibilities are each  $\leq 1$

When PROC NETFLOW determines it should stop because a usual stopping condition is met, it will stop only if

- **complementarity**  $\leq 1500$  or
- **complementarity**  $\leq 2500$  and **duality gap**  $\leq 0.05$  and the total bound, constraint, and dual infeasibilities are each  $\leq 1$

### Interior Point: Upper Bounds

If the LP model had upper bounds ( $0 \leq x \leq u$  where  $u$  is the upper bound vector), then the primal and dual problems, the duality gap, and the KKT conditions would have to be expanded.

The primal linear program to be solved is

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax = b \\ & 0 \leq x \leq u \end{array}$$

where  $0 \leq x \leq u$  is split into  $x \geq 0$  and  $x \leq u$ . Let  $z$  be primal slack so that  $x + z = u$ , and associate dual variables  $w$  with these constraints. The interior point algorithm solves the system of equations to satisfy the Karush-Kuhn-Tucker (KKT) conditions for optimality:

$$\begin{array}{l} Ax = b \\ x + z = u \\ A^T y + s - w = c \\ x^T s = 0 \\ z^T w = 0 \\ x, s, z, w \geq 0 \end{array}$$

These are the conditions for feasibility, with the *complementarity* conditions  $x^T s = 0$  and  $z^T w = 0$  added. Complementarity forces the optimal objectives of the primal and dual to be equal,  $c^T x_{opt} = b^T y_{opt} - u^T w_{opt}$ , as

$$0 = z_{opt}^T w_{opt} = (u - x_{opt})^T w_{opt} = u^T w_{opt} - x_{opt}^T w_{opt}$$

$$\begin{aligned} 0 &= x_{opt}^T s_{opt} = s_{opt}^T x_{opt} = (c - A^T y_{opt} + w_{opt})^T x_{opt} \\ &= c^T x_{opt} - y_{opt}^T (Ax_{opt}) + w_{opt}^T x_{opt} = c^T x_{opt} - b^T y_{opt} + u^T w_{opt} \end{aligned}$$

Before the optimum is reached, a solution  $(x, y, s, z, w)$  might not satisfy the KKT conditions:

- Primal bound constraints may be violated,  $infeas_b = u - x - z \neq 0$ .
- Primal constraints may be violated,  $infeas_c = b - Ax \neq 0$ .
- Dual constraints may be violated,  $infeas_d = c - A^T y - s + w \neq 0$ .
- Complementarity conditions may not be satisfied,  $x^T s \neq 0$  and  $z^T w \neq 0$ .

The calculations of the interior point algorithm can easily be derived in a fashion similar to calculations for when an LP has no upper bounds. See the paper by Lustig, Marsten, and Shanno (1992). An important point is that upper bounds can be handled by specializing the algorithm and *not* by generating the constraints  $x + z = u$  and adding these to the main primal constraints  $Ax = b$ .

### Getting Started: Linear Programming Models: Interior Point Algorithm

To solve linear programming problem using PROC NETFLOW, you save a representation of the variables and the constraints in one or two SAS data sets. These data sets are then passed to PROC NETFLOW for solution. There are various forms that a problem's data can take. You can use any one or a combination of several of these forms.

The **ARCDATA=** data set contains information about the variables of the problem. Although this data set is called ARCDATA, it contains data for no arcs. Instead, all data in this data set are related to variables.

The **ARCDATA=** data set can be used to specify information about variables, including objective function coefficients, lower and upper value bounds, and names. These data are the elements of the vectors  $d$ ,  $m$ , and  $v$  in problem (NPSC). Data for a variable can be given in more than one observation.

When the data for a constrained network problem is being provided, the **ARCDATA=** data set always contains information necessary for arcs, their tail and head nodes, and optionally the supply and demand information of these nodes. When the data for a linear programming problem is being provided, none of this information is present, as the model has no arcs. This is the way PROC NETFLOW decides which type of problem it is to solve.

PROC NETFLOW was originally designed to solve models with networks, so an **ARCDATA=** data set is always expected. If an **ARCDATA=** data set is not specified, by default the last data set created before PROC NETFLOW is invoked is assumed to be an **ARCDATA=** data set. However, these characteristics of PROC NETFLOW are not helpful when a linear programming problem is being solved and all data are provided in a single data set specified by the **CONDATA=** data set, and that data set is not the last data set created before PROC NETFLOW starts. In this case, you must specify that an **ARCDATA=** data set and a **CONDATA=** data set are both equal to the input data set. PROC NETFLOW then knows that a linear programming problem is to be solved, and the data reside in one data set.

The **CONDATA=** data set describes the constraints and their right-hand sides. These data are elements of the matrix  $Q$  and the vector  $r$ .

Constraint types are also specified in the **CONDATA=** data set. You can include in this data set variable data such as upper bound values, lower value bounds, and objective function coefficients. It is possible to give all information about some or all variables in the **CONDATA=** data set.

A variable is identified in this data set by its name. If you specify a variable's name in the **ARCDATA=** data set, then this name is used to associate data in the **CONDATA=** data set with that variable.

If you use the **dense** constraint input format, these variable names are names of SAS variables in the **VAR** list of the **CONDATA=** data set.

If you use the `sparse` constraint input format, these variable names are values of the `COLUMN` list SAS variable of `CONDATA=` data set.

When using the interior point algorithm, the execution of PROC NETFLOW has two stages. In the preliminary (zeroth) stage, the data are read from the `ARCDATA=` data set (if used) and the `CONDATA=` data set. Error checking is performed. In the next stage, the linear program is preprocessed, then the optimal solution to the linear program is found. The solution is saved in the `CONOUT=` data set. This data set is also named in the `PROC NETFLOW`, `RESET`, and `SAVE` statements.

See the section “Getting Started: Network Models: Interior Point Algorithm” on page 426 for a fuller description of the stages of the interior point algorithm.

### Introductory Example: Linear Programming Models: Interior Point Algorithm

Consider the linear programming problem in the section “An Introductory Example” on page 177 in the chapter on the LP procedure.

```
data dcon1;
  input _id_ $17.
         a_light a_heavy brega naphthal naphthai
         heatingo jet_1 jet_2
         _type_ $ _rhs_;
  datalines;
profit      -175 -165 -205  0  0  0 300 300 max      .
naphtha_l_conv  .035 .030 .045 -1  0  0  0  0  eq      0
naphtha_i_conv  .100 .075 .135  0 -1  0  0  0  eq      0
heatingo_conv  .390 .300 .430  0  0 -1  0  0  eq      0
recipe_1        0    0    0  0 .3 .7 -1  0  eq      0
recipe_2        0    0    0 .2  0 .8  0 -1  eq      0
available      110  165   80  .  .  .  .  . upperbd .
;
```

To find the minimum cost solution and to examine all or parts of the optimum, you use `PRINT` statements.

- **print problem/short;** outputs information for all variables and all constraint coefficients. See Figure 7.19.
- **print some\_variables(j:)/short;** is information about a set of variables, (in this case, those with names that start with the character string preceding the colon). See Figure 7.20.
- **print some\_cons(recipe\_1)/short;** is information about a set of constraints (here, that set only has one member, the constraint called `recipe_1`). See Figure 7.21.
- **print con\_variables(\_all\_,brega)/short;** lists the constraint information for a set of variables (here, that set only has one member, the variable called `brega`). See Figure 7.22.
- **print con\_variables(recipe:,n: jet\_1)/short;** coefficient information for those in a set of constraints belonging to a set of variables. See Figure 7.23.

```

proc netflow
  arcdata=dcon1
  condata=dcon1
  conout=solutn1;
run;
print problem/short;

print some_variables(j:)/short;
print some_cons(recipe_1)/short;
print con_variables(_all_,brega)/short;
print con_variables(recipe:,n: jet_1)/short;

```

The following messages, which appear on the SAS log, summarize the model as read by PROC NETFLOW and note the progress toward a solution:

```

NOTE: ARCDATA (or the last data set created if ARCDATA was not specified) and
      CONDATA are the same data set WORK.DCON1 so will assume a Linear
      Programming problem is to be solved.
NOTE: Number of variables= 8 .
NOTE: Number of <= constraints= 0 .
NOTE: Number of == constraints= 5 .
NOTE: Number of >= constraints= 0 .
NOTE: Number of constraint coefficients= 18 .
NOTE: After preprocessing, number of <= constraints= 0.
NOTE: After preprocessing, number of == constraints= 0.
NOTE: After preprocessing, number of >= constraints= 0.
NOTE: The preprocessor eliminated 5 constraints from the problem.
NOTE: The preprocessor eliminated 18 constraint coefficients from the problem.
NOTE: After preprocessing, number of variables= 0.
NOTE: The preprocessor eliminated 8 variables from the problem.
NOTE: The optimum has been determined by the Preprocessor.
NOTE: Objective= 1544.
NOTE: The data set WORK.SOLUTN1 has 8 observations and 6 variables.

```

**Figure 7.19** PRINT PROBLEM/SHORT;

| The NETFLOW Procedure |          |         |          |          |         |
|-----------------------|----------|---------|----------|----------|---------|
| _N_                   | _NAME_   | _OBJFN_ | _UPPERBD | _LOWERBD | _VALUE_ |
| 1                     | a_heavy  | -165    | 165      | 0        | 0       |
| 2                     | a_light  | -175    | 110      | 0        | 110     |
| 3                     | brega    | -205    | 80       | 0        | 80      |
| 4                     | heatingo | 0       | 99999999 | 0        | 77.3    |
| 5                     | jet_1    | 300     | 99999999 | 0        | 60.65   |
| 6                     | jet_2    | 300     | 99999999 | 0        | 63.33   |
| 7                     | naphthai | 0       | 99999999 | 0        | 21.8    |
| 8                     | naphthal | 0       | 99999999 | 0        | 7.45    |



Figure 7.19 continued

| The NETFLOW Procedure |                |               |              |               |                |                 |
|-----------------------|----------------|---------------|--------------|---------------|----------------|-----------------|
| <u>_N_</u>            | <u>_id_</u>    | <u>_type_</u> | <u>_rhs_</u> | <u>_NAME_</u> | <u>_OBJFN_</u> | <u>_UPPERBD</u> |
| 1                     | heating_o_conv | EQ            | 0            | a_light       | -175           | 110             |
| 2                     | heating_o_conv | EQ            | 0            | a_heavy       | -165           | 165             |
| 3                     | heating_o_conv | EQ            | 0            | brega         | -205           | 80              |
| 4                     | heating_o_conv | EQ            | 0            | heatingo      | 0              | 99999999        |
| 5                     | naphtha_i_conv | EQ            | 0            | a_light       | -175           | 110             |
| 6                     | naphtha_i_conv | EQ            | 0            | a_heavy       | -165           | 165             |
| 7                     | naphtha_i_conv | EQ            | 0            | brega         | -205           | 80              |
| 8                     | naphtha_i_conv | EQ            | 0            | naphthai      | 0              | 99999999        |
| 9                     | naphtha_l_conv | EQ            | 0            | a_light       | -175           | 110             |
| 10                    | naphtha_l_conv | EQ            | 0            | a_heavy       | -165           | 165             |
| 11                    | naphtha_l_conv | EQ            | 0            | brega         | -205           | 80              |
| 12                    | naphtha_l_conv | EQ            | 0            | naphthal      | 0              | 99999999        |
| 13                    | recipe_1       | EQ            | 0            | naphthai      | 0              | 99999999        |
| 14                    | recipe_1       | EQ            | 0            | heatingo      | 0              | 99999999        |
| 15                    | recipe_1       | EQ            | 0            | jet_1         | 300            | 99999999        |
| 16                    | recipe_2       | EQ            | 0            | naphthal      | 0              | 99999999        |
| 17                    | recipe_2       | EQ            | 0            | heatingo      | 0              | 99999999        |
| 18                    | recipe_2       | EQ            | 0            | jet_2         | 300            | 99999999        |

| <u>_N_</u> | <u>_LOWERBD</u> | <u>_VALUE_</u> | <u>_COEF_</u> |
|------------|-----------------|----------------|---------------|
| 1          | 0               | 110            | 0.39          |
| 2          | 0               | 0              | 0.3           |
| 3          | 0               | 80             | 0.43          |
| 4          | 0               | 77.3           | -1            |
| 5          | 0               | 110            | 0.1           |
| 6          | 0               | 0              | 0.075         |
| 7          | 0               | 80             | 0.135         |
| 8          | 0               | 21.8           | -1            |
| 9          | 0               | 110            | 0.035         |
| 10         | 0               | 0              | 0.03          |
| 11         | 0               | 80             | 0.045         |
| 12         | 0               | 7.45           | -1            |
| 13         | 0               | 21.8           | 0.3           |
| 14         | 0               | 77.3           | 0.7           |
| 15         | 0               | 60.65          | -1            |
| 16         | 0               | 7.45           | 0.2           |
| 17         | 0               | 77.3           | 0.8           |
| 18         | 0               | 63.33          | -1            |

**Figure 7.20** PRINT SOME\_VARIABLES(J:)/SHORT;

| The NETFLOW Procedure |        |         |          |          |         |
|-----------------------|--------|---------|----------|----------|---------|
| _N_                   | _NAME_ | _OBJFN_ | _UPPERBD | _LOWERBD | _VALUE_ |
| 1                     | jet_1  | 300     | 99999999 | 0        | 60.65   |
| 2                     | jet_2  | 300     | 99999999 | 0        | 63.33   |

**Figure 7.21** PRINT SOME\_CONS(RECIPE\_1)/SHORT;

| The NETFLOW Procedure |          |        |       |          |         |          |
|-----------------------|----------|--------|-------|----------|---------|----------|
| _N_                   | _id_     | _type_ | _rhs_ | _NAME_   | _OBJFN_ | _UPPERBD |
| 1                     | recipe_1 | EQ     | 0     | naphthai | 0       | 99999999 |
| 2                     | recipe_1 | EQ     | 0     | heatingo | 0       | 99999999 |
| 3                     | recipe_1 | EQ     | 0     | jet_1    | 300     | 99999999 |

| _N_ | _LOWERBD | _VALUE_ | _COEF_ |
|-----|----------|---------|--------|
| 1   | 0        | 21.8    | 0.3    |
| 2   | 0        | 77.3    | 0.7    |
| 3   | 0        | 60.65   | -1     |

**Figure 7.22** PRINT CON\_VARIABLES(\_ALL\_,BREGA)/SHORT;

| The NETFLOW Procedure |                |        |       |        |         |          |
|-----------------------|----------------|--------|-------|--------|---------|----------|
| _N_                   | _id_           | _type_ | _rhs_ | _NAME_ | _OBJFN_ | _UPPERBD |
| 1                     | heating_o_conv | EQ     | 0     | brega  | -205    | 80       |
| 2                     | naphtha_i_conv | EQ     | 0     | brega  | -205    | 80       |
| 3                     | naphtha_l_conv | EQ     | 0     | brega  | -205    | 80       |

| _N_ | _LOWERBD | _VALUE_ | _COEF_ |
|-----|----------|---------|--------|
| 1   | 0        | 80      | 0.43   |
| 2   | 0        | 80      | 0.135  |
| 3   | 0        | 80      | 0.045  |

**Figure 7.23** PRINT CON\_VARIABLES(RECIPE:,N: JET\_1)/SHORT;

| The NETFLOW Procedure |          |         |        |          |         |          |
|-----------------------|----------|---------|--------|----------|---------|----------|
| _N_                   | _id_     | _type_  | _rhs_  | _NAME_   | _OBJFN_ | _UPPERBD |
| 1                     | recipe_1 | EQ      | 0      | naphthai | 0       | 99999999 |
| 2                     | recipe_1 | EQ      | 0      | jet_1    | 300     | 99999999 |
| 3                     | recipe_2 | EQ      | 0      | naphthal | 0       | 99999999 |
| _N_                   | _LOWERBD | _VALUE_ | _COEF_ |          |         |          |
| 1                     | 0        | 21.8    | 0.3    |          |         |          |
| 2                     | 0        | 60.65   | -1     |          |         |          |
| 3                     | 0        | 7.45    | 0.2    |          |         |          |

Unlike PROC LP, which displays the solution and other information as output, PROC NETFLOW saves the optimum in output SAS data sets you specify. For this example, the solution is saved in the SOLUTN1 data set. It can be displayed with PROC PRINT as

```
proc print data=solutn1;
  var _name_ _objfn_ _upperbd _lowerbd _value_ _fcost_;
  sum _fcost_;
  title3 'LP Optimum';
run;
```

Notice, in the CONOUT=SOLUTN1 (Figure 7.24), the optimal value through each variable in the linear program is given in the variable named \_VALUE\_, and the cost of value for each variable is given in the variable \_FCOST\_.

**Figure 7.24** CONOUT=SOLUTN1

| LP Optimum |          |         |          |          |         |         |
|------------|----------|---------|----------|----------|---------|---------|
| Obs        | _NAME_   | _OBJFN_ | _UPPERBD | _LOWERBD | _VALUE_ | _FCOST_ |
| 1          | a_heavy  | -165    | 165      | 0        | 0.00    | 0       |
| 2          | a_light  | -175    | 110      | 0        | 110.00  | -19250  |
| 3          | brega    | -205    | 80       | 0        | 80.00   | -16400  |
| 4          | heatingo | 0       | 99999999 | 0        | 77.30   | 0       |
| 5          | jet_1    | 300     | 99999999 | 0        | 60.65   | 18195   |
| 6          | jet_2    | 300     | 99999999 | 0        | 63.33   | 18999   |
| 7          | naphthai | 0       | 99999999 | 0        | 21.80   | 0       |
| 8          | naphthal | 0       | 99999999 | 0        | 7.45    | 0       |
|            |          |         |          |          |         | =====   |
|            |          |         |          |          |         | 1544    |

The same model can be specified in the [sparse](#) format as in the following scon2 data set. This format enables you to omit the zero coefficients.

```
data scon2;
  format _type_ $8. _col_ $8. _row_ $16. ;
  input _type_ $ _col_ $ _row_ $ _coef_;
  datalines;
max      .          profit                .
eq       .          napha_l_conv          .
eq       .          napha_i_conv          .
eq       .          heating_oil_conv      .
eq       .          recipe_1              .
eq       .          recipe_2              .
upperbd  .          available             .
.         a_light   profit                -175
.         a_light   napha_l_conv          .035
.         a_light   napha_i_conv          .100
.         a_light   heating_oil_conv      .390
.         a_light   available             110
.         a_heavy   profit                -165
.         a_heavy   napha_l_conv          .030
.         a_heavy   napha_i_conv          .075
.         a_heavy   heating_oil_conv      .300
.         a_heavy   available             165
.         brega     profit                -205
.         brega     napha_l_conv          .045
.         brega     napha_i_conv          .135
.         brega     heating_oil_conv      .430
.         brega     available             80
.         naphthal  napha_l_conv          -1
.         naphthal  recipe_2              .2
.         naphthai  napha_i_conv          -1
.         naphthai  recipe_1              .3
.         heatingo  heating_oil_conv      -1
.         heatingo  recipe_1              .7
.         heatingo  recipe_2              .8
.         jet_1     profit                300
.         jet_1     recipe_1              -1
.         jet_2     profit                300
.         jet_2     recipe_2              -1
;
```

To find the minimum cost solution, invoke PROC NETFLOW (note the [SPARSECONDATA](#) option which must be specified) as follows:

```
proc netflow
  sparsecondata
  condata=scon2
  conout=solutn2;
run;
```

A data set that is used as an **ARC DATA**= data set can be initialized as follows:

```
data vars3;
  input _name_ $ profit available;
  datalines;
a_heavy -165 165
a_light -175 110
brega -205 80
heatingo 0 .
jet_1 300 .
jet_2 300 .
naphthai 0 .
naphthal 0 .
;
```

The following **CON DATA**= data set is the original **dense** format **CON DATA**= dcon1 data set with the variable information removed. (You could have left some or all of that information in **CON DATA** as PROC NETFLOW “merges” data, but doing that and checking for consistency uses time.)

```
data dcon3;
  input _id_ $17.
  a_light a_heavy brega naphthal naphthai
  heatingo jet_1 jet_2
  _type_ $ _rhs_;
  datalines;
naphtha_l_conv .035 .030 .045 -1 0 0 0 0 eq 0
naphtha_i_conv .100 .075 .135 0 -1 0 0 0 eq 0
heating_o_conv .390 .300 .430 0 0 -1 0 0 eq 0
recipe_1 0 0 0 0 .3 .7 -1 0 eq 0
recipe_2 0 0 0 .2 0 .8 0 -1 eq 0
;
```

It is important to note that it is now necessary to specify the **MAXIMIZE** option; otherwise, PROC NETFLOW will optimize to the minimum (which, incidentally, has a total objective = -3539.25). You must indicate that the SAS variable profit in the **ARC DATA**=vars3 data set has values that are objective function coefficients, by specifying the **OBJFN** statement. The **UPPERBD** must be specified as the SAS variable available that has as values upper bounds.

```
proc netflow
  maximize          /* ***** necessary ***** */
  arcdata=vars3
  condata=dcon3
  conout=solutn3;
  objfn profit;
  upperbd available;
run;
```

The **ARC DATA**=vars3 data set can become more concise by noting that the model variables heatingo, naphthai, and naphthal have zero objective function coefficients (the default) and default upper bounds, so those observations need not be present.

```

data vars4;
    input _name_ $ profit available;
    datalines;
a_heavy  -165 165
a_light  -175 110
brega    -205 80
jet_1     300 .
jet_2     300 .
;

```

The `CONDATA=dcon3` data set can become more concise by noting that all the constraints have the same type (eq) and zero (the default) rhs values. This model is a good candidate for using the `DEFCTYPE=` option.

The `DEFCTYPE=` option can be useful not only when *all* constraints have the same type as is the case here, but also when *most* constraints have the same type, or if you prefer to change the default type from  $\leq$  to  $=$  or  $\geq$ . The essential constraint type data in `CONDATA=` data set is that which overrides the `DEFCTYPE=` type you specified.

```

data dcon4;
    input _id_ $17.
           a_light a_heavy brega naphthal naphthai
           heatingo jet_1 jet_2;
    datalines;
naphtha_l_conv  .035 .030 .045 -1 0 0 0 0
naphtha_i_conv  .100 .075 .135 0 -1 0 0 0
heating_o_conv  .390 .300 .430 0 0 -1 0 0
recipe_1        0 0 0 0 .3 .7 -1 0
recipe_2        0 0 0 .2 0 .8 0 -1
;
proc netflow
    maximize defctype=eq
    arcdata=vars3
    condata=dcon3
    conout=solutn3;
    objfn profit;
    upperbd available;
run;

```

Several different ways of using an `ARCADATA=` data set and a *sparse* format `CONDATA=` data set for this linear program follow. The following `CONDATA=` data set is the result of removing the profit and available data from the original *sparse* format `CONDATA=scon2` data set.

```

data scon5;
    format _type_ $8. _col_ $8. _row_ $16. ;
    input _type_ $ _col_ $ _row_ $ _coef_;
    datalines;
eq      .      napha_l_conv      .
eq      .      napha_i_conv      .
eq      .      heating_oil_conv   .
eq      .      recipe_1           .
eq      .      recipe_2           .
.      a_light  napha_l_conv      .035

```

```

.      a_light      napha_i_conv      .100
.      a_light      heating_oil_conv   .390
.      a_heavy      napha_l_conv       .030
.      a_heavy      napha_i_conv       .075
.      a_heavy      heating_oil_conv   .300
.      brega        napha_l_conv       .045
.      brega        napha_i_conv       .135
.      brega        heating_oil_conv   .430
.      naphthal     napha_l_conv       -1
.      naphthal     recipe_2           .2
.      naphthai     napha_i_conv       -1
.      naphthai     recipe_1           .3
.      heatingo     heating_oil_conv   -1
.      heatingo     recipe_1           .7
.      heatingo     recipe_2           .8
.      jet_1        recipe_1           -1
.      jet_2        recipe_2           -1
;
proc netflow
  maximize
  sparsesecondata
  arcdata=vars3      /* or arcdata=vars4 */
  condata=scon5
  conout=solutn5;
  objfn profit;
  upperbd available;
run;

```

The `CONDATA=scon5` data set can become more concise by noting that all the constraints have the same type (eq) and zero (the default) rhs values. Use the `DEFCONTYPE=` option again. Once the first 5 observations of the `CONDATA=scon5` data set are removed, the `_type_` SAS variable has values that are missing in the remaining observations. Therefore, this SAS variable can be removed.

```

data scon6;
  input _col_ $ _row_&$16. _coef_;
  datalines;
a_light  napha_l_conv      .035
a_light  napha_i_conv      .100
a_light  heating_oil_conv  .390
a_heavy  napha_l_conv      .030
a_heavy  napha_i_conv      .075
a_heavy  heating_oil_conv  .300
brega    napha_l_conv      .045
brega    napha_i_conv      .135
brega    heating_oil_conv  .430
naphthal napha_l_conv      -1
naphthal recipe_2          .2
naphthai napha_i_conv      -1
naphthai recipe_1          .3
heatingo heating_oil_conv  -1
heatingo recipe_1          .7
heatingo recipe_2          .8
jet_1    recipe_1          -1
jet_2    recipe_2          -1
;

```

```

proc netflow
  maximize
  defcontype=eq
  sparsecondata
  arcdata=vars3      /* or arcdata=vars4 */
  condata=scon6
  conout=solutn6;
  objfn profit;
  upperbd available;
run;

```

### Interactivity: Linear Programming Models: Interior Point algorithm

PROC NETFLOW can be used interactively. You begin by giving the **PROC NETFLOW** statement, and you must specify the **CONDATA=** data set. If necessary, specify the **ARCADATA=** data set.

The variable lists should be given next. If you have variables in the input data sets that have special names (for example, a variable in the **ARCADATA=** data set named **\_COST\_** that has objective function coefficients as values), it may not be necessary to have many or any variable lists.

The **PRINT**, **QUIT**, **SAVE**, **SHOW**, **RESET**, and **RUN** statements follow and can be listed in any order. The **QUIT** statements can be used only once. The others can be used as many times as needed.

The **CONOPT** and **PIVOT** are not relevant to the interior point algorithm and should not be used.

Use the **RESET** or **SAVE** statement to change the name of the output data set. There is only one output data set, the **CONOUT=** data set. With the **RESET** statement, you can also indicate the reasons why optimization should stop, (for example, you can indicate the maximum number of iterations that can be performed). PROC NETFLOW then has a chance to either execute the next statement or, if the next statement is one that PROC NETFLOW does not recognize (the next PROC or DATA step in the SAS session), do any allowed optimization and finish. If no new statement has been submitted, you are prompted for one. Some options of the **RESET** statement enable you to control aspects of the interior point algorithm. Specifying certain values for these options can reduce the time it takes to solve a problem. Note that any of the **RESET** options can be specified in the **PROC NETFLOW** statement.

The **RUN** statement starts optimization. Once the optimization has started, it runs until the optimum is reached. The **RUN** statement should be specified at most once.

The **QUIT** statement immediately stops PROC NETFLOW. The **SAVE** statement has options that enable you to name the output data set; information about the current solution is saved in this output data set. Use the **SHOW** statement if you want to examine the values of options of other statements. Information about the amount of optimization that has been done and the **STATUS** of the current solution can also be displayed using the **SHOW** statement.

The **PRINT** statement instructs PROC NETFLOW to display parts of the problem. The ways the **PRINT** statements are specified are identical whether the interior point algorithm or the simplex algorithm is used; however, there are minor differences in what is displayed for each variable or constraint coefficient.

**PRINT VARIABLES** produces information on all arcs. **PRINT SOME\_VARIABLES** limits this output to a subset of variables. There are similar **PRINT** statements for constraints:

```

PRINT CONSTRAINTS;
PRINT SOME_CONS;

```



**PRINT CON\_VARIABLES** enables you to limit constraint information that is obtained to members of a set of variables that have nonzero constraint coefficients in a set of constraints.

For example, an interactive PROC NETFLOW run might look something like this:

```
proc netflow
    condata=data set
    other options;
    variable list specifications;    /* if necessary */
    reset options;
    print options;    /* look at problem          */
run;                    /* do some optimization    */
    print options;    /* look at the optimal solution */
    save options;     /* keep optimal solution      */
```

If you are interested only in finding the optimal solution, have used SAS variables that have special names in the input data sets, and want to use default setting for everything, then the following statement is all you need:

```
proc netflow condata= data set ;
```

### Functional Summary: Linear Programming Models: Interior Point Algorithm

The following table outlines the options available for the NETFLOW procedure when the interior point algorithm is being used to solve a linear programming problem, classified by function.

**Table 7.13** Functional Summary, Linear Programming Models

| Description                                  | Statement    | Option         |
|--|--------------|----------------|
| <b>Input Data Set Options:</b>               |              |                |
| Arcs input data set                          | PROC NETFLOW | ARCDATA=       |
| Constraint input data set                    | PROC NETFLOW | CONDATA=       |
| <b>Output Data Set Option:</b>               |              |                |
| Solution data set                            | PROC NETFLOW | CONOUT=        |
| <b>Data Set Read Options:</b>                |              |                |
| CONDATA has sparse data format               | PROC NETFLOW | SPARSECONDATA  |
| Default constraint type                      | PROC NETFLOW | DEFCONTYPE=    |
| Special COLUMN variable value                | PROC NETFLOW | TYPEOBS=       |
| Special COLUMN variable value                | PROC NETFLOW | RHSOBS=        |
| Data for a constraint found once in CONDATA  | PROC NETFLOW | CON_SINGLE_OBS |
| Data for a coefficient found once in CONDATA | PROC NETFLOW | NON_REPLIC=    |
| Data are grouped, exploited during data read | PROC NETFLOW | GROUPED=       |
| <b>Problem Size Specification Options:</b>   |              |                |
| Approximate number of variables              | PROC NETFLOW | NNAS=          |
| Approximate number of coefficients           | PROC NETFLOW | NCOEFS=        |
| Approximate number of constraints            | PROC NETFLOW | NCONS=         |

| Description                                      | Statement    | Option             |
|--|--------------|--------------------|
| <b>Network Options:</b>                          |              |                    |
| Default variable objective function coefficient  | PROC NETFLOW | DEFCOST=           |
| Default variable upper bound                     | PROC NETFLOW | DEFCAPACITY=       |
| Default variable lower bound                     | PROC NETFLOW | DEFMINFLOW=        |
| <b>Memory Control Options:</b>                   |              |                    |
| Issue memory usage messages to SAS log           | PROC NETFLOW | MEMREP             |
| Number of bytes to use for main memory           | PROC NETFLOW | BYTES=             |
| Proportion of memory for arrays                  | PROC NETFLOW | COREFACTOR=        |
| maximum bytes for a single array                 | PROC NETFLOW | MAXARRAYBYTES=     |
| <b>Interior Point Algorithm Options:</b>         |              |                    |
| Use interior point algorithm                     | PROC NETFLOW | INTPOINT           |
| Factorization method                             | RESET        | FACT_METHOD=       |
| Allowed amount of dual infeasibility             | RESET        | TOLDINF=           |
| Allowed amount of primal infeasibility           | RESET        | TOLPINF=           |
| Allowed total amount of dual infeasibility       | RESET        | TOLTOTDINF=        |
| Allowed total amount of primal infeasibility     | RESET        | TOLTOTPINF=        |
| Cut-off tolerance for Cholesky factorization     | RESET        | CHOLTINYTOL=       |
| Density threshold for Cholesky processing        | RESET        | DENSETHR=          |
| Step-length multiplier                           | RESET        | PDSTEPMULT=        |
| Preprocessing type                               | RESET        | PRSLTYPE=          |
| Print optimization progress on SAS log           | RESET        | PRINTLEVEL2=       |
| Write optimization time to SAS log               | RESET        | OPTIM_TIMER        |
| <b>Interior Point Stopping Criteria Options:</b> |              |                    |
| Maximum number of interior point iterations      | RESET        | MAXITERB=          |
| Primal-dual (duality) gap tolerance              | RESET        | PDGAPTOL=          |
| Stop because of complementarity                  | RESET        | STOP_C=            |
| Stop because of duality gap                      | RESET        | STOP_DG=           |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | STOP_IB=           |
| Stop because of <i>infeas<sub>c</sub></i>        | RESET        | STOP_IC=           |
| Stop because of <i>infeas<sub>d</sub></i>        | RESET        | STOP_ID=           |
| Stop because of complementarity                  | RESET        | AND_STOP_C=        |
| Stop because of duality gap                      | RESET        | AND_STOP_DG=       |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | AND_STOP_IB=       |
| Stop because of <i>infeas<sub>c</sub></i>        | RESET        | AND_STOP_IC=       |
| Stop because of <i>infeas<sub>d</sub></i>        | RESET        | AND_STOP_ID=       |
| Stop because of complementarity                  | RESET        | KEEPPGOING_C=      |
| Stop because of duality gap                      | RESET        | KEEPPGOING_DG=     |
| Stop because of <i>infeas<sub>b</sub></i>        | RESET        | KEEPPGOING_IB=     |
| Stop because of <i>infeas<sub>c</sub></i>        | RESET        | KEEPPGOING_IC=     |
| Stop because of <i>infeas<sub>d</sub></i>        | RESET        | KEEPPGOING_ID=     |
| Stop because of complementarity                  | RESET        | AND_KEEPPGOING_C=  |
| Stop because of duality gap                      | RESET        | AND_KEEPPGOING_DG= |

| Description   | Statement    | Option             |
|---|--------------|--------------------|
| Stop because of <i>infeas<sub>b</sub></i>                               | RESET        | AND_KEEPPGOING_IB= |
| Stop because of <i>infeas<sub>c</sub></i>                               | RESET        | AND_KEEPPGOING_IC= |
| Stop because of <i>infeas<sub>d</sub></i>                               | RESET        | AND_KEEPPGOING_ID= |
| <b>PRINT Statement Options:</b>   |              |                    |
| Display everything  | PRINT        | PROBLEM            |
| Display variable information  | PRINT        | VARIABLES          |
| Display constraint information  | PRINT        | CONSTRAINTS        |
| Display information for some variables                                  | PRINT        | SOME_VARIABLES     |
| Display information for some constraints                                | PRINT        | SOME_CONS          |
| Display information for some constraints associated with some variables | PRINT        | CON_VARIABLES      |
| <b>PRINT Statement Qualifiers:</b>                                      |              |                    |
| Produce a short report  | PRINT        | / SHORT            |
| Produce a long report   | PRINT        | / LONG             |
| Display arcs/variables with zero flow/value                             | PRINT        | / ZERO             |
| Display arcs/variables with nonzero flow/value                          | PRINT        | / NONZERO          |
| <b>SHOW Statement Options:</b>  |              |                    |
| Show problem, optimization status                                       | SHOW         | STATUS             |
| Show LP model parameters  | SHOW         | NETSTMT            |
| Show data sets that have been or will be created                        | SHOW         | DATASETS           |
| <b>Miscellaneous Options:</b>   |              |                    |
| Infinity value  | PROC NETFLOW | INFINITY=          |
| Scale constraint row, variable column coefficients, or both             | PROC NETFLOW | SCALE=             |
| Maximization instead of minimization                                    | PROC NETFLOW | MAXIMIZE           |

## Generalized Networks: NETFLOW Procedure

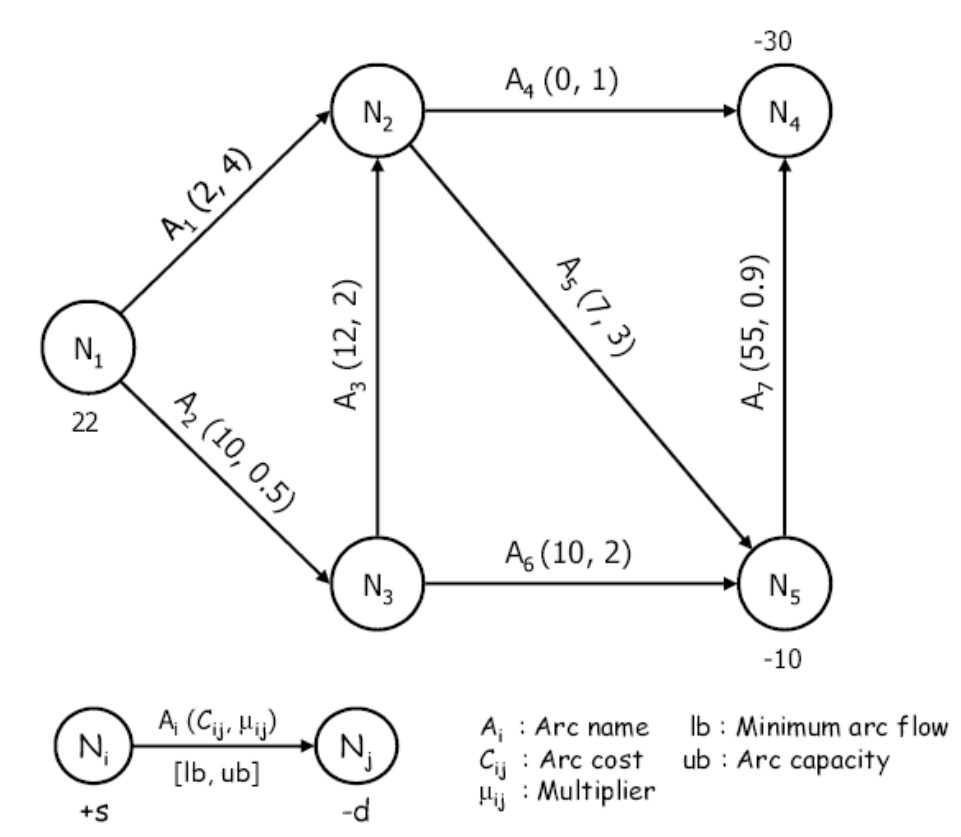
In this section we introduce how to use the NETFLOW procedure to solve *generalized* network programming problems.

## What Is a Generalized Network?

It is well known that in a pure network the sum of flows entering an arc is equal to the sum of flows leaving it. However, in a generalized network there may be a gain or a loss as flow traverses an arc. Each arc has a multiplier to represent these gains or losses.

To illustrate what is meant, consider the network shown in Figure 7.25.

**Figure 7.25** Generalized Network Example



You can think of this as a network representing a supply node ( $N_1$ ), trans-shipment nodes ( $N_2$ ,  $N_3$ ), and demand nodes ( $N_4$ ,  $N_5$ ). As indicated by the legend, the number below a node represents its **supdem** value. Above each arc is its name, followed by the arc cost and arc multiplier in parentheses. The lower and upper bounds on flow allowed to **enter** an arc are represented in square brackets below it. When no bounds are specified (as in Figure 7.25), they are assumed to be  $[0, 99999999]$ .

Now consider the node pair ( $N_1$ ,  $N_2$ ). The information on arc  $A_1$  says that it costs 2 per unit of flow to traverse it, and for each unit of flow entering the arc, four units get accumulated at node  $N_2$ . The corresponding component in the objective function is two times the flow through arc  $A_1$  leaving node  $N_1$ , not two times the flow through arc  $A_1$  arriving at node  $N_2$ .

A commonly encountered example of a generalized network is in power generation: as electricity is transmitted over wires, there is some unavoidable loss along the way. This loss is represented by a multiplier less than 1.0.

Arc multipliers need not always be less than 1.0. For instance, in financial models, a flow through an arc could represent money in a bank account earning interest. In that case, the arc would have a multiplier greater than 1.0.

Generalized networks offer convenience when flow commodity changes. For a pure network, care must be taken to ensure the flow commodity is the same throughout the entire model. For example, in a model to determine how sugar should be grown, refined, packaged, and sold, the flow commodity might be kilograms of sugar, and all numerical parameters throughout the model (all supplies, arc costs, capacities, bounds, demands, etc.) must be in terms of kilograms of sugar. Some arcs might correspond to the movement of 5-kilogram bags of sugar. If a generalized network formulation is used, the arc that represents packaging could be given a multiplier of 0.2, so flow through arcs that convey flow corresponding to bags of sugar will have arc costs in terms of dollars per bag, and capacities, bounds, demands, etc. in terms of number of bags.

In the following sections we describe in detail how to provide data for arc multipliers, how to deal with excess supply or demand in pure and generalized networks, how to model maximum flow problems, and how to handle networks with missing supply and demand nodes, and ranges on supply and demand.

---

## How to Specify Data for Arc Multipliers

If you are familiar with using the NETFLOW procedure to solve pure network problems, then solving generalized network problems is fairly simple. You just need to provide the additional data for the arc multipliers. Arcs by default have a multiplier of 1.0, so you only need to provide arc multipliers that are not equal to 1.0. You can specify the arc multiplier data in either or both of the ARCDATA= and CONDATA= data sets. The procedure scans the SAS variables in the ARCDATA= data set, and if it finds a name `_MULT_` (or a similar name with letters of different case), then it assumes that the SAS variable contains data for arc multipliers. CONDATA= is scanned for special type values that indicates data are arc multipliers.

The rest of this section describes the various ways in which you can specify data for the arc multipliers. The network in [Figure 7.25](#) is used for illustration.

### All Arc Multiplier Data in the ARCDATA= Data Set

You can specify all the arc multiplier data in the ARCDATA= data set. The following code creates the input SAS data sets:

```

/*****
*
* Generalized Networks:
* How to Specify Data for Arc Multipliers
*
*****/

/* All Arc Multiplier Data in the ARCDATA= Data Set */

data nodes;
    input _node_ $ _sd_ ;
datalines;
N1 22
N4 -30
N5 -10
;

```

```

data arcs;
    input _from_ $ _to_ $ _cost_ _mult_;
datalines;
N1 N2    2    4
N1 N3   10 0.5
N2 N4    0    1
N2 N5    7    3
N3 N2   12    2
N3 N5   10    2
N5 N4   55 0.9
;

```

Let us first look at the data for this problem. There is a variable named `_mult_` in the `ARC DATA=` data set, so PROC NETFLOW assumes it represents the arc multipliers. The SAS variable `_sd_` represents the supdem value of a node. A positive or missing S value indicates supply, and a negative or missing D value indicates demand.

The optimal solution can be obtained from the `CONOUT=` data set. Note that you need to specify the `CONOUT=` data set even if the network has no side constraints; you cannot use the `ARCOUT=` data set.

You can use the following SAS code to run PROC NETFLOW:

```

title1 'The NETFLOW Procedure';
proc netflow
    bytes      = 100000
    nodedata   = nodes
    arcdata    = arcs
    conout     = solution;
run;

```

The optimal solution is displayed in [Output 7.26](#).

**Figure 7.26** Output of the Example Problem

| The NETFLOW Procedure |        |      |        |          |      |        |          |          |         |         |
|-----------------------|--------|------|--------|----------|------|--------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _mult_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | N1     | N2   | 2      | 99999999 | 0    | 4.0    | 22       | .        | 6.0000  | 12.000  |
| 2                     | N3     | N2   | 12     | 99999999 | 0    | 2.0    | .        | .        | 3.0000  | 36.000  |
| 3                     | N1     | N3   | 10     | 99999999 | 0    | 0.5    | 22       | .        | 16.0000 | 160.000 |
| 4                     | N2     | N4   | 0      | 99999999 | 0    | 1.0    | .        | 30       | 30.0000 | 0.000   |
| 5                     | N5     | N4   | 55     | 99999999 | 0    | 0.9    | .        | 30       | -0.0000 | -0.000  |
| 6                     | N2     | N5   | 7      | 99999999 | 0    | 3.0    | .        | 10       | 0.0000  | 0.000   |
| 7                     | N3     | N5   | 10     | 99999999 | 0    | 2.0    | .        | 10       | 5.0000  | 50.000  |

### All Arc Multiplier Data in CONDATA= Data Set

Let us now solve the same problem, but with all the arc multipliers specified in the `CONDATA=` data set. The `CONDATA=` data set can have either a sparse format or a dense format. The following code illustrates the dense format representation:

```

data arcs1b;
    input _from_ $ _to_ $ _cost_;
datalines;
N1 N2    2
N1 N3   10
N2 N4    0
N2 N5    7
N3 N2   12
N3 N5   10
N5 N4   55
;

data MUdense;
    input _type_ $ N1_N2 N1_N3 N2_N4 N2_N5 N3_N2 N3_N5 N5_N4;
datalines;
mult 4.0 0.5 1.0 0.3 2.0 2.0 0.9
;

```

You can use the following SAS code to obtain the solution:

```

proc netflow
    gennet
    nodedata = nodes
    arcdata  = arcs1b
    condata  = MUdense
    conout   = soln1b;
run;

```

Note that a new option, GENNET, has been specified in the call to PROC NETFLOW. This option is necessary when the network is generalized and there are no arc multiplier data in the ARCDATA= data set. If this option is not specified, then the procedure assumes that the network is pure (without arc multipliers) and sets up the excess supply node and the excess arcs.

The sparse format representation is as follows:

```

data MUsparse;
    input _type_ $ _col_ $ _coef_;
datalines;
mult N1_N2 4.0
mult N1_N3 0.5
mult N2_N4 1.0
mult N2_N5 0.3
mult N3_N2 2.0
mult N3_N5 2.0
mult N5_N4 0.9
;

```

You can use the following SAS code to obtain the solution:

```

proc netflow
    gennet    sparsecondata
    nodedata  = nodes
    arcdata   = arcs1b
    condata   = MUsparse

```

```
conout    = soln1c;
run;
```

Note that you need to specify the SPARSECONDATA option in the call to PROC NETFLOW.

### Arc Multiplier Data in Both ARCDATA= and CONDATA= Data Sets

You can also provide some multiplier data in the ARCDATA= data set, and the rest in the CONDATA= data set as follows:

```
data arcs1c;
  input _from_ $ _to_ $ _cost_ _mult_;
datalines;
N1 N2    2    4
N1 N3   10   .5
N2 N4    0    .
N2 N5    7    .
N3 N2   12    .
N3 N5   10    .
N5 N4   55    .
;

data MUdense1;
  input _type_ $ N2_N4 N2_N5 N3_N2 N3_N5 N5_N4;
datalines;
mult 1.0  0.3  2.0  2.0  0.9
;
```

The procedure merges the data when all the input data sets have been read.

### Specifying Arc Multiplier Data Using a List Statement

You can also specify the name of the multiplier variable in the list statement MULT, or MULTIPLIER. For example, if the name of the variable is lossrate, then use the following:

```
proc netflow
...
;
mult lossrate;
run;
```

You may also use MULT, GAIN, or LOSS (or similar names with letters of different case) as a value of the TYPE list SAS variable.

---

## Using the New EXCESS= Option in Pure Networks: NETFLOW Procedure

In this section we describe how to use the new EXCESS= option to solve a wide variety of problems. These include the following:



- networks with excess supply or demand
- networks containing nodes with unknown supply and demand values
- maximum flow problems
- networks with nodes having supply and demand ranges

---

## Handling Excess Supply or Demand

The supdem value of a node can be specified in the following formats:

- in the NODEDATA= data set, using the `_supdem_` or `_sd_` list variable
- in the ARCDATA= data set, using the `_SUPPLY_` and `_DEMAND_` list variables

If there is only one supply (demand) node, then use the `SOURCE=` (`SINK=`) option to refer to it, and use the `SUPPLY=` (`DEMAND=`) option to specify its supdem value.

To ensure feasibility, there are different methods by which flow can be added to or drained from the network. This extra flow can be added to or drained from the network at either the supply or demand nodes. The new `EXCESS=` option is used to address such instances.

For pure networks there are two valid values that can be specified for the `EXCESS=` option: `EXCESS=ARCS` and `EXCESS=SLACKS`.

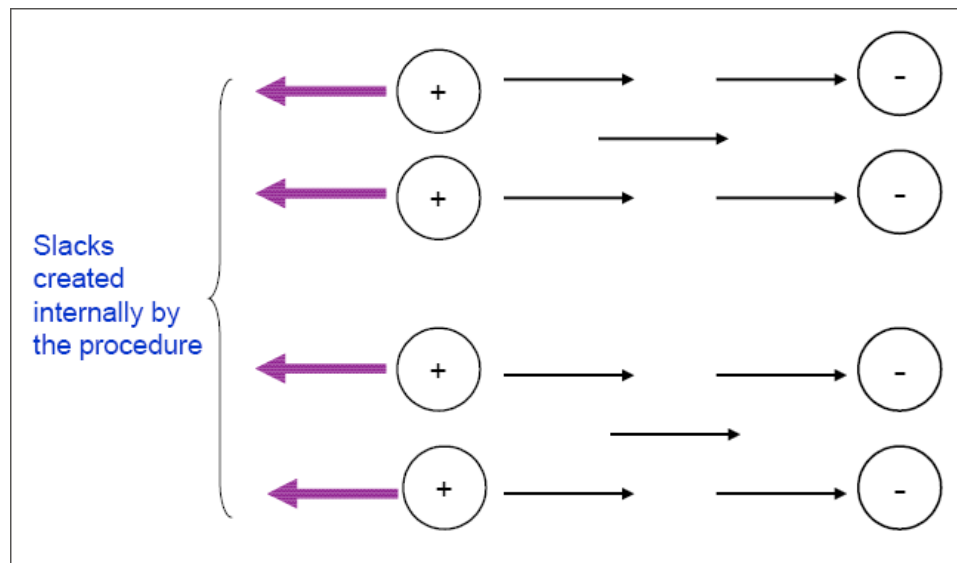
`EXCESS=ARCS` is the default value. An extra node, referred to as `_EXCESS_`, is added to the network and is connected to the actual network by “excess” arcs.

- If total supply exceeds total demand, then `_EXCESS_` is an extra demand node with demand equal to total supply minus total demand.
  - If the `THRUNET` option is specified, the “excess” arcs are directed away from any actual demand node (even nodes with missing `D` demand) and toward `_EXCESS_`.
  - Or else if there are demand nodes with missing `D` demands, the “excess” arcs are directed away from these nodes and toward `_EXCESS_`.
  - Or else the “excess” arcs are directed away from the supply nodes and toward `_EXCESS_`.
- If the total demand exceeds the total supply, then `_EXCESS_` is an extra supply node with supply equal to the total demand minus the total supply.
  - If the `THRUNET` option is specified, the “excess” arcs are directed away from `_EXCESS_` and toward any actual supply node (even nodes with missing `S` supply.)
  - Or else if there are supply nodes with missing `S` supplies, the “excess” arcs are directed away from `_EXCESS_` and toward these nodes.
  - Or else the “excess” arcs are directed away from `_EXCESS_` and toward the demand nodes.

The node `_EXCESS_` and the associated arcs are created to ensure that the problem presented to the optimizer has a total supply equal to the total demand. They are neither displayed in the optimal solution nor saved in any output SAS data set.

If `EXCESS=SLACKS` is specified, then slack variables are created for some flow conservation constraints instead of having the node `_EXCESS_` and “excess” arcs. The flow conservation constraint (which was an inequality) is now converted to an equality with the addition of the slack variable. Alternatively, you can think of these slacks as arcs with one of their end nodes missing — they are directed from a node but not toward any other node (or directed toward a node but not from any other node). Figure 7.27 presents a clearer picture of this.

**Figure 7.27** `EXCESS=SLACKS`, Total Supply Exceeds Total Demand, `THRUNET` Not Specified, No Nodes with Missing Demand



**NOTE:** When you specify `EXCESS=SLACKS`, the interior point solver is used. The output SAS data set needs to be specified by the `CONOUT=` data set, even if side constraints are not present. Also, when you specify the `EXCESS=SLACKS` option, the size of the model submitted to the optimizer is smaller than with `EXCESS=ARCS` since it no longer has the `_EXCESS_` node and the excess arcs associated with it.

## Handling Missing Supply and Demand Simultaneously

Another new feature in the NETFLOW procedure is that it enables you to specify a network containing both nodes with missing S supply values and nodes with missing D demand values. This feature is a powerful modeling tool, and we show in the later sections how to use it to formulate and solve [maximum flow problems](#) and network models with [range constraints on supply and demand](#).

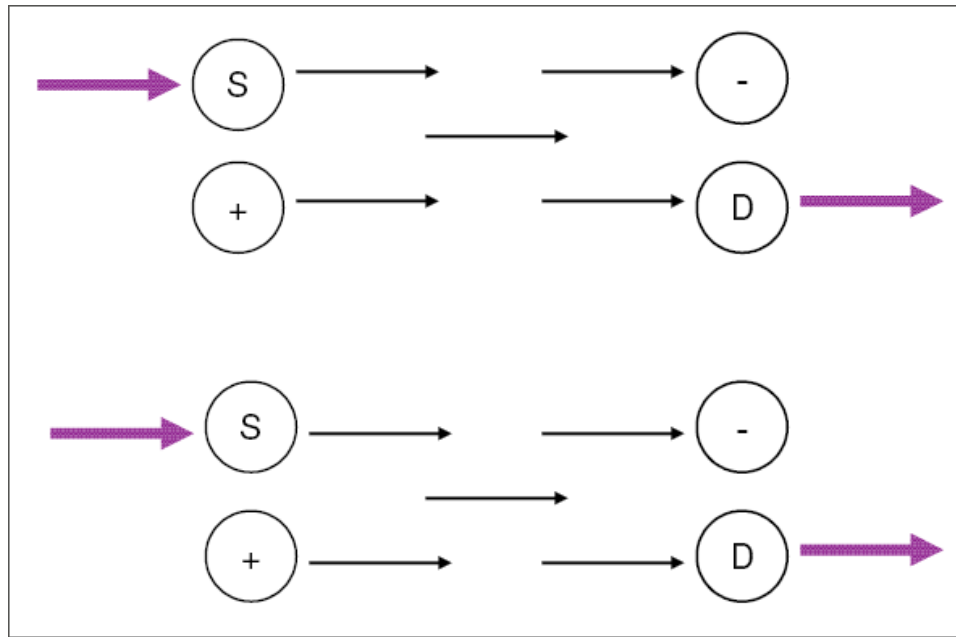
Whenever a network is detected to have both nodes with missing S supply values and nodes with missing D demand values, a special value of the `EXCESS=` option is assigned internally by the procedure; any value you specify for the `EXCESS=` option is overridden. The procedure solves the problem in the following manner:

- Nodes with positive (negative) `supdem` values supply (demand) the exact amount of flow specified.

- Nodes with missing S supply (missing D demand) values supply (demand) flow quantities that are determined by optimization.

Figure 7.28 displays how the slack variables are set up by the procedure internally. These variables are neither a part of the input data set nor displayed in any output SAS data set or printed output.

**Figure 7.28** A Network with Both Missing S Supply and Missing D Demand Nodes



## Maximum Flow Problems

The maximum flow problem (MFP) can be stated as follows: Given a directed graph  $G = (N, A)$  with capacity  $u_{ij} \geq 0$  on each arc  $(i, j) \in A$ , a source node  $s$  and a sink node  $t$ , find the maximum flow that can go from  $s$  to  $t$ , while obeying the flow conservation constraints at each node. You can solve such problems using the MAXFLOW option in the call to PROC NETFLOW.

Ordinarily many, if not all, arcs in an MFP network have capacities, and it is common that these arcs have zero costs. However, the NETFLOW procedure enables you to have nonzero costs to influence the optimal solution in cases where multiple maximum flow patterns are known to exist.

The following two subsections explain the role of the EXCESS= option in solving pure and generalized maximum flow problems.

### The EXCESS=ARCS Option

Consider a maximum flow problem involving a pure network. Assume that you do not explicitly specify the EXCESS= option (the EXCESS=ARCS option is used by the procedure by default). The NETFLOW procedure sets up the problem in the following manner:

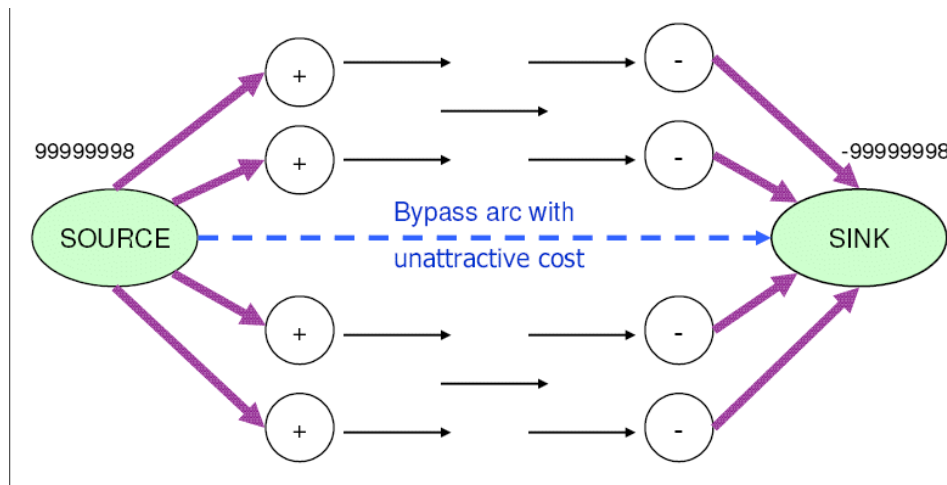
1. The source node is assigned a supdem value equal to INFINITY–1.

2. The sink node is assigned a supdem value equal to  $-(\text{INFINITY}-1)$ .
3. If there is no existing arc between the source node and the sink node, an arc called the *bypass arc* directed from the source node to the sink node is added.
4. If there is an existing arc between the source node and the sink node, a dummy node is used to break up what would have been a single bypass arc: *source*  $\rightarrow$  *sink* gets transformed into two arcs, *source*  $\rightarrow$  *dummy*  $\rightarrow$  *sink*.
5. If you are maximizing, then the cost of the bypass arc(s) is equal to  $-1$  if all other arcs have zero costs; otherwise the cost of the bypass arc(s) is equal to  $-(\text{INFINITY} / \text{BYPASSDIV})$ .
6. If you are minimizing, then the cost of the bypass arc(s) is equal to  $1$  if all other arcs have zero costs; otherwise the cost of the bypass arc(s) is equal to  $\text{INFINITY} / \text{BYPASSDIV}$ .

You can specify the value of the `INFINITY=` option in the procedure statement, or you can use the default value of 99999999. You can also specify the `BYPASSDIV=` option. The default value for the `BYPASSDIV=` option is 100.

This scenario is depicted in Figure 7.29. Since the cost of the bypass arc is unattractive, the optimization process minimizes the flow through it, thereby maximizing the flow through the real network. See the first subsection in Example 7.10 for an illustration.

**Figure 7.29** Pure Maximum Flow Problem, `EXCESS=ARCS` Option Specified



This method of setting up a maximum flow problem does come with a drawback. It is likely to produce incorrect results if the following occur:

- the maximum flow is greater than  $\text{INFINITY}-1$ , or
- the cost of the bypass arc is insufficiently unattractive to ensure that the entire flow traverses the real network and not through the bypass arc

Additionally, numbers of large magnitude can cause problems during optimization, including numerical instability and loss of precision. In the next section, we explain how to overcome these difficulties when solving maximum flow problems.

### The EXCESS=SLACKS Option

Assume you have a pure maximum flow problem and you specify the EXCESS=SLACKS option. The NETFLOW procedure sets up the problem in the following manner:

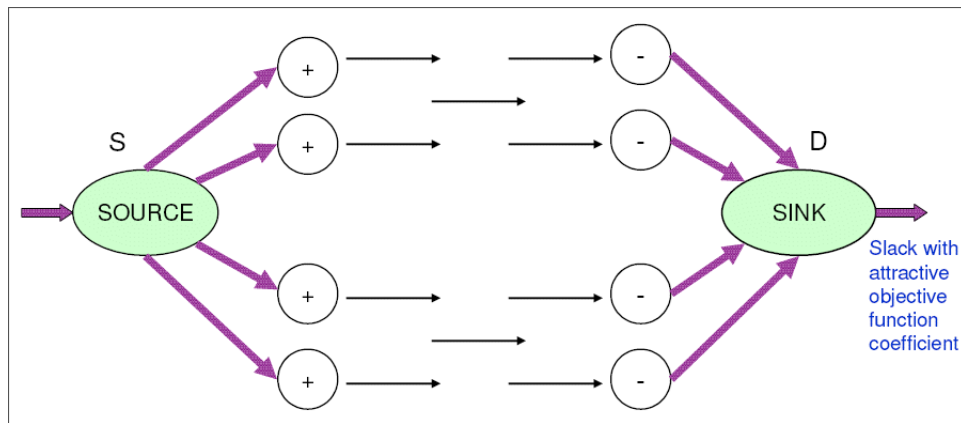
- The source node is assigned a missing S supply value.
- The sink node is assigned a missing D demand value.

Since this network contains a node with a missing S supply value and a node with a missing D demand value, we have a situation similar to the one described in the section “[Handling Missing Supply and Demand Simultaneously](#)” on page 464. Both of these nodes have slack variables. Usually, slack variables have zero objective function coefficients, but because the MAXFLOW option is specified, one of the slack variables must be attractive enough to make it worthwhile for flow to traverse the network. [Figure 7.30](#) presents the scenario clearly.

If you are maximizing, then the objective function coefficient of the slack variable associated with the sink node is  $-1$  if all other arcs have zero costs. Otherwise it is  $-(\text{INFINITY} / \text{BYPASSDIV})$ . If you are minimizing, then the objective function coefficient of the slack variable associated with the sink node is  $1$  if all arcs have zero costs. Otherwise it is  $\text{INFINITY} / \text{BYPASSDIV}$ . See the second subsection in [Example 7.10](#) for an illustration of the EXCESS=SLACKS option in pure maximum flow problems.

**NOTE:** If the MAXFLOW option is not specified, these slack variables assume zero objective function coefficients, and the MFP may not be solved properly.

**Figure 7.30** Pure Maximum Flow Problem with EXCESS=SLACKS Option Specified

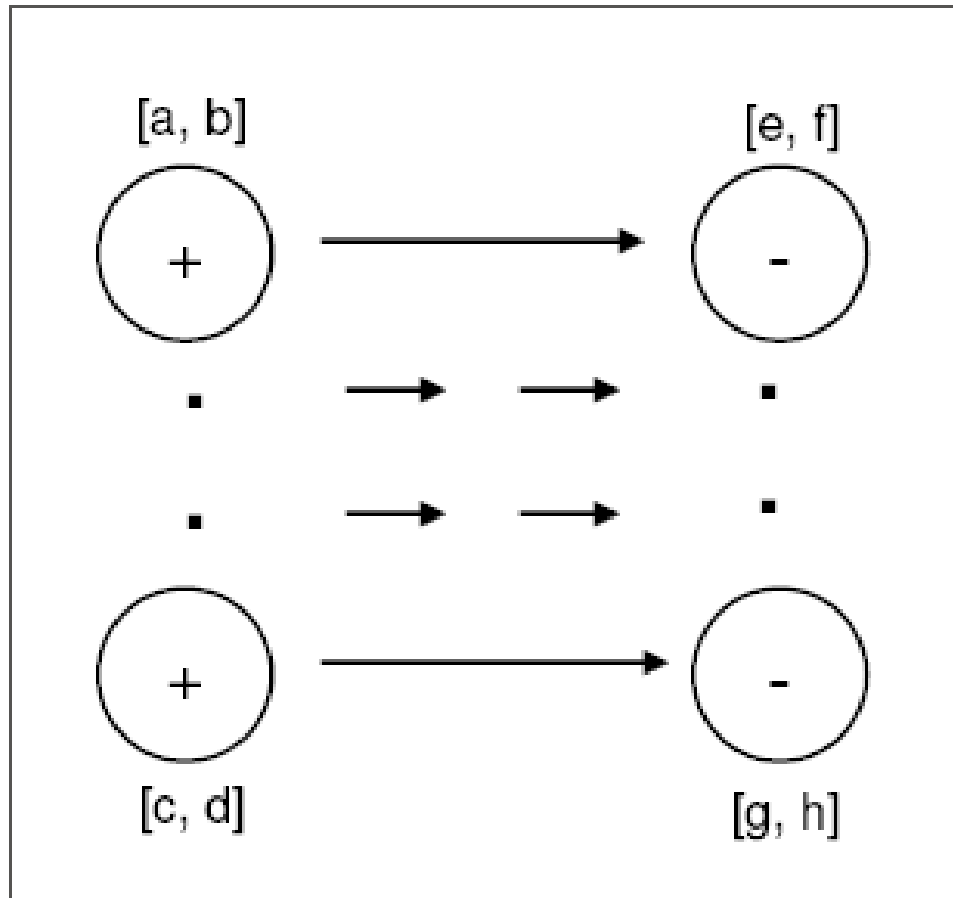


When you use the MAXFLOW option, the procedure sets up the problem in such a way that maximum flow traverses the network. This enables you to transform certain types of problems into maximum flow problems. One such instance is when you have a network where the amount of flow that is supplied or demanded falls within a range of values. The following section describes how to solve such problems.

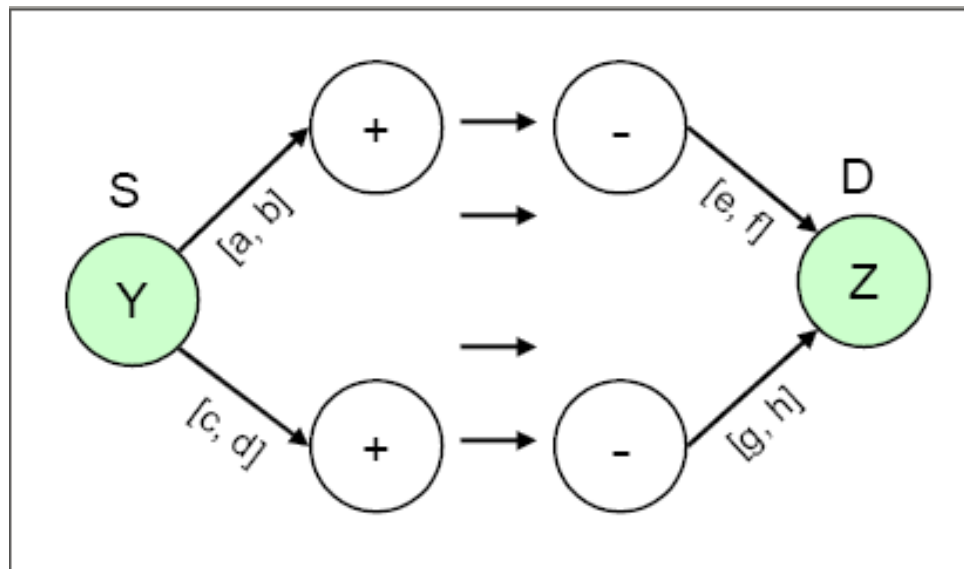
## Handling Supply and Demand Ranges

Consider the scenario depicted by Figure 7.31, where the supply and demand nodes have ranges; i.e., the amounts they can supply or demand are constrained to be within certain lower and upper bounds.

**Figure 7.31** Network with Ranges on Supplies and Demands



To model this situation, you first need to add a supply node with missing  $S$  supply value (the  $Y$  node in Figure 7.32) and a demand node with missing  $D$  demand value (the  $Z$  node in Figure 7.32). The bounds on the supply and demand nodes get transformed into upper/lower bounds on the arcs that connect them to nodes  $Y$  and  $Z$ , respectively. It might be necessary to have costs for these arcs to make it worthwhile for flow to traverse them, and subsequently to traverse the actual network. In practice, these costs represent procurement costs, profit from sales, etc.

**Figure 7.32** Network with Ranges of Supplies and Demands: Transformed Model

You could set up all your network models in this fashion, not only in scenarios in which there are supply and demand ranges. For instance, this modeling technique could be used under the following conditions:

- if there are no ranges
- if the network is generalized, and you do not know whether to specify EXCESS=SUPPLY or EXCESS=DEMAND
- if some of the lower bounds are zero or some capacities are infinite, in which case you simply do not specify the capacity

---

## Using the New EXCESS= Option in Generalized Networks: NETFLOW Procedure

In this section we briefly describe how to use the new EXCESS= option in generalized networks. We provide simple scenarios to enable you to understand what happens internally in the solver when different values for the EXCESS= option are specified.

---

### Total Supply and Total Demand: How Generalized Networks Differ from Pure Networks

For a pure network, it is easy to check for excess supply or excess demand. If the sum of positive supdem values exceeds (is less than) the absolute value of the sum of negative supdem values, then the network has excess supply (demand).

However, in a generalized network you need to specify whether the network should have excess supply or excess demand. To do that you can specify the option `EXCESS=SUPPLY` or `EXCESS=DEMAND`, respectively.

Although the total supply and total demand of a generalized network can be determined, you may not know beforehand if excess flow must be added to, removed from, or left unused by the network. For example, consider a simple network, one consisting of two nodes, A and B, connected by a single arc,  $A \rightarrow B$ . Suppose the supply of node A is 10 and the demand of node B is 30. If this is a pure network, then the network solved must be either  $\_EXCESS\_ \rightarrow A \rightarrow B$  if the `THRUNET` option is not specified and the flow through the arc between A and B is 30 units, or  $A \rightarrow B \leftarrow \_EXCESS\_$  if the `THRUNET` option is specified and the flow through the arc from A to B is 10 units. `\_EXCESS\_` is the name of an extra node that is set up by the procedure behind the scenes, and in both cases it would have a supply capacity of 20 units, which is the flow through the excess arc. However, if the network is generalized, and the arc from A to B has a multiplier of 3.0, then the flow through the arc from A to B would be 10 units, and the network would be feasible without any excess node and arcs. Indeed, no excess node and arcs would be created, even though total supply and total demand are unequal. Therefore, once the NETFLOW procedure detects that the network has arc multipliers that are not 1.0, it might not set up the excess node and the excess arcs.

In [Example 7.11](#) we illustrate the use of the `EXCESS=` option to solve generalized networks that have total supply equal to total demand, but have arcs with varying multipliers.

In the section “[Handling Missing Supply and Demand Simultaneously](#)” on page 464, we discuss the case where a network has both nodes with missing S supply values and nodes with missing D demand values. In the next two subsections we analyze scenarios where a network has nodes with either missing S supply values or missing D demand values, but not both.

---

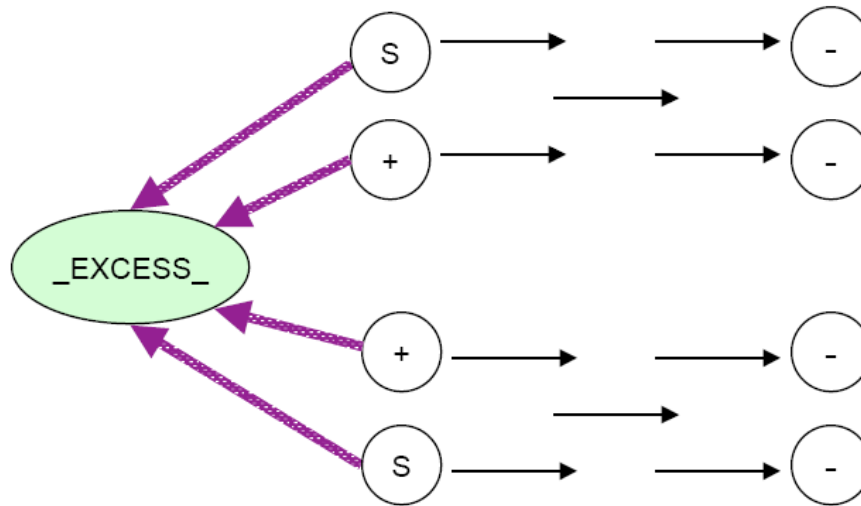
## The `EXCESS=SUPPLY` Option

If you specify the `EXCESS=SUPPLY` option, then there are three possible scenarios to deal with:

Case 1: No Node with Missing D Demand, `THRUNET` Not Specified (see [Figure 7.33](#))

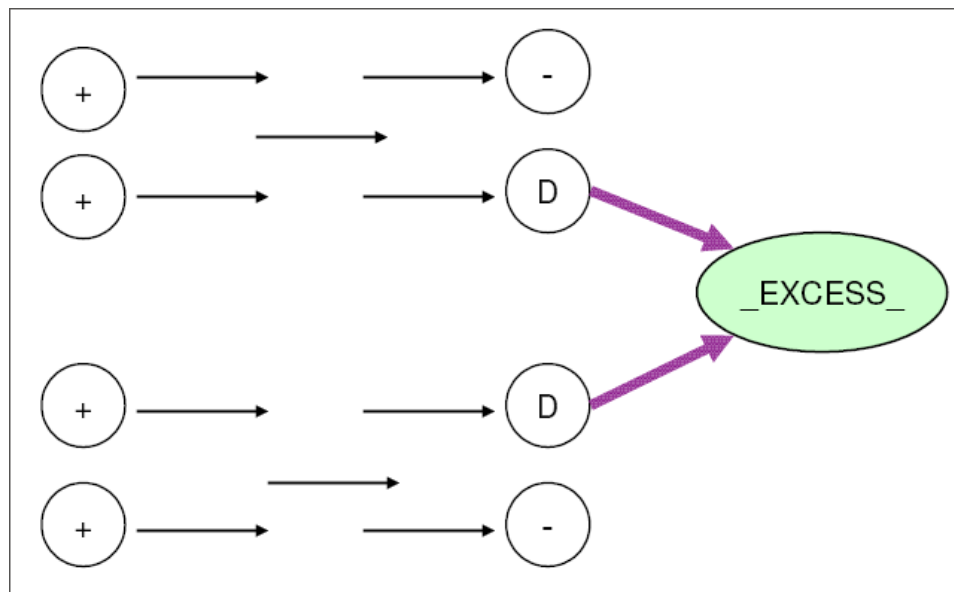
Drain the excess supply from all supply nodes.



**Figure 7.33** Nodes with Missing S Supply, THRUNET Specified

Case 2: Some Nodes with Missing D Demand, THRUNET Not Specified (see [Figure 7.34](#))

Drain the excess supply from nodes that have missing D demand values. If a node has a missing D demand value, then the amount it demands is determined by optimization. For a demand node with negative supdem value, that value negated is equal to the sum of flows on all actual arcs directed toward that node.

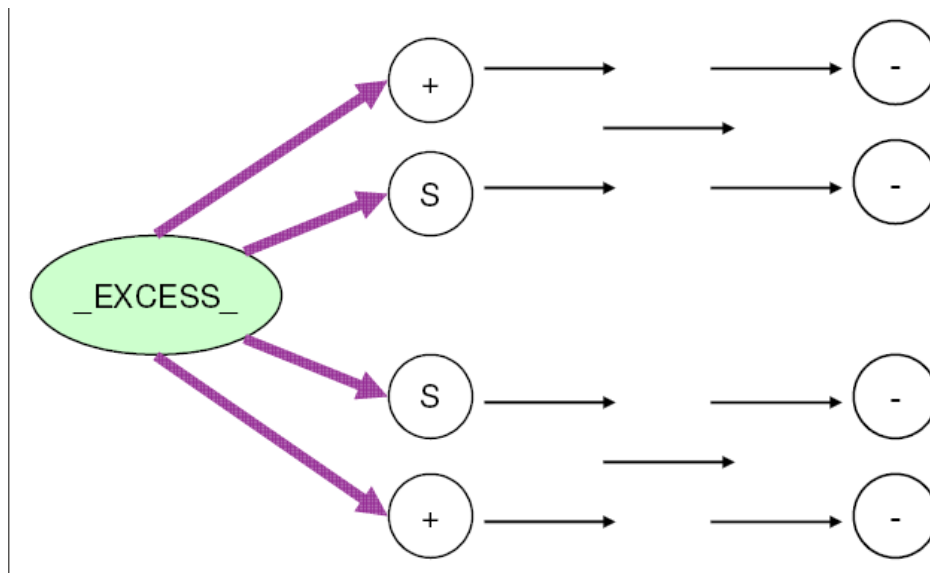
**Figure 7.34** Nodes with Missing D Demand

Case 3: THRUNET Specified (see [Figure 7.35](#))

Drain the excess supply from all demand nodes. If a node has a negative supdem value, that value negated is the lower bound on the sum of flows on all actual arcs directed toward that node. If a

node has a missing D demand value, then the amount it demands is determined by optimization.

**Figure 7.35** Nodes with Missing D Demand, THRUNET Specified



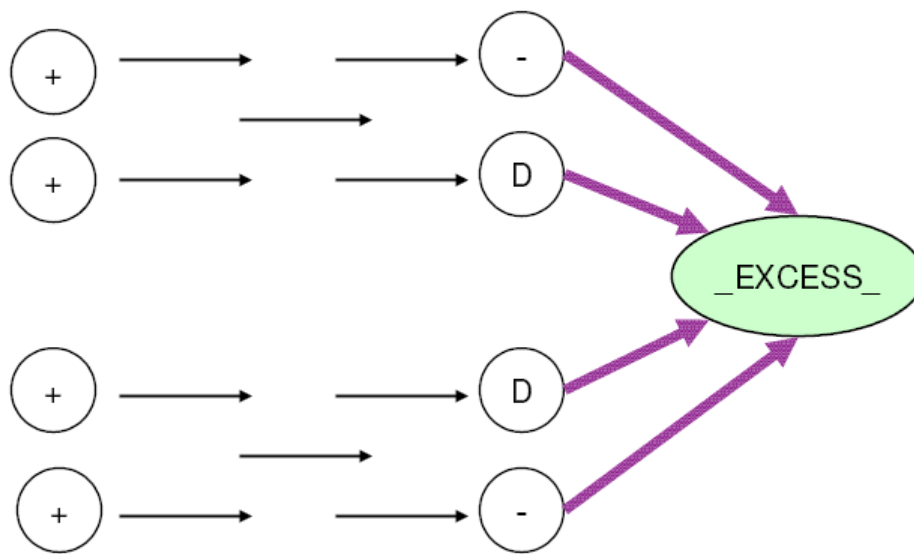
## The EXCESS=DEMAND Option

If you specify the EXCESS=DEMAND option, then there are three possible scenarios to deal with:

Case 1: No Node with Missing S Supply, THRUNET Not Specified (see Figure 7.36)

Supply the excess demand to all demand nodes directly.

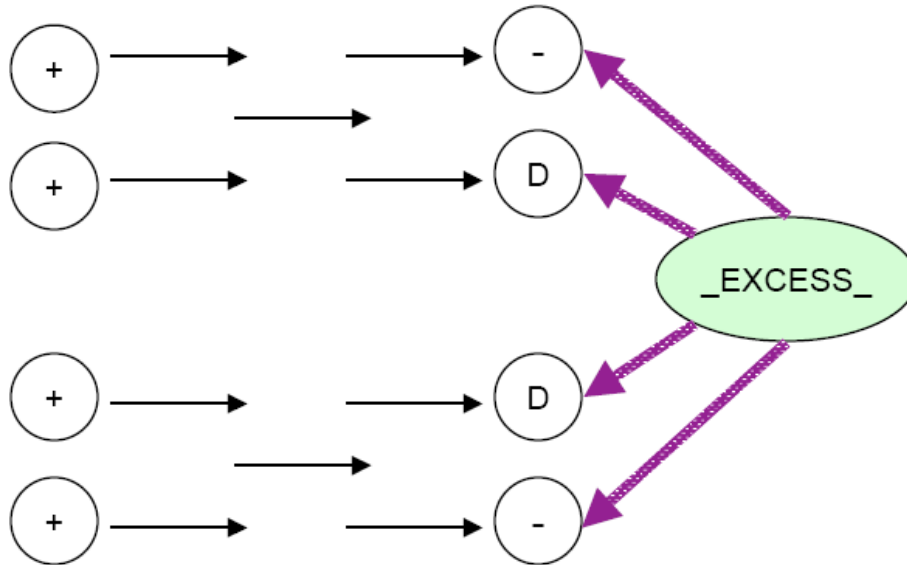
**Figure 7.36** Nodes with Missing D Demand



Case 2: Some Nodes with Missing S Supply, THRUNET Not Specified (see [Figure 7.37](#))

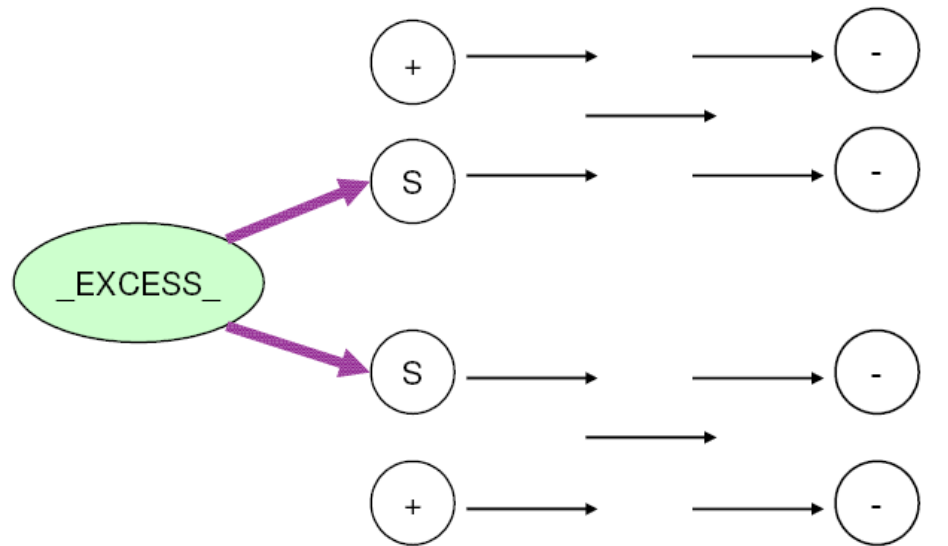
Supply the excess demand by the nodes that have a missing S supply value. If a node has a missing S supply value, then the amount it supplies is determined by optimization. For a supply node with a positive supdem value, that value is equal to the sum of flows on all actual arcs directed away from that node.

**Figure 7.37** Nodes with Missing S Supply



Case 3: THRUNET Specified (see [Figure 7.38](#))

Supply the excess demand by all supply nodes. If a node has a positive supdem value, that value is the lower bound on the sum of flows on all actual arcs directed away from that node. If a node has a missing S supply value, then the amount it supplies is determined by optimization.

**Figure 7.38** Nodes with Missing S Supply, THRUNET Specified

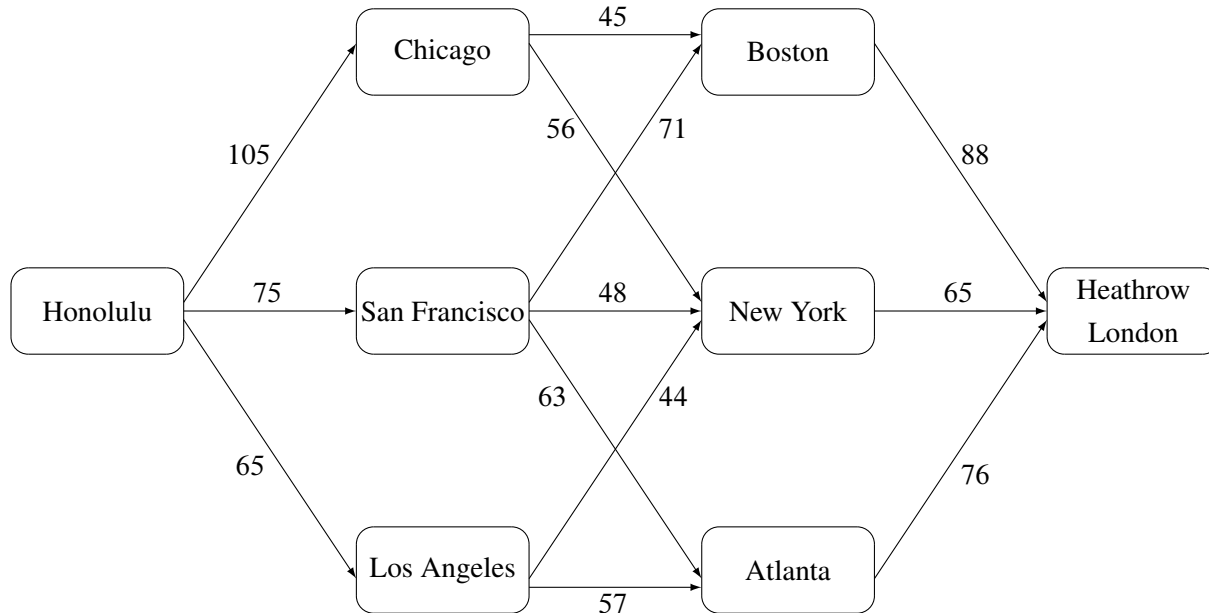
## Examples: NETFLOW Procedure

The following examples illustrate some of the capabilities of PROC NETFLOW. These examples, together with the other SAS/OR examples, can be found in the SAS sample library.

### Example 7.1: Shortest Path Problem

Whole pineapples are served in a restaurant in London. To ensure freshness, the pineapples are purchased in Hawaii and air freighted from Honolulu to Heathrow in London. The network diagram in [Figure 7.39](#) outlines the different routes that the pineapples could take.

The cost to freight a pineapple is known for each arc. You can use PROC NETFLOW to determine what routes should be used to minimize total shipping cost. The shortest path is the least cost path that all pineapples should use. The **SHORTPATH** option indicates this type of network problem.

**Figure 7.39** Pineapple Routes: Shortest Path Problem

The **SINK=** option value HEATHROW LONDON is not a valid SAS variable name so it must be enclosed in single quotes. The **TAILNODE** list variable is FFROM. Because the name of this variable is not **\_TAIL\_** or **\_FROM\_**, the **TAILNODE** list must be specified in the **PROC NETFLOW** statement. The **HEADNODE** list must also be explicitly specified because the variable that belongs to this list does not have the name **\_HEAD\_** or **\_TO\_**, but is TTO.

```

title 'Shortest Path Problem';
title2 'How to get Hawaiian Pineapples to a London Restaurant';
data aircost1;
  input  ffrom&$13.  tto&$15.  _cost_ ;
  datalines;
Honolulu      Chicago      105
Honolulu      San Francisco  75
Honolulu      Los Angeles   68
Chicago       Boston       45
Chicago       New York      56
San Francisco Boston       71
San Francisco New York      48
San Francisco Atlanta      63
Los Angeles   New York      44
Los Angeles   Atlanta      57
Boston        Heathrow London 88
New York      Heathrow London 65
Atlanta       Heathrow London 76
;

proc netflow
  shortpath
  sourcenode=Honolulu
  sinknode='Heathrow London' /* Quotes for embedded blank */
  ARCDATA=aircost1

```

```
    arcout=spath;  
    tail    ffrom;  
    head    tto;  
run;  
  
proc print data=spath;  
    sum _fcost_;  
run;
```

The length at optimality is written to the SAS log as

```
NOTE: Number of nodes= 8 .  
NOTE: Number of arcs= 13 .  
NOTE: Number of iterations performed (neglecting any constraints)= 5 .  
NOTE: Of these, 3 were degenerate.  
NOTE: Optimum (neglecting any constraints) found.  
NOTE: Shortest path= 177 .  
NOTE: The data set WORK.SPITH has 13 observations and 13 variables.
```

The output data set [ARCOUT=SPATH](#) in [Output 7.1.1](#) shows that the best route for the pineapples is from Honolulu to Los Angeles to New York to Heathrow London.

### Output 7.1.1 ARCOUT=SPATH

| Shortest Path Problem                                 |               |                 |        |          |      |          |          |
|---|---------------|-----------------|--------|----------|------|----------|----------|
| How to get Hawaiian Pineapples to a London Restaurant |               |                 |        |          |      |          |          |
| Obs   | ffrom         | tto             | _cost_ | _CAPAC_  | _LO_ | _SUPPLY_ | _DEMAND_ |
| 1   | San Francisco | Atlanta         | 63     | 99999999 | 0    | .        | .        |
| 2   | Los Angeles   | Atlanta         | 57     | 99999999 | 0    | .        | .        |
| 3   | Chicago       | Boston          | 45     | 99999999 | 0    | .        | .        |
| 4   | San Francisco | Boston          | 71     | 99999999 | 0    | .        | .        |
| 5   | Honolulu      | Chicago         | 105    | 99999999 | 0    | 1        | .        |
| 6   | Boston        | Heathrow London | 88     | 99999999 | 0    | .        | 1        |
| 7   | New York      | Heathrow London | 65     | 99999999 | 0    | .        | 1        |
| 8   | Atlanta       | Heathrow London | 76     | 99999999 | 0    | .        | 1        |
| 9   | Honolulu      | Los Angeles     | 68     | 99999999 | 0    | 1        | .        |
| 10  | Chicago       | New York        | 56     | 99999999 | 0    | .        | .        |
| 11  | San Francisco | New York        | 48     | 99999999 | 0    | .        | .        |
| 12  | Los Angeles   | New York        | 44     | 99999999 | 0    | .        | .        |
| 13  | Honolulu      | San Francisco   | 75     | 99999999 | 0    | 1        | .        |

| Obs | _FLOW_ | _FCOST_ | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_         |
|-----|--------|---------|---------|---------|---------|------------------|
| 1   | 0      | 0       | 37      | 9       | 3       | LOWERBD NONBASIC |
| 2   | 0      | 0       | 24      | 10      | 4       | LOWERBD NONBASIC |
| 3   | 0      | 0       | 49      | 4       | 2       | LOWERBD NONBASIC |
| 4   | 0      | 0       | 45      | 5       | 3       | LOWERBD NONBASIC |
| 5   | 0      | 0       | .       | 1       | 1       | KEY_ARC BASIC    |
| 6   | 0      | 0       | 12      | 11      | 5       | LOWERBD NONBASIC |
| 7   | 1      | 65      | .       | 12      | 6       | KEY_ARC BASIC    |
| 8   | 0      | 0       | .       | 13      | 7       | KEY_ARC BASIC    |
| 9   | 1      | 68      | .       | 3       | 1       | KEY_ARC BASIC    |
| 10  | 0      | 0       | 49      | 6       | 2       | LOWERBD NONBASIC |
| 11  | 0      | 0       | 11      | 7       | 3       | LOWERBD NONBASIC |
| 12  | 1      | 44      | .       | 8       | 4       | KEY_ARC BASIC    |
| 13  | 0      | 0       | .       | 2       | 1       | KEY_ARC BASIC    |

=====

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## Example 7.2: Minimum Cost Flow Problem

You can continue to use the pineapple example in [Example 7.1](#) by supposing that the airlines now stipulate that no more than 350 pineapples per week can be handled in any single leg of the journey. The restaurant uses 500 pineapples each week. How many pineapples should take each route between Hawaii and London?

You will probably have more minimum cost flow problems because they are more general than maximal flow and shortest path problems. A shortest path formulation is no longer valid because the sink node does not demand one flow unit.

All arcs have the same capacity of 350 pineapples. Because of this, the `DEFCAPACITY=` option can be specified in the PROC NETFLOW statement, rather than having a `CAPACITY` list variable in `ARCDATA=aircost1`. You can have a `CAPACITY` list variable, but the value of this variable would be 350 in all observations, so using the `DEFCAPACITY=` option is more convenient. You would have to use the `CAPACITY` list variable if arcs had differing capacities. You can use both the `DEFCAPACITY=` option and a `CAPACITY` list variable.

There is only one supply node and one demand node. These can be named in the `SOURCE=` and `SINK=` options. `DEMAND=500` is specified for the restaurant demand. There is no need to specify `SUPPLY=500`, as this is assumed.

```

title 'Minimum Cost Flow Problem';
title2 'How to get Hawaiian Pineapples to a London Restaurant';
proc netflow
  defcapacity=350
  sourcenode='Honolulu'
  sinknode='Heathrow London' /* Quotes for embedded blank */
  demand=500
  arcdata=aircost1
  arcout=arcout1
  nodeout=nodeout1;
  tail      ffrom;
  head      tto;
  set future1;
  run;
  quit;

proc print data=arcout1; sum _fcost_; run;

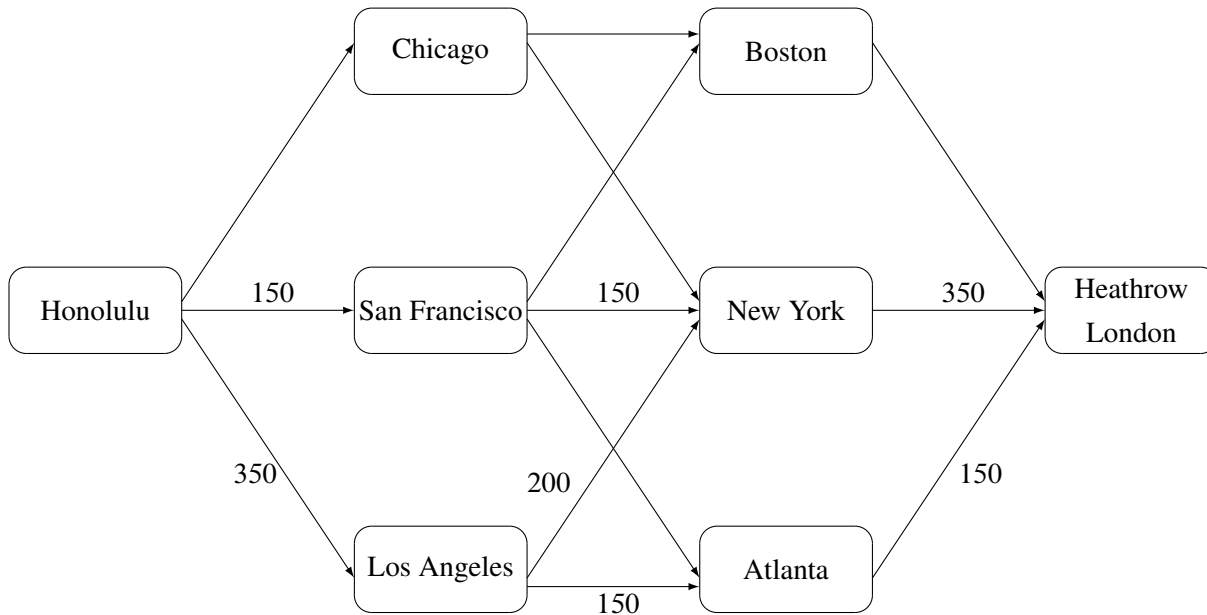
proc print data=nodeout1;
run;
```



The following notes appear on the SAS log:

```
NOTE: SOURCENODE was assigned supply of the total network demand= 500 .
NOTE: Number of nodes= 8 .
NOTE: Number of supply nodes= 1 .
NOTE: Number of demand nodes= 1 .
NOTE: Total supply= 500 , total demand= 500 .
NOTE: Number of arcs= 13 .
NOTE: Number of iterations performed (neglecting any constraints)= 8 .
NOTE: Of these, 4 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= 93750 .
NOTE: The data set WORK.ARCOUT1 has 13 observations and 13 variables.
NOTE: The data set WORK.NODEOUT1 has 9 observations and 10 variables.
```

**Figure 7.40** Pineapple Routes: Minimum Cost Flow Solution



The routes and numbers of pineapples in each arc can be seen in the output data set **ARCOUT**=arcout1 in [Output 7.2.1](#). **NODEOUT**=NODEOUT1 is shown in [Output 7.2.2](#).

**Output 7.2.1** ARCOUNT=ARCOUT1

| Minimum Cost Flow Problem                             |               |                 |        |         |      |          |          |
|---|---------------|-----------------|--------|---------|------|----------|----------|
| How to get Hawaiian Pineapples to a London Restaurant |               |                 |        |         |      |          |          |
| Obs   | ffrom         | tto             | _cost_ | _CAPAC_ | _LO_ | _SUPPLY_ | _DEMAND_ |
| 1   | San Francisco | Atlanta         | 63     | 350     | 0    | .        | .        |
| 2   | Los Angeles   | Atlanta         | 57     | 350     | 0    | .        | .        |
| 3   | Chicago       | Boston          | 45     | 350     | 0    | .        | .        |
| 4   | San Francisco | Boston          | 71     | 350     | 0    | .        | .        |
| 5   | Honolulu      | Chicago         | 105    | 350     | 0    | 500      | .        |
| 6   | Boston        | Heathrow London | 88     | 350     | 0    | .        | 500      |
| 7   | New York      | Heathrow London | 65     | 350     | 0    | .        | 500      |
| 8   | Atlanta       | Heathrow London | 76     | 350     | 0    | .        | 500      |
| 9   | Honolulu      | Los Angeles     | 68     | 350     | 0    | 500      | .        |
| 10  | Chicago       | New York        | 56     | 350     | 0    | .        | .        |
| 11  | San Francisco | New York        | 48     | 350     | 0    | .        | .        |
| 12  | Los Angeles   | New York        | 44     | 350     | 0    | .        | .        |
| 13  | Honolulu      | San Francisco   | 75     | 350     | 0    | 500      | .        |

| Obs   | _FLOW_ | _FCOST_ | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_ |          |
|-------|--------|---------|---------|---------|---------|----------|----------|
| 1     | 0      | 0       | 2       | 9       | 3       | LOWERBD  | NONBASIC |
| 2     | 150    | 8550    | .       | 10      | 4       | KEY_ARC  | BASIC    |
| 3     | 0      | 0       | 4       | 4       | 2       | LOWERBD  | NONBASIC |
| 4     | 0      | 0       | .       | 5       | 3       | KEY_ARC  | BASIC    |
| 5     | 0      | 0       | .       | 1       | 1       | KEY_ARC  | BASIC    |
| 6     | 0      | 0       | 22      | 11      | 5       | LOWERBD  | NONBASIC |
| 7     | 350    | 22750   | -24     | 12      | 6       | UPPERBD  | NONBASIC |
| 8     | 150    | 11400   | .       | 13      | 7       | KEY_ARC  | BASIC    |
| 9     | 350    | 23800   | -11     | 3       | 1       | UPPERBD  | NONBASIC |
| 10    | 0      | 0       | 38      | 6       | 2       | LOWERBD  | NONBASIC |
| 11    | 150    | 7200    | .       | 7       | 3       | KEY_ARC  | BASIC    |
| 12    | 200    | 8800    | .       | 8       | 4       | KEY_ARC  | BASIC    |
| 13    | 150    | 11250   | .       | 2       | 1       | KEY_ARC  | BASIC    |
| ===== |        |         |         |         |         |          |          |
| 93750 |        |         |         |         |         |          |          |

**Output 7.2.2** NODEOUT=NODEOUT1

| Minimum Cost Flow Problem<br>How to get Hawaiian Pineapples to a London Restaurant |                  |                                 |                            |                            |                       |   |                       |                                 |                  |                                 |
|--|------------------|---------------------------------|----------------------------|----------------------------|-----------------------|---|-----------------------|---------------------------------|------------------|---------------------------------|
| O<br>b<br>j<br>e<br>c<br>t<br>i<br>v<br>e  | N<br>o<br>d<br>e | S<br>u<br>b<br>n<br>o<br>d<br>e | D<br>e<br>m<br>a<br>n<br>d | S<br>u<br>p<br>p<br>l<br>y | P<br>r<br>i<br>c<br>e | T<br>r<br>a<br>n<br>s<br>p<br>o<br>r<br>t<br>c<br>o<br>s<br>t | S<br>t<br>o<br>c<br>k | A<br>r<br>c<br>h<br>i<br>v<br>e | F<br>l<br>o<br>w | B<br>a<br>l<br>a<br>n<br>c<br>e |
|  |                  |                                 |                            |                            |                       |   |                       |                                 |                  |                                 |
|  |                  |                                 |                            |                            |                       |   |                       |                                 |                  |                                 |
|  |                  |                                 |                            |                            |                       |   |                       |                                 |                  |                                 |
| 1  | _ROOT_           | 0                               | 0                          | 9                          | 0                     | 1   | 0                     | -1                              | 81               | -14                             |
| 2  | Atlanta          | .                               | -136                       | 7                          | 4                     | 8   | 2                     | 10                              | 150              | 9                               |
| 3  | Boston           | .                               | -146                       | 5                          | 3                     | 2   | 1                     | 5                               | 0                | 4                               |
| 4  | Chicago          | .                               | -105                       | 2                          | 1                     | 9   | 1                     | 1                               | 0                | 1                               |
| 5  | Heathrow London  | -500                            | -212                       | 8                          | 7                     | 5   | 1                     | 13                              | 150              | 11                              |
| 6  | Honolulu         | 500                             | 0                          | 1                          | 9                     | 3   | 8                     | -14                             | 0                | -1                              |
| 7  | Los Angeles      | .                               | -79                        | 4                          | 6                     | 7   | 3                     | -8                              | 200              | 3                               |
| 8  | New York         | .                               | -123                       | 6                          | 3                     | 4   | 4                     | 7                               | 150              | 6                               |
| 9  | San Francisco    | .                               | -75                        | 3                          | 1                     | 6   | 6                     | 2                               | 150              | 2                               |

**Example 7.3: Using a Warm Start**

Suppose that the airlines state that the freight cost per pineapple in flights that leave Chicago has been reduced by 30. How many pineapples should take each route between Hawaii and London? This example illustrates how PROC NETFLOW uses a warm start.

In [Example 7.2](#), the `RESET` statement of PROC NETFLOW is used to specify `FUTURE1`. A `NODEOUT=` data set is also specified. The warm start information is saved in the `arcout1` and `nodeout1` data sets.

In the following DATA step, the costs, reduced costs, and flows in the `arcout1` data set are saved in variables called `oldcost`, `oldflow`, and `oldfc`. These variables form an implicit `ID` list in the following PROC NETFLOW run and will appear in `ARCOUT=arcout2`. Thus, it is easy to compare the previous optimum and the new optimum.

```

title 'Minimum Cost Flow Problem - Warm Start';
title2 'How to get Hawaiian Pineapples to a London Restaurant';
data aircost2;
  set arcout1;
  oldcost=_cost_;
  oldflow=_flow_;
  oldfc=_fcost_;
  if ffrom='Chicago' then _cost_=_cost_-30;

proc netflow
  warm
  arcdata=aircost2
  nodedata=nodeout1
  arcout=arcout2;

```

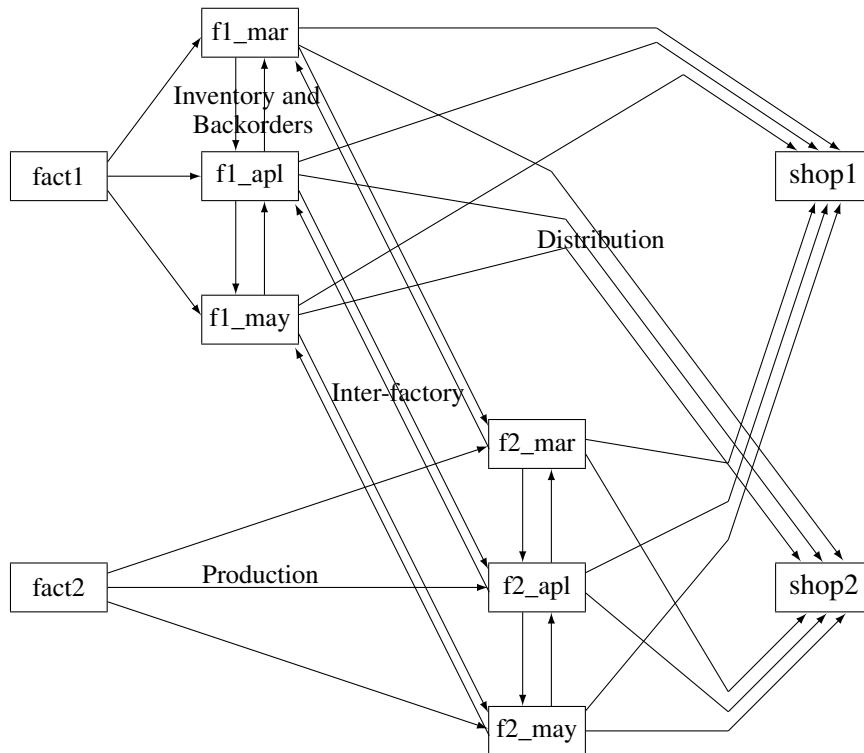
```
        tail    ffrom;  
        head    tto;  
        run;  
        quit;  
  
proc print data=arcout2;  
  var ffrom tto _cost_ oldcost _capac_ _lo_  
    _flow_ oldflow _fcost_ oldfc;  
  sum _fcost_ oldfc;  
run;
```

The following notes appear on the SAS log:

```
NOTE: Number of nodes= 8 .  
NOTE: Number of supply nodes= 1 .  
NOTE: Number of demand nodes= 1 .  
NOTE: The greater of total supply and total demand= 500 .  
NOTE: Number of iterations performed (neglecting any constraints)= 3 .  
NOTE: Of these, 1 were degenerate.  
NOTE: Optimum (neglecting any constraints) found.  
NOTE: Minimal total cost= 93150 .  
NOTE: The data set WORK.ARCOUT2 has 13 observations and 16 variables.
```



Figure 7.41 TV Problem



There are two similarly structured networks, one for the 19-inch televisions and the other for the 25-inch screen TVs. The minimum cost production, inventory, and distribution plan for both TV types can be determined in the same run of PROC NETFLOW. To ensure that node names are unambiguous, the names of nodes in the 19-inch network have suffix `_1`, and the node names in the 25-inch network have suffix `_2`.

The `FUTURE1` option is specified because further processing could be required. Information concerning an optimal solution is retained so it can be used to warm start later optimizations. Warm start information is mostly in variables named `_NNUMB_`, `_PRED_`, `_TRAV_`, `_SCESS_`, `_ARCID_`, and `_FBQ_` and in observations for nodes named `_EXCESS_` and `_ROOT_`, that are in the `NODEOUT=NODE2` output data set. (PROC NETFLOW uses similar devices to store warm start information in the `DUALOUT=` data set when the `FUTURE2` option is specified.) Variables `_ANUMB_` and `_TNUMB_` and observations for arcs directed from or toward a node called `_EXCESS_` are present in `ARCOUT=arc1`. (PROC NETFLOW uses similar devices to store warm start information in the `CONOUT=` data set when the `FUTURE2` option is specified.)

The following code shows how to save the problem data in data sets and solve the model with PROC NETFLOW.

```

title 'Minimum Cost Flow problem';
title2 'Production Planning/Inventory/Distribution';
data node0;
  input _node_ $ _supdem_ ;
  datalines;
fact1_1    1000
fact2_1     850
fact1_2    1000
fact2_2    1500
shop1_1    -900

```

```

shop2_1    -900
shop1_2    -900
shop2_2    -1450
;

data arc0;
  input _tail_ $ _head_ $ _cost_ _capac_ _lo_ diagonal factory
        key_id $10. mth_made $ _name_&$17. ;
  datalines;
fact1_1  f1_mar_1  127.9  500 50 19 1 production March prod f1 19 mar
fact1_1  f1_apr_1   78.6  600 50 19 1 production April prod f1 19 apl
fact1_1  f1_may_1   95.1  400 50 19 1 production May   .
f1_mar_1 f1_apr_1   15     50  . 19 1 storage   March .
f1_apr_1 f1_may_1   12     50  . 19 1 storage   April .
f1_apr_1 f1_mar_1   28     20  . 19 1 backorder April back f1 19 apl
f1_may_1 f1_apr_1   28     20  . 19 1 backorder May   back f1 19 may
f1_mar_1 f2_mar_1   11     .   . 19 . f1_to_2  March .
f1_apr_1 f2_apr_1   11     .   . 19 . f1_to_2  April .
f1_may_1 f2_may_1   16     .   . 19 . f1_to_2  May   .
f1_mar_1 shop1_1  -327.65 250  . 19 1 sales     March .
f1_apr_1 shop1_1  -300    250  . 19 1 sales     April .
f1_may_1 shop1_1  -285    250  . 19 1 sales     May   .
f1_mar_1 shop2_1  -362.74 250  . 19 1 sales     March .
f1_apr_1 shop2_1  -300    250  . 19 1 sales     April .
f1_may_1 shop2_1  -245    250  . 19 1 sales     May   .
fact2_1  f2_mar_1   88.0  450 35 19 2 production March prod f2 19 mar
fact2_1  f2_apr_1   62.4  480 35 19 2 production April prod f2 19 apl
fact2_1  f2_may_1  133.8  250 35 19 2 production May   .
f2_mar_1 f2_apr_1   18     30  . 19 2 storage   March .
f2_apr_1 f2_may_1   20     30  . 19 2 storage   April .
f2_apr_1 f2_mar_1   17     15  . 19 2 backorder April back f2 19 apl
f2_may_1 f2_apr_1   25     15  . 19 2 backorder May   back f2 19 may
f2_mar_1 f1_mar_1   10     40  . 19 . f2_to_1  March .
f2_apr_1 f1_apr_1   11     40  . 19 . f2_to_1  April .
f2_may_1 f1_may_1   13     40  . 19 . f2_to_1  May   .
f2_mar_1 shop1_1  -297.4  250  . 19 2 sales     March .
f2_apr_1 shop1_1  -290    250  . 19 2 sales     April .
f2_may_1 shop1_1  -292    250  . 19 2 sales     May   .
f2_mar_1 shop2_1  -272.7  250  . 19 2 sales     March .
f2_apr_1 shop2_1  -312    250  . 19 2 sales     April .
f2_may_1 shop2_1  -299    250  . 19 2 sales     May   .
fact1_2  f1_mar_2  217.9  400 40 25 1 production March prod f1 25 mar
fact1_2  f1_apr_2  174.5  550 50 25 1 production April prod f1 25 apl
fact1_2  f1_may_2  133.3  350 40 25 1 production May   .
f1_mar_2 f1_apr_2   20     40  . 25 1 storage   March .
f1_apr_2 f1_may_2   18     40  . 25 1 storage   April .
f1_apr_2 f1_mar_2   32     30  . 25 1 backorder April back f1 25 apl
f1_may_2 f1_apr_2   41     15  . 25 1 backorder May   back f1 25 may
f1_mar_2 f2_mar_2   23     .   . 25 . f1_to_2  March .
f1_apr_2 f2_apr_2   23     .   . 25 . f1_to_2  April .
f1_may_2 f2_may_2   26     .   . 25 . f1_to_2  May   .
f1_mar_2 shop1_2  -559.76 .   . 25 1 sales     March .
f1_apr_2 shop1_2  -524.28 .   . 25 1 sales     April .
f1_may_2 shop1_2  -475.02 .   . 25 1 sales     May   .

```

```

f1_mar_2 shop2_2 -623.89 . . 25 1 sales March .
f1_apr_2 shop2_2 -549.68 . . 25 1 sales April .
f1_may_2 shop2_2 -460.00 . . 25 1 sales May .
fact2_2 f2_mar_2 182.0 650 35 25 2 production March prod f2 25 mar
fact2_2 f2_apr_2 196.7 680 35 25 2 production April prod f2 25 apl
fact2_2 f2_may_2 201.4 550 35 25 2 production May .
f2_mar_2 f2_apr_2 28 50 . 25 2 storage March .
f2_apr_2 f2_may_2 38 50 . 25 2 storage April .
f2_apr_2 f2_mar_2 31 15 . 25 2 backorder April back f2 25 apl
f2_may_2 f2_apr_2 54 15 . 25 2 backorder May back f2 25 may
f2_mar_2 f1_mar_2 20 25 . 25 . f2_to_1 March .
f2_apr_2 f1_apr_2 21 25 . 25 . f2_to_1 April .
f2_may_2 f1_may_2 43 25 . 25 . f2_to_1 May .
f2_mar_2 shop1_2 -567.83 500 . 25 2 sales March .
f2_apr_2 shop1_2 -542.19 500 . 25 2 sales April .
f2_may_2 shop1_2 -461.56 500 . 25 2 sales May .
f2_mar_2 shop2_2 -542.83 500 . 25 2 sales March .
f2_apr_2 shop2_2 -559.19 500 . 25 2 sales April .
f2_may_2 shop2_2 -489.06 500 . 25 2 sales May .
;

proc netflow
    nodedata=node0
    arcdata=arc0;
    set future1
        nodeout=node2
        arcout=arc1;
    run;
    quit;

options ls=80 ps = 50;
proc print data=arc1 heading=h width=min;
var _tail_ _head_ _cost_ _capac_ _lo_ _name_ _supply_ _demand_ _flow_ _fcost_;
sum _fcost_;
run;

options ls=80 ps = 50;
proc print data=arc1 heading=h width=min;
var _rcost_ _anumb_ _tnumb_ _status_ diagonal factory key_id mth_made;
run;

proc print data=node2;
run;

```



The following notes appear on the SAS log:

```
NOTE: Number of nodes= 20 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 4 .
NOTE: Total supply= 4350 , total demand= 4150 .
NOTE: Number of arcs= 64 .
NOTE: Number of iterations performed (neglecting any constraints)= 75 .
NOTE: Of these, 1 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= -1281110.35 .
NOTE: The data set WORK.ARC1 has 68 observations and 18 variables.
NOTE: The data set WORK.NODE2 has 22 observations and 10 variables.
```

The solution is given in the `NODEOUT=node2` and `ARCOUT=arc1` data sets. In the `ARCOUT=` data set, shown in [Output 7.4.1](#) and [Output 7.4.2](#), the variables `diagonal`, `factory`, `key_id`, and `month_made` form an implicit `ID` list. The `diagonal` variable has one of two values, 19 or 25. `factory` also has one of two values, 1 or 2, to denote the factory where either production or storage occurs, from where TVs are either sold to shops or satisfy backorders. `PRODUCTION`, `STORAGE`, `SALES`, and `BACKORDER` are values of the `key_id` variable.

Other values of this variable, `F1_TO_2` and `F2_TO_1`, are used when flow through arcs represents the transportation of TVs between factories. The `month_made` variable has values `MARCH`, `APRIL`, and `MAY`, the months when TVs that are modeled as flow through an arc were made (assuming that no televisions are stored for more than one month and none manufactured in May are used to fill March backorders).

These `ID` variables can be used after the `PROC NETFLOW` run to produce reports and perform analysis on particular parts of the company's operation. For example, reports can be generated for production numbers for each factory; optimal sales figures for each shop; and how many TVs should be stored, used to fill backorders, sent to the other factory, or any combination of these, for TVs with a particular screen, those produced in a particular month, or both.

## Output 7.4.1 ARCOU=ARC1

| Minimum Cost Flow problem<br>Production Planning/Inventory/Distribution |          |          |        |          |      |                |
|---|----------|----------|--------|----------|------|----------------|
| Obs   | _tail_   | _head_   | _cost_ | _capac_  | _lo_ | _name_         |
| 1   | fact1_1  | EXCESS_  | 0.00   | 99999999 | 0    |                |
| 2   | fact2_1  | EXCESS_  | 0.00   | 99999999 | 0    |                |
| 3   | fact1_2  | EXCESS_  | 0.00   | 99999999 | 0    |                |
| 4   | fact2_2  | EXCESS_  | 0.00   | 99999999 | 0    |                |
| 5   | fact1_1  | f1_apr_1 | 78.60  | 600      | 50   | prod f1 19 apl |
| 6   | f1_mar_1 | f1_apr_1 | 15.00  | 50       | 0    |                |
| 7   | f1_may_1 | f1_apr_1 | 28.00  | 20       | 0    | back f1 19 may |
| 8   | f2_apr_1 | f1_apr_1 | 11.00  | 40       | 0    |                |
| 9   | fact1_2  | f1_apr_2 | 174.50 | 550      | 50   | prod f1 25 apl |
| 10  | f1_mar_2 | f1_apr_2 | 20.00  | 40       | 0    |                |
| 11  | f1_may_2 | f1_apr_2 | 41.00  | 15       | 0    | back f1 25 may |
| 12  | f2_apr_2 | f1_apr_2 | 21.00  | 25       | 0    |                |
| 13  | fact1_1  | f1_mar_1 | 127.90 | 500      | 50   | prod f1 19 mar |
| 14  | f1_apr_1 | f1_mar_1 | 28.00  | 20       | 0    | back f1 19 apl |
| 15  | f2_mar_1 | f1_mar_1 | 10.00  | 40       | 0    |                |
| 16  | fact1_2  | f1_mar_2 | 217.90 | 400      | 40   | prod f1 25 mar |
| 17  | f1_apr_2 | f1_mar_2 | 32.00  | 30       | 0    | back f1 25 apl |
| 18  | f2_mar_2 | f1_mar_2 | 20.00  | 25       | 0    |                |
| 19  | fact1_1  | f1_may_1 | 95.10  | 400      | 50   |                |
| 20  | f1_apr_1 | f1_may_1 | 12.00  | 50       | 0    |                |
| 21  | f2_may_1 | f1_may_1 | 13.00  | 40       | 0    |                |
| Obs   | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_  |      |                |
| 1   | 1000     | 200      | 5      | 0.00     |      |                |
| 2   | 850      | 200      | 45     | 0.00     |      |                |
| 3   | 1000     | 200      | 10     | 0.00     |      |                |
| 4   | 1500     | 200      | 140    | 0.00     |      |                |
| 5   | 1000     | .        | 600    | 47160.00 |      |                |
| 6   | .        | .        | 0      | 0.00     |      |                |
| 7   | .        | .        | 0      | 0.00     |      |                |
| 8   | .        | .        | 0      | 0.00     |      |                |
| 9   | 1000     | .        | 550    | 95975.00 |      |                |
| 10  | .        | .        | 0      | 0.00     |      |                |
| 11  | .        | .        | 15     | 615.00   |      |                |
| 12  | .        | .        | 0      | 0.00     |      |                |
| 13  | 1000     | .        | 345    | 44125.50 |      |                |
| 14  | .        | .        | 20     | 560.00   |      |                |
| 15  | .        | .        | 40     | 400.00   |      |                |
| 16  | 1000     | .        | 400    | 87160.00 |      |                |
| 17  | .        | .        | 30     | 960.00   |      |                |
| 18  | .        | .        | 25     | 500.00   |      |                |
| 19  | 1000     | .        | 50     | 4755.00  |      |                |
| 20  | .        | .        | 50     | 600.00   |      |                |
| 21  | .        | .        | 0      | 0.00     |      |                |

## Output 7.4.1 continued

| Minimum Cost Flow problem<br>Production Planning/Inventory/Distribution |          |          |        |           |      |                |
|---|----------|----------|--------|-----------|------|----------------|
| Obs   | _tail_   | _head_   | _cost_ | _capac_   | _lo_ | _name_         |
| 22  | fact1_2  | f1_may_2 | 133.30 | 350       | 40   |                |
| 23  | f1_apr_2 | f1_may_2 | 18.00  | 40        | 0    |                |
| 24  | f2_may_2 | f1_may_2 | 43.00  | 25        | 0    |                |
| 25  | f1_apr_1 | f2_apr_1 | 11.00  | 99999999  | 0    |                |
| 26  | fact2_1  | f2_apr_1 | 62.40  | 480       | 35   | prod f2 19 apl |
| 27  | f2_mar_1 | f2_apr_1 | 18.00  | 30        | 0    |                |
| 28  | f2_may_1 | f2_apr_1 | 25.00  | 15        | 0    | back f2 19 may |
| 29  | f1_apr_2 | f2_apr_2 | 23.00  | 99999999  | 0    |                |
| 30  | fact2_2  | f2_apr_2 | 196.70 | 680       | 35   | prod f2 25 apl |
| 31  | f2_mar_2 | f2_apr_2 | 28.00  | 50        | 0    |                |
| 32  | f2_may_2 | f2_apr_2 | 54.00  | 15        | 0    | back f2 25 may |
| 33  | f1_mar_1 | f2_mar_1 | 11.00  | 99999999  | 0    |                |
| 34  | fact2_1  | f2_mar_1 | 88.00  | 450       | 35   | prod f2 19 mar |
| 35  | f2_apr_1 | f2_mar_1 | 17.00  | 15        | 0    | back f2 19 apl |
| 36  | f1_mar_2 | f2_mar_2 | 23.00  | 99999999  | 0    |                |
| 37  | fact2_2  | f2_mar_2 | 182.00 | 650       | 35   | prod f2 25 mar |
| 38  | f2_apr_2 | f2_mar_2 | 31.00  | 15        | 0    | back f2 25 apl |
| 39  | f1_may_1 | f2_may_1 | 16.00  | 99999999  | 0    |                |
| 40  | fact2_1  | f2_may_1 | 133.80 | 250       | 35   |                |
| 41  | f2_apr_1 | f2_may_1 | 20.00  | 30        | 0    |                |
| 42  | f1_may_2 | f2_may_2 | 26.00  | 99999999  | 0    |                |
| Obs   | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_   |      |                |
| 22  | 1000     | .        | 40     | 5332.00   |      |                |
| 23  | .        | .        | 0      | 0.00      |      |                |
| 24  | .        | .        | 0      | 0.00      |      |                |
| 25  | .        | .        | 30     | 330.00    |      |                |
| 26  | 850      | .        | 480    | 29952.00  |      |                |
| 27  | .        | .        | 0      | 0.00      |      |                |
| 28  | .        | .        | 0      | 0.00      |      |                |
| 29  | .        | .        | 0      | 0.00      |      |                |
| 30  | 1500     | .        | 680    | 133756.00 |      |                |
| 31  | .        | .        | 0      | 0.00      |      |                |
| 32  | .        | .        | 15     | 810.00    |      |                |
| 33  | .        | .        | 0      | 0.00      |      |                |
| 34  | 850      | .        | 290    | 25520.00  |      |                |
| 35  | .        | .        | 0      | 0.00      |      |                |
| 36  | .        | .        | 0      | 0.00      |      |                |
| 37  | 1500     | .        | 645    | 117390.00 |      |                |
| 38  | .        | .        | 0      | 0.00      |      |                |
| 39  | .        | .        | 100    | 1600.00   |      |                |
| 40  | 850      | .        | 35     | 4683.00   |      |                |
| 41  | .        | .        | 15     | 300.00    |      |                |
| 42  | .        | .        | 0      | 0.00      |      |                |

## Output 7.4.1 continued

| Minimum Cost Flow problem<br>Production Planning/Inventory/Distribution |          |          |         |            |      |        |
|---|----------|----------|---------|------------|------|--------|
| Obs   | _tail_   | _head_   | _cost_  | _capac_    | _lo_ | _name_ |
| 43  | fact2_2  | f2_may_2 | 201.40  | 550        | 35   |        |
| 44  | f2_apr_2 | f2_may_2 | 38.00   | 50         | 0    |        |
| 45  | f1_mar_1 | shop1_1  | -327.65 | 250        | 0    |        |
| 46  | f1_apr_1 | shop1_1  | -300.00 | 250        | 0    |        |
| 47  | f1_may_1 | shop1_1  | -285.00 | 250        | 0    |        |
| 48  | f2_mar_1 | shop1_1  | -297.40 | 250        | 0    |        |
| 49  | f2_apr_1 | shop1_1  | -290.00 | 250        | 0    |        |
| 50  | f2_may_1 | shop1_1  | -292.00 | 250        | 0    |        |
| 51  | f1_mar_2 | shop1_2  | -559.76 | 99999999   | 0    |        |
| 52  | f1_apr_2 | shop1_2  | -524.28 | 99999999   | 0    |        |
| 53  | f1_may_2 | shop1_2  | -475.02 | 99999999   | 0    |        |
| 54  | f2_mar_2 | shop1_2  | -567.83 | 500        | 0    |        |
| 55  | f2_apr_2 | shop1_2  | -542.19 | 500        | 0    |        |
| 56  | f2_may_2 | shop1_2  | -461.56 | 500        | 0    |        |
| 57  | f1_mar_1 | shop2_1  | -362.74 | 250        | 0    |        |
| 58  | f1_apr_1 | shop2_1  | -300.00 | 250        | 0    |        |
| 59  | f1_may_1 | shop2_1  | -245.00 | 250        | 0    |        |
| 60  | f2_mar_1 | shop2_1  | -272.70 | 250        | 0    |        |
| 61  | f2_apr_1 | shop2_1  | -312.00 | 250        | 0    |        |
| 62  | f2_may_1 | shop2_1  | -299.00 | 250        | 0    |        |
| 63  | f1_mar_2 | shop2_2  | -623.89 | 99999999   | 0    |        |
| Obs   | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_    |      |        |
| 43  | 1500     | .        | 35      | 7049.00    |      |        |
| 44  | .        | .        | 0       | 0.00       |      |        |
| 45  | .        | 900      | 155     | -50785.75  |      |        |
| 46  | .        | 900      | 250     | -75000.00  |      |        |
| 47  | .        | 900      | 0       | 0.00       |      |        |
| 48  | .        | 900      | 250     | -74350.00  |      |        |
| 49  | .        | 900      | 245     | -71050.00  |      |        |
| 50  | .        | 900      | 0       | 0.00       |      |        |
| 51  | .        | 900      | 0       | 0.00       |      |        |
| 52  | .        | 900      | 0       | 0.00       |      |        |
| 53  | .        | 900      | 25      | -11875.50  |      |        |
| 54  | .        | 900      | 500     | -283915.00 |      |        |
| 55  | .        | 900      | 375     | -203321.25 |      |        |
| 56  | .        | 900      | 0       | 0.00       |      |        |
| 57  | .        | 900      | 250     | -90685.00  |      |        |
| 58  | .        | 900      | 250     | -75000.00  |      |        |
| 59  | .        | 900      | 0       | 0.00       |      |        |
| 60  | .        | 900      | 0       | 0.00       |      |        |
| 61  | .        | 900      | 250     | -78000.00  |      |        |
| 62  | .        | 900      | 150     | -44850.00  |      |        |
| 63  | .        | 1450     | 455     | -283869.95 |      |        |

**Output 7.4.1** *continued*

| Minimum Cost Flow problem                  |          |          |         |             |      |        |
|--|----------|----------|---------|-------------|------|--------|
| Production Planning/Inventory/Distribution |          |          |         |             |      |        |
| Obs  | _tail_   | _head_   | _cost_  | _capac_     | _lo_ | _name_ |
| 64   | f1_apr_2 | shop2_2  | -549.68 | 99999999    | 0    |        |
| 65   | f1_may_2 | shop2_2  | -460.00 | 99999999    | 0    |        |
| 66   | f2_mar_2 | shop2_2  | -542.83 | 500         | 0    |        |
| 67   | f2_apr_2 | shop2_2  | -559.19 | 500         | 0    |        |
| 68   | f2_may_2 | shop2_2  | -489.06 | 500         | 0    |        |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_     |      |        |
| 64   | .        | 1450     | 535     | -294078.80  |      |        |
| 65   | .        | 1450     | 0       | 0.00        |      |        |
| 66   | .        | 1450     | 120     | -65139.60   |      |        |
| 67   | .        | 1450     | 320     | -178940.80  |      |        |
| 68   | .        | 1450     | 20      | -9781.20    |      |        |
|  |          |          |         | =====       |      |        |
|  |          |          |         | -1281110.35 |      |        |

Output 7.4.2 ARCOU=ARC1 (continued)

| Minimum Cost Flow problem                  |         |         |         |          |          |
|--|---------|---------|---------|----------|----------|
| Production Planning/Inventory/Distribution |         |         |         |          |          |
| Obs  | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_ |          |
| 1  | .       | 65      | 1       | KEY_ARC  | BASIC    |
| 2  | .       | 66      | 10      | KEY_ARC  | BASIC    |
| 3  | .       | 67      | 11      | KEY_ARC  | BASIC    |
| 4  | .       | 68      | 20      | KEY_ARC  | BASIC    |
| 5  | -0.650  | 4       | 1       | UPPERBD  | NONBASIC |
| 6  | 63.650  | 5       | 2       | LOWERBD  | NONBASIC |
| 7  | 43.000  | 6       | 4       | LOWERBD  | NONBASIC |
| 8  | 22.000  | 7       | 6       | LOWERBD  | NONBASIC |
| 9  | -14.350 | 36      | 11      | UPPERBD  | NONBASIC |
| 10   | 94.210  | 37      | 12      | LOWERBD  | NONBASIC |
| 11   | -16.660 | 38      | 14      | UPPERBD  | NONBASIC |
| 12   | 30.510  | 39      | 16      | LOWERBD  | NONBASIC |
| 13   | .       | 1       | 1       | KEY_ARC  | BASIC    |
| 14   | -20.650 | 2       | 3       | UPPERBD  | NONBASIC |
| 15   | -29.900 | 3       | 5       | UPPERBD  | NONBASIC |
| 16   | -45.160 | 33      | 11      | UPPERBD  | NONBASIC |
| 17   | -42.210 | 34      | 13      | UPPERBD  | NONBASIC |
| 18   | -61.060 | 35      | 15      | UPPERBD  | NONBASIC |
| 19   | 0.850   | 8       | 1       | LOWERBD  | NONBASIC |
| 20   | -3.000  | 9       | 3       | UPPERBD  | NONBASIC |
| 21   | 29.000  | 10      | 7       | LOWERBD  | NONBASIC |

| Obs | diagonal | factory | key_id     | mth_made |
|-----|----------|---------|------------|----------|
| 1   | .        | .       |            |          |
| 2   | .        | .       |            |          |
| 3   | .        | .       |            |          |
| 4   | .        | .       |            |          |
| 5   | 19       | 1       | production | April    |
| 6   | 19       | 1       | storage    | March    |
| 7   | 19       | 1       | backorder  | May      |
| 8   | 19       | .       | f2_to_1    | April    |
| 9   | 25       | 1       | production | April    |
| 10  | 25       | 1       | storage    | March    |
| 11  | 25       | 1       | backorder  | May      |
| 12  | 25       | .       | f2_to_1    | April    |
| 13  | 19       | 1       | production | March    |
| 14  | 19       | 1       | backorder  | April    |
| 15  | 19       | .       | f2_to_1    | March    |
| 16  | 25       | 1       | production | March    |
| 17  | 25       | 1       | backorder  | April    |
| 18  | 25       | .       | f2_to_1    | March    |
| 19  | 19       | 1       | production | May      |
| 20  | 19       | 1       | storage    | April    |
| 21  | 19       | .       | f2_to_1    | May      |

## Output 7.4.2 continued

Minimum Cost Flow problem  
Production Planning/Inventory/Distribution

| Obs | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_         |
|-----|---------|---------|---------|------------------|
| 22  | 2.110   | 40      | 11      | LOWERBD NONBASIC |
| 23  | 75.660  | 41      | 13      | LOWERBD NONBASIC |
| 24  | 40.040  | 42      | 17      | LOWERBD NONBASIC |
| 25  | .       | 14      | 3       | KEY_ARC BASIC    |
| 26  | -27.850 | 15      | 10      | UPPERBD NONBASIC |
| 27  | 15.750  | 16      | 5       | LOWERBD NONBASIC |
| 28  | 45.000  | 17      | 7       | LOWERBD NONBASIC |
| 29  | 13.490  | 46      | 13      | LOWERBD NONBASIC |
| 30  | -1.660  | 47      | 20      | UPPERBD NONBASIC |
| 31  | 11.640  | 48      | 15      | LOWERBD NONBASIC |
| 32  | -16.130 | 49      | 17      | UPPERBD NONBASIC |
| 33  | 50.900  | 11      | 2       | LOWERBD NONBASIC |
| 34  | .       | 12      | 10      | KEY_ARC BASIC    |
| 35  | 19.250  | 13      | 6       | LOWERBD NONBASIC |
| 36  | 104.060 | 43      | 12      | LOWERBD NONBASIC |
| 37  | .       | 44      | 20      | KEY_ARC BASIC    |
| 38  | 47.360  | 45      | 16      | LOWERBD NONBASIC |
| 39  | .       | 18      | 4       | KEY_ARC BASIC    |
| 40  | 23.550  | 19      | 10      | LOWERBD NONBASIC |
| 41  | .       | 20      | 6       | KEY_ARC BASIC    |
| 42  | 28.960  | 50      | 14      | LOWERBD NONBASIC |

| Obs | diagonal | factory | key_id     | mth_made |
|-----|----------|---------|------------|----------|
| 22  | 25       | 1       | production | May      |
| 23  | 25       | 1       | storage    | April    |
| 24  | 25       | .       | f2_to_1    | May      |
| 25  | 19       | .       | f1_to_2    | April    |
| 26  | 19       | 2       | production | April    |
| 27  | 19       | 2       | storage    | March    |
| 28  | 19       | 2       | backorder  | May      |
| 29  | 25       | .       | f1_to_2    | April    |
| 30  | 25       | 2       | production | April    |
| 31  | 25       | 2       | storage    | March    |
| 32  | 25       | 2       | backorder  | May      |
| 33  | 19       | .       | f1_to_2    | March    |
| 34  | 19       | 2       | production | March    |
| 35  | 19       | 2       | backorder  | April    |
| 36  | 25       | .       | f1_to_2    | March    |
| 37  | 25       | 2       | production | March    |
| 38  | 25       | 2       | backorder  | April    |
| 39  | 19       | .       | f1_to_2    | May      |
| 40  | 19       | 2       | production | May      |
| 41  | 19       | 2       | storage    | April    |
| 42  | 25       | .       | f1_to_2    | May      |

## Output 7.4.2 continued

Minimum Cost Flow problem  
Production Planning/Inventory/Distribution

| Obs | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_         |
|-----|---------|---------|---------|------------------|
| 43  | 73.170  | 51      | 20      | LOWERBD NONBASIC |
| 44  | 108.130 | 52      | 16      | LOWERBD NONBASIC |
| 45  | .       | 21      | 2       | KEY_ARC BASIC    |
| 46  | -21.000 | 22      | 3       | UPPERBD NONBASIC |
| 47  | 9.000   | 23      | 4       | LOWERBD NONBASIC |
| 48  | -9.650  | 24      | 5       | UPPERBD NONBASIC |
| 49  | .       | 25      | 6       | KEY_ARC BASIC    |
| 50  | 18.000  | 26      | 7       | LOWERBD NONBASIC |
| 51  | 47.130  | 53      | 12      | LOWERBD NONBASIC |
| 52  | 8.400   | 54      | 13      | LOWERBD NONBASIC |
| 53  | .       | 55      | 14      | KEY_ARC BASIC    |
| 54  | -42.000 | 56      | 15      | UPPERBD NONBASIC |
| 55  | .       | 57      | 16      | KEY_ARC BASIC    |
| 56  | 10.500  | 58      | 17      | LOWERBD NONBASIC |
| 57  | -46.090 | 27      | 2       | UPPERBD NONBASIC |
| 58  | -32.000 | 28      | 3       | UPPERBD NONBASIC |
| 59  | 38.000  | 29      | 4       | LOWERBD NONBASIC |
| 60  | 4.050   | 30      | 5       | LOWERBD NONBASIC |
| 61  | -33.000 | 31      | 6       | UPPERBD NONBASIC |
| 62  | .       | 32      | 7       | KEY_ARC BASIC    |
| 63  | .       | 59      | 12      | KEY_ARC BASIC    |

| Obs | diagonal | factory | key_id     | mth_made |
|-----|----------|---------|------------|----------|
| 43  | 25       | 2       | production | May      |
| 44  | 25       | 2       | storage    | April    |
| 45  | 19       | 1       | sales      | March    |
| 46  | 19       | 1       | sales      | April    |
| 47  | 19       | 1       | sales      | May      |
| 48  | 19       | 2       | sales      | March    |
| 49  | 19       | 2       | sales      | April    |
| 50  | 19       | 2       | sales      | May      |
| 51  | 25       | 1       | sales      | March    |
| 52  | 25       | 1       | sales      | April    |
| 53  | 25       | 1       | sales      | May      |
| 54  | 25       | 2       | sales      | March    |
| 55  | 25       | 2       | sales      | April    |
| 56  | 25       | 2       | sales      | May      |
| 57  | 19       | 1       | sales      | March    |
| 58  | 19       | 1       | sales      | April    |
| 59  | 19       | 1       | sales      | May      |
| 60  | 19       | 2       | sales      | March    |
| 61  | 19       | 2       | sales      | April    |
| 62  | 19       | 2       | sales      | May      |
| 63  | 25       | 1       | sales      | March    |



**Output 7.4.2** *continued*

| Minimum Cost Flow problem                  |          |         |         |          |          |
|--|----------|---------|---------|----------|----------|
| Production Planning/Inventory/Distribution |          |         |         |          |          |
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_ | _STATUS_ |          |
| 64   | .        | 60      | 13      | KEY_ARC  | BASIC    |
| 65   | 32.020   | 61      | 14      | LOWERBD  | NONBASIC |
| 66   | .        | 62      | 15      | KEY_ARC  | BASIC    |
| 67   | .        | 63      | 16      | KEY_ARC  | BASIC    |
| 68   | .        | 64      | 17      | KEY_ARC  | BASIC    |
| Obs  | diagonal | factory | key_id  | mth_made |          |
| 64   | 25       | 1       | sales   | April    |          |
| 65   | 25       | 1       | sales   | May      |          |
| 66   | 25       | 2       | sales   | March    |          |
| 67   | 25       | 2       | sales   | April    |          |
| 68   | 25       | 2       | sales   | May      |          |

## Output 7.4.3 NODEOUT=NODE2

| Minimum Cost Flow problem<br>Production Planning/Inventory/Distribution |          |       |               |    |    |    |    |     |     |     |
|---|----------|-------|---------------|----|----|----|----|-----|-----|-----|
|   | —        | s     | —             | N  | —  | —  | S  | —   | —   |     |
|   | n        | u     | D             | N  | P  | T  | C  | R   | F   | —   |
| O   | d        | p     | U             | U  | R  | R  | E  | C   | L   | F   |
| b   | e        | m     | A             | M  | E  | A  | S  | I   | O   | B   |
| s   | —        | —     | L             | B  | D  | V  | S  | D   | W   | Q   |
| 1   | _ROOT_   | 238   | 0.00          | 22 | 0  | 8  | 0  | 3   | 166 | -69 |
| 2   | _EXCESS_ | -200  | -100000198.75 | 21 | 1  | 11 | 13 | 65  | 5   | 65  |
| 3   | f1_apr_1 | .     | -100000278.00 | 3  | 6  | 7  | 1  | -14 | 30  | 4   |
| 4   | f1_apr_2 | .     | -100000387.60 | 13 | 19 | 17 | 1  | -60 | 535 | 36  |
| 5   | f1_mar_1 | .     | -100000326.65 | 2  | 8  | 1  | 15 | -21 | 155 | 1   |
| 6   | f1_mar_2 | .     | -100000461.81 | 12 | 19 | 13 | 1  | -59 | 455 | 33  |
| 7   | f1_may_1 | .     | -100000293.00 | 4  | 7  | 2  | 1  | -18 | 100 | 8   |
| 8   | f1_may_2 | .     | -100000329.94 | 14 | 18 | 12 | 1  | -55 | 25  | 40  |
| 9   | f2_apr_1 | .     | -100000289.00 | 6  | 8  | 3  | 5  | -25 | 245 | 14  |
| 10  | f2_apr_2 | .     | -100000397.11 | 16 | 19 | 18 | 3  | -63 | 320 | 46  |
| 11  | f2_mar_1 | .     | -100000286.75 | 5  | 10 | 22 | 1  | 12  | 255 | 11  |
| 12  | f2_mar_2 | .     | -100000380.75 | 15 | 20 | 19 | 8  | 44  | 610 | 43  |
| 13  | f2_may_1 | .     | -100000309.00 | 7  | 6  | 9  | 3  | 20  | 15  | 18  |
| 14  | f2_may_2 | .     | -100000326.98 | 17 | 19 | 10 | 1  | -64 | 20  | 50  |
| 15  | fact1_1  | 1000  | -100000198.75 | 1  | 2  | 21 | 14 | -1  | 295 | -1  |
| 16  | fact1_2  | 1000  | -100000198.75 | 11 | 21 | 20 | 1  | -67 | 10  | -33 |
| 17  | fact2_1  | 850   | -100000198.75 | 10 | 21 | 5  | 2  | -66 | 45  | -33 |
| 18  | fact2_2  | 1500  | -100000198.75 | 20 | 21 | 15 | 9  | -68 | 140 | -65 |
| 19  | shop1_1  | -900  | -99999999.00  | 8  | 22 | 6  | 21 | 0   | 0   | 21  |
| 20  | shop1_2  | -900  | -99999854.92  | 18 | 16 | 14 | 2  | 57  | 375 | 53  |
| 21  | shop2_1  | -900  | -100000010.00 | 9  | 7  | 4  | 1  | 32  | 150 | 27  |
| 22  | shop2_2  | -1450 | -99999837.92  | 19 | 15 | 16 | 7  | 62  | 120 | 59  |

## Example 7.5: Using an Unconstrained Solution Warm Start

This example examines the effect of changing some of the arc costs. The backorder penalty costs are increased by twenty percent. The sales profit of 25-inch TVs sent to the shops in May is increased by thirty units. The backorder penalty costs of 25-inch TVs manufactured in May for April consumption is decreased by thirty units. The production cost of 19- and 25-inch TVs made in May are decreased by five units and twenty units, respectively. How does the optimal solution of the network after these arc cost alterations compare with the optimum of the original network? If you want to use the warm start facilities of PROC NETFLOW to solve this undefined problem, specify the **WARM** option. Notice that the **FUTURE1** option was specified in the last PROC NETFLOW run.

The following SAS statements produce the new **NODEOUT=** and **ARCOUT=** data sets.

```

title 'Minimum Cost Flow problem- Unconstrained Warm Start';
title2 'Production Planning/Inventory/Distribution';
data arc2;
  set arc1;
  oldcost=_cost_;
  oldfc=_fcost_;
  oldflow=_flow_;
  if key_id='backorder'
    then _cost_=_cost_*1.2;
    else if _tail_='f2_may_2' then _cost_=_cost_-30;
  if key_id='production' & mth_made='May' then
    if diagonal=19 then _cost_=_cost_-5;
    else _cost_=_cost_-20;

proc netflow
  warm future1
  nodedata=node2
  arcdata=arc2
  nodeout=node3
  arcout=arc3;
run;
quit;

options ls=80 ps = 50;
proc print data=arc3 heading=h width=min;
sum _fcost_;
var _tail_ _head_ _capac_ _lo_ _supply_ _demand_ _name_ _cost_ _flow_ _fcost_;
run;

options ls=80 ps = 50;
proc print data=arc3 heading=h width=min;
sum oldfc;
var oldcost oldflow oldfc diagonal factory key_id mth_made _anumb_ _tnumb_;
run;

proc print data=node3;
run;

```

The following notes appear on the SAS log:

```

NOTE: Number of nodes= 21 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 5 .
NOTE: The greater of total supply and total demand= 4350 .
NOTE: Number of iterations performed (neglecting any constraints)= 8 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= -1285086.45 .
NOTE: The data set WORK.ARC3 has 68 observations and 21 variables.
NOTE: The data set WORK.NODE3 has 22 observations and 10 variables.

```

The solution is displayed in [Output 7.5.1](#) and [Output 7.5.2](#). The associated NODEOUT data set is in [Output 7.5.3](#).

**Output 7.5.1** ARCOUT=ARC3

| Minimum Cost Flow problem- Unconstrained Warm Start<br>Production Planning/Inventory/Distribution |                |          |          |         |          |          |
|---|----------------|----------|----------|---------|----------|----------|
| Obs   | _tail_         | _head_   | _capac_  | _lo_    | _SUPPLY_ | _DEMAND_ |
| 1   | fact1_1        | _EXCESS_ | 99999999 | 0       | 1000     | 200      |
| 2   | fact2_1        | _EXCESS_ | 99999999 | 0       | 850      | 200      |
| 3   | fact1_2        | _EXCESS_ | 99999999 | 0       | 1000     | 200      |
| 4   | fact2_2        | _EXCESS_ | 99999999 | 0       | 1500     | 200      |
| 5   | fact1_1        | f1_apr_1 | 600      | 50      | 1000     | .        |
| 6   | f1_mar_1       | f1_apr_1 | 50       | 0       | .        | .        |
| 7   | f1_may_1       | f1_apr_1 | 20       | 0       | .        | .        |
| 8   | f2_apr_1       | f1_apr_1 | 40       | 0       | .        | .        |
| 9   | fact1_2        | f1_apr_2 | 550      | 50      | 1000     | .        |
| 10  | f1_mar_2       | f1_apr_2 | 40       | 0       | .        | .        |
| 11  | f1_may_2       | f1_apr_2 | 15       | 0       | .        | .        |
| 12  | f2_apr_2       | f1_apr_2 | 25       | 0       | .        | .        |
| 13  | fact1_1        | f1_mar_1 | 500      | 50      | 1000     | .        |
| 14  | f1_apr_1       | f1_mar_1 | 20       | 0       | .        | .        |
| 15  | f2_mar_1       | f1_mar_1 | 40       | 0       | .        | .        |
| 16  | fact1_2        | f1_mar_2 | 400      | 40      | 1000     | .        |
| 17  | f1_apr_2       | f1_mar_2 | 30       | 0       | .        | .        |
| 18  | f2_mar_2       | f1_mar_2 | 25       | 0       | .        | .        |
| 19  | fact1_1        | f1_may_1 | 400      | 50      | 1000     | .        |
| 20  | f1_apr_1       | f1_may_1 | 50       | 0       | .        | .        |
| 21  | f2_may_1       | f1_may_1 | 40       | 0       | .        | .        |
| Obs   | _name_         | _cost_   | _FLOW_   | _FCOST_ |          |          |
| 1   |                | 0.00     | 5        | 0.0     |          |          |
| 2   |                | 0.00     | 45       | 0.0     |          |          |
| 3   |                | 0.00     | 0        | 0.0     |          |          |
| 4   |                | 0.00     | 150      | 0.0     |          |          |
| 5   | prod f1 19 apl | 78.60    | 540      | 42444.0 |          |          |
| 6   |                | 15.00    | 0        | 0.0     |          |          |
| 7   | back f1 19 may | 33.60    | 0        | 0.0     |          |          |
| 8   |                | 11.00    | 0        | 0.0     |          |          |
| 9   | prod f1 25 apl | 174.50   | 250      | 43625.0 |          |          |
| 10  |                | 20.00    | 0        | 0.0     |          |          |
| 11  | back f1 25 may | 49.20    | 15       | 738.0   |          |          |
| 12  |                | 21.00    | 0        | 0.0     |          |          |
| 13  | prod f1 19 mar | 127.90   | 340      | 43486.0 |          |          |
| 14  | back f1 19 apl | 33.60    | 20       | 672.0   |          |          |
| 15  |                | 10.00    | 40       | 400.0   |          |          |
| 16  | prod f1 25 mar | 217.90   | 400      | 87160.0 |          |          |
| 17  | back f1 25 apl | 38.40    | 30       | 1152.0  |          |          |
| 18  |                | 20.00    | 25       | 500.0   |          |          |
| 19  |                | 90.10    | 115      | 10361.5 |          |          |
| 20  |                | 12.00    | 0        | 0.0     |          |          |
| 21  |                | 13.00    | 0        | 0.0     |          |          |

Output 7.5.1 continued

| Minimum Cost Flow problem- Unconstrained Warm Start<br>Production Planning/Inventory/Distribution |                |          |          |           |          |          |
|---|----------------|----------|----------|-----------|----------|----------|
| Obs   | _tail_         | _head_   | _capac_  | _lo_      | _SUPPLY_ | _DEMAND_ |
| 22  | fact1_2        | f1_may_2 | 350      | 40        | 1000     | .        |
| 23  | f1_apr_2       | f1_may_2 | 40       | 0         | .        | .        |
| 24  | f2_may_2       | f1_may_2 | 25       | 0         | .        | .        |
| 25  | f1_apr_1       | f2_apr_1 | 99999999 | 0         | .        | .        |
| 26  | fact2_1        | f2_apr_1 | 480      | 35        | 850      | .        |
| 27  | f2_mar_1       | f2_apr_1 | 30       | 0         | .        | .        |
| 28  | f2_may_1       | f2_apr_1 | 15       | 0         | .        | .        |
| 29  | f1_apr_2       | f2_apr_2 | 99999999 | 0         | .        | .        |
| 30  | fact2_2        | f2_apr_2 | 680      | 35        | 1500     | .        |
| 31  | f2_mar_2       | f2_apr_2 | 50       | 0         | .        | .        |
| 32  | f2_may_2       | f2_apr_2 | 15       | 0         | .        | .        |
| 33  | f1_mar_1       | f2_mar_1 | 99999999 | 0         | .        | .        |
| 34  | fact2_1        | f2_mar_1 | 450      | 35        | 850      | .        |
| 35  | f2_apr_1       | f2_mar_1 | 15       | 0         | .        | .        |
| 36  | f1_mar_2       | f2_mar_2 | 99999999 | 0         | .        | .        |
| 37  | fact2_2        | f2_mar_2 | 650      | 35        | 1500     | .        |
| 38  | f2_apr_2       | f2_mar_2 | 15       | 0         | .        | .        |
| 39  | f1_may_1       | f2_may_1 | 99999999 | 0         | .        | .        |
| 40  | fact2_1        | f2_may_1 | 250      | 35        | 850      | .        |
| 41  | f2_apr_1       | f2_may_1 | 30       | 0         | .        | .        |
| 42  | f1_may_2       | f2_may_2 | 99999999 | 0         | .        | .        |
| Obs   | _name_         | _cost_   | _FLOW_   | _FCOST_   |          |          |
| 22  |                | 113.30   | 350      | 39655.00  |          |          |
| 23  |                | 18.00    | 0        | 0.00      |          |          |
| 24  |                | 13.00    | 0        | 0.00      |          |          |
| 25  |                | 11.00    | 20       | 220.00    |          |          |
| 26  | prod f2 19 apl | 62.40    | 480      | 29952.00  |          |          |
| 27  |                | 18.00    | 0        | 0.00      |          |          |
| 28  | back f2 19 may | 30.00    | 0        | 0.00      |          |          |
| 29  |                | 23.00    | 0        | 0.00      |          |          |
| 30  | prod f2 25 apl | 196.70   | 680      | 133756.00 |          |          |
| 31  |                | 28.00    | 0        | 0.00      |          |          |
| 32  | back f2 25 may | 64.80    | 0        | 0.00      |          |          |
| 33  |                | 11.00    | 0        | 0.00      |          |          |
| 34  | prod f2 19 mar | 88.00    | 290      | 25520.00  |          |          |
| 35  | back f2 19 apl | 20.40    | 0        | 0.00      |          |          |
| 36  |                | 23.00    | 0        | 0.00      |          |          |
| 37  | prod f2 25 mar | 182.00   | 635      | 115570.00 |          |          |
| 38  | back f2 25 apl | 37.20    | 0        | 0.00      |          |          |
| 39  |                | 16.00    | 115      | 1840.00   |          |          |
| 40  |                | 128.80   | 35       | 4508.00   |          |          |
| 41  |                | 20.00    | 0        | 0.00      |          |          |
| 42  |                | 26.00    | 335      | 8710.00   |          |          |

## Output 7.5.1 continued

| Minimum Cost Flow problem- Unconstrained Warm Start<br>Production Planning/Inventory/Distribution |          |          |          |            |          |          |
|---|----------|----------|----------|------------|----------|----------|
| Obs   | _tail_   | _head_   | _capac_  | _lo_       | _SUPPLY_ | _DEMAND_ |
| 43  | fact2_2  | f2_may_2 | 550      | 35         | 1500     | .        |
| 44  | f2_apr_2 | f2_may_2 | 50       | 0          | .        | .        |
| 45  | f1_mar_1 | shop1_1  | 250      | 0          | .        | 900      |
| 46  | f1_apr_1 | shop1_1  | 250      | 0          | .        | 900      |
| 47  | f1_may_1 | shop1_1  | 250      | 0          | .        | 900      |
| 48  | f2_mar_1 | shop1_1  | 250      | 0          | .        | 900      |
| 49  | f2_apr_1 | shop1_1  | 250      | 0          | .        | 900      |
| 50  | f2_may_1 | shop1_1  | 250      | 0          | .        | 900      |
| 51  | f1_mar_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 52  | f1_apr_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 53  | f1_may_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 54  | f2_mar_2 | shop1_2  | 500      | 0          | .        | 900      |
| 55  | f2_apr_2 | shop1_2  | 500      | 0          | .        | 900      |
| 56  | f2_may_2 | shop1_2  | 500      | 0          | .        | 900      |
| 57  | f1_mar_1 | shop2_1  | 250      | 0          | .        | 900      |
| 58  | f1_apr_1 | shop2_1  | 250      | 0          | .        | 900      |
| 59  | f1_may_1 | shop2_1  | 250      | 0          | .        | 900      |
| 60  | f2_mar_1 | shop2_1  | 250      | 0          | .        | 900      |
| 61  | f2_apr_1 | shop2_1  | 250      | 0          | .        | 900      |
| 62  | f2_may_1 | shop2_1  | 250      | 0          | .        | 900      |
| 63  | f1_mar_2 | shop2_2  | 99999999 | 0          | .        | 1450     |
| Obs   | _name_   | _cost_   | _FLOW_   | _FCOST_    |          |          |
| 43  |          | 181.40   | 35       | 6349.00    |          |          |
| 44  |          | 38.00    | 0        | 0.00       |          |          |
| 45  |          | -327.65  | 150      | -49147.50  |          |          |
| 46  |          | -300.00  | 250      | -75000.00  |          |          |
| 47  |          | -285.00  | 0        | 0.00       |          |          |
| 48  |          | -297.40  | 250      | -74350.00  |          |          |
| 49  |          | -290.00  | 250      | -72500.00  |          |          |
| 50  |          | -292.00  | 0        | 0.00       |          |          |
| 51  |          | -559.76  | 0        | 0.00       |          |          |
| 52  |          | -524.28  | 0        | 0.00       |          |          |
| 53  |          | -475.02  | 0        | 0.00       |          |          |
| 54  |          | -567.83  | 500      | -283915.00 |          |          |
| 55  |          | -542.19  | 400      | -216876.00 |          |          |
| 56  |          | -491.56  | 0        | 0.00       |          |          |
| 57  |          | -362.74  | 250      | -90685.00  |          |          |
| 58  |          | -300.00  | 250      | -75000.00  |          |          |
| 59  |          | -245.00  | 0        | 0.00       |          |          |
| 60  |          | -272.70  | 0        | 0.00       |          |          |
| 61  |          | -312.00  | 250      | -78000.00  |          |          |
| 62  |          | -299.00  | 150      | -44850.00  |          |          |
| 63  |          | -623.89  | 455      | -283869.95 |          |          |

**Output 7.5.1** *continued*

| Minimum Cost Flow problem- Unconstrained Warm Start<br>Production Planning/Inventory/Distribution |          |         |          |             |          |          |
|---|----------|---------|----------|-------------|----------|----------|
| Obs   | _tail_   | _head_  | _capac_  | _lo_        | _SUPPLY_ | _DEMAND_ |
| 64  | f1_apr_2 | shop2_2 | 99999999 | 0           | .        | 1450     |
| 65  | f1_may_2 | shop2_2 | 99999999 | 0           | .        | 1450     |
| 66  | f2_mar_2 | shop2_2 | 500      | 0           | .        | 1450     |
| 67  | f2_apr_2 | shop2_2 | 500      | 0           | .        | 1450     |
| 68  | f2_may_2 | shop2_2 | 500      | 0           | .        | 1450     |
| Obs   | _name_   | _cost_  | _FLOW_   | _FCOST_     |          |          |
| 64  |          | -549.68 | 235      | -129174.80  |          |          |
| 65  |          | -460.00 | 0        | 0.00        |          |          |
| 66  |          | -542.83 | 110      | -59711.30   |          |          |
| 67  |          | -559.19 | 280      | -156573.20  |          |          |
| 68  |          | -519.06 | 370      | -192052.20  |          |          |
|   |          |         |          | =====       |          |          |
|   |          |         |          | -1285086.45 |          |          |

## Output 7.5.2 ARCOU=ARC3 (continued)

Minimum Cost Flow problem- Unconstrained Warm Start  
Production Planning/Inventory/Distribution

| Obs | oldcost | oldflow | oldfc    | diagonal | factory |
|-----|---------|---------|----------|----------|---------|
| 1   | 0.00    | 5       | 0.00     | .        | .       |
| 2   | 0.00    | 45      | 0.00     | .        | .       |
| 3   | 0.00    | 10      | 0.00     | .        | .       |
| 4   | 0.00    | 140     | 0.00     | .        | .       |
| 5   | 78.60   | 600     | 47160.00 | 19       | 1       |
| 6   | 15.00   | 0       | 0.00     | 19       | 1       |
| 7   | 28.00   | 0       | 0.00     | 19       | 1       |
| 8   | 11.00   | 0       | 0.00     | 19       | .       |
| 9   | 174.50  | 550     | 95975.00 | 25       | 1       |
| 10  | 20.00   | 0       | 0.00     | 25       | 1       |
| 11  | 41.00   | 15      | 615.00   | 25       | 1       |
| 12  | 21.00   | 0       | 0.00     | 25       | .       |
| 13  | 127.90  | 345     | 44125.50 | 19       | 1       |
| 14  | 28.00   | 20      | 560.00   | 19       | 1       |
| 15  | 10.00   | 40      | 400.00   | 19       | .       |
| 16  | 217.90  | 400     | 87160.00 | 25       | 1       |
| 17  | 32.00   | 30      | 960.00   | 25       | 1       |
| 18  | 20.00   | 25      | 500.00   | 25       | .       |
| 19  | 95.10   | 50      | 4755.00  | 19       | 1       |
| 20  | 12.00   | 50      | 600.00   | 19       | 1       |
| 21  | 13.00   | 0       | 0.00     | 19       | .       |

| Obs | key_id     | mth_made | _ANUMB_ | _TNUMB_ |
|-----|------------|----------|---------|---------|
| 1   |            |          | 65      | 1       |
| 2   |            |          | 66      | 10      |
| 3   |            |          | 67      | 11      |
| 4   |            |          | 68      | 20      |
| 5   | production | April    | 4       | 1       |
| 6   | storage    | March    | 5       | 2       |
| 7   | backorder  | May      | 6       | 4       |
| 8   | f2_to_1    | April    | 7       | 6       |
| 9   | production | April    | 36      | 11      |
| 10  | storage    | March    | 37      | 12      |
| 11  | backorder  | May      | 38      | 14      |
| 12  | f2_to_1    | April    | 39      | 16      |
| 13  | production | March    | 1       | 1       |
| 14  | backorder  | April    | 2       | 3       |
| 15  | f2_to_1    | March    | 3       | 5       |
| 16  | production | March    | 33      | 11      |
| 17  | backorder  | April    | 34      | 13      |
| 18  | f2_to_1    | March    | 35      | 15      |
| 19  | production | May      | 8       | 1       |
| 20  | storage    | April    | 9       | 3       |
| 21  | f2_to_1    | May      | 10      | 7       |



Output 7.5.2 continued

Minimum Cost Flow problem- Unconstrained Warm Start  
Production Planning/Inventory/Distribution

| Obs | oldcost | oldflow | oldfc     | diagonal | factory |
|-----|---------|---------|-----------|----------|---------|
| 22  | 133.30  | 40      | 5332.00   | 25       | 1       |
| 23  | 18.00   | 0       | 0.00      | 25       | 1       |
| 24  | 43.00   | 0       | 0.00      | 25       | .       |
| 25  | 11.00   | 30      | 330.00    | 19       | .       |
| 26  | 62.40   | 480     | 29952.00  | 19       | 2       |
| 27  | 18.00   | 0       | 0.00      | 19       | 2       |
| 28  | 25.00   | 0       | 0.00      | 19       | 2       |
| 29  | 23.00   | 0       | 0.00      | 25       | .       |
| 30  | 196.70  | 680     | 133756.00 | 25       | 2       |
| 31  | 28.00   | 0       | 0.00      | 25       | 2       |
| 32  | 54.00   | 15      | 810.00    | 25       | 2       |
| 33  | 11.00   | 0       | 0.00      | 19       | .       |
| 34  | 88.00   | 290     | 25520.00  | 19       | 2       |
| 35  | 17.00   | 0       | 0.00      | 19       | 2       |
| 36  | 23.00   | 0       | 0.00      | 25       | .       |
| 37  | 182.00  | 645     | 117390.00 | 25       | 2       |
| 38  | 31.00   | 0       | 0.00      | 25       | 2       |
| 39  | 16.00   | 100     | 1600.00   | 19       | .       |
| 40  | 133.80  | 35      | 4683.00   | 19       | 2       |
| 41  | 20.00   | 15      | 300.00    | 19       | 2       |
| 42  | 26.00   | 0       | 0.00      | 25       | .       |

| Obs | key_id     | mth_made | _ANUMB_ | _TNUMB_ |
|-----|------------|----------|---------|---------|
| 22  | production | May      | 40      | 11      |
| 23  | storage    | April    | 41      | 13      |
| 24  | f2_to_1    | May      | 42      | 17      |
| 25  | f1_to_2    | April    | 14      | 3       |
| 26  | production | April    | 15      | 10      |
| 27  | storage    | March    | 16      | 5       |
| 28  | backorder  | May      | 17      | 7       |
| 29  | f1_to_2    | April    | 46      | 13      |
| 30  | production | April    | 47      | 20      |
| 31  | storage    | March    | 48      | 15      |
| 32  | backorder  | May      | 49      | 17      |
| 33  | f1_to_2    | March    | 11      | 2       |
| 34  | production | March    | 12      | 10      |
| 35  | backorder  | April    | 13      | 6       |
| 36  | f1_to_2    | March    | 43      | 12      |
| 37  | production | March    | 44      | 20      |
| 38  | backorder  | April    | 45      | 16      |
| 39  | f1_to_2    | May      | 18      | 4       |
| 40  | production | May      | 19      | 10      |
| 41  | storage    | April    | 20      | 6       |
| 42  | f1_to_2    | May      | 50      | 14      |

## Output 7.5.2 continued

Minimum Cost Flow problem- Unconstrained Warm Start  
Production Planning/Inventory/Distribution

| Obs | oldcost | oldflow | oldfc      | diagonal | factory |
|-----|---------|---------|------------|----------|---------|
| 43  | 201.40  | 35      | 7049.00    | 25       | 2       |
| 44  | 38.00   | 0       | 0.00       | 25       | 2       |
| 45  | -327.65 | 155     | -50785.75  | 19       | 1       |
| 46  | -300.00 | 250     | -75000.00  | 19       | 1       |
| 47  | -285.00 | 0       | 0.00       | 19       | 1       |
| 48  | -297.40 | 250     | -74350.00  | 19       | 2       |
| 49  | -290.00 | 245     | -71050.00  | 19       | 2       |
| 50  | -292.00 | 0       | 0.00       | 19       | 2       |
| 51  | -559.76 | 0       | 0.00       | 25       | 1       |
| 52  | -524.28 | 0       | 0.00       | 25       | 1       |
| 53  | -475.02 | 25      | -11875.50  | 25       | 1       |
| 54  | -567.83 | 500     | -283915.00 | 25       | 2       |
| 55  | -542.19 | 375     | -203321.25 | 25       | 2       |
| 56  | -461.56 | 0       | 0.00       | 25       | 2       |
| 57  | -362.74 | 250     | -90685.00  | 19       | 1       |
| 58  | -300.00 | 250     | -75000.00  | 19       | 1       |
| 59  | -245.00 | 0       | 0.00       | 19       | 1       |
| 60  | -272.70 | 0       | 0.00       | 19       | 2       |
| 61  | -312.00 | 250     | -78000.00  | 19       | 2       |
| 62  | -299.00 | 150     | -44850.00  | 19       | 2       |
| 63  | -623.89 | 455     | -283869.95 | 25       | 1       |

| Obs | key_id     | mth_made | _ANUMB_ | _TNUMB_ |
|-----|------------|----------|---------|---------|
| 43  | production | May      | 51      | 20      |
| 44  | storage    | April    | 52      | 16      |
| 45  | sales      | March    | 21      | 2       |
| 46  | sales      | April    | 22      | 3       |
| 47  | sales      | May      | 23      | 4       |
| 48  | sales      | March    | 24      | 5       |
| 49  | sales      | April    | 25      | 6       |
| 50  | sales      | May      | 26      | 7       |
| 51  | sales      | March    | 53      | 12      |
| 52  | sales      | April    | 54      | 13      |
| 53  | sales      | May      | 55      | 14      |
| 54  | sales      | March    | 56      | 15      |
| 55  | sales      | April    | 57      | 16      |
| 56  | sales      | May      | 58      | 17      |
| 57  | sales      | March    | 27      | 2       |
| 58  | sales      | April    | 28      | 3       |
| 59  | sales      | May      | 29      | 4       |
| 60  | sales      | March    | 30      | 5       |
| 61  | sales      | April    | 31      | 6       |
| 62  | sales      | May      | 32      | 7       |
| 63  | sales      | March    | 59      | 12      |

**Output 7.5.2** *continued*

**Minimum Cost Flow problem- Unconstrained Warm Start  
Production Planning/Inventory/Distribution**

| Obs | oldcost | oldflow | oldfc       | diagonal | factory |
|-----|---------|---------|-------------|----------|---------|
| 64  | -549.68 | 535     | -294078.80  | 25       | 1       |
| 65  | -460.00 | 0       | 0.00        | 25       | 1       |
| 66  | -542.83 | 120     | -65139.60   | 25       | 2       |
| 67  | -559.19 | 320     | -178940.80  | 25       | 2       |
| 68  | -489.06 | 20      | -9781.20    | 25       | 2       |
|     |         |         | =====       |          |         |
|     |         |         | -1281110.35 |          |         |

| Obs | key_id | mth_made | _ANUMB_ | _TNUMB_ |
|-----|--------|----------|---------|---------|
| 64  | sales  | April    | 60      | 13      |
| 65  | sales  | May      | 61      | 14      |
| 66  | sales  | March    | 62      | 15      |
| 67  | sales  | April    | 63      | 16      |
| 68  | sales  | May      | 64      | 17      |

Output 7.5.3 NODEOUT=NODE3

| Minimum Cost Flow problem- Unconstrained Warm Start<br>Production Planning/Inventory/Distribution |          |       |               |    |    |    |    |     |     |     |
|---|----------|-------|---------------|----|----|----|----|-----|-----|-----|
|   | —        | s     | —             | N  | —  | —  | S  | A   | —   | —   |
|   | n        | p     | D             | N  | P  | T  | C  | R   | F   | —   |
| O   | d        | e     | A             | U  | R  | R  | E  | C   | L   | F   |
| b   | e        | m     | L             | M  | E  | A  | S  | I   | O   | B   |
| s   | —        | —     | —             | B  | D  | V  | S  | D   | W   | Q   |
| 1   | _ROOT_   | 238   | 0.00          | 22 | 0  | 8  | 0  | 3   | 166 | -69 |
| 2   | _EXCESS_ | -200  | -100000198.75 | 21 | 1  | 20 | 13 | 65  | 5   | 65  |
| 3   | f1_apr_1 | .     | -100000277.35 | 3  | 1  | 6  | 2  | 4   | 490 | 4   |
| 4   | f1_apr_2 | .     | -100000387.60 | 13 | 19 | 11 | 2  | -60 | 235 | 36  |
| 5   | f1_mar_1 | .     | -100000326.65 | 2  | 8  | 1  | 20 | -21 | 150 | 1   |
| 6   | f1_mar_2 | .     | -100000461.81 | 12 | 19 | 13 | 1  | -59 | 455 | 33  |
| 7   | f1_may_1 | .     | -100000288.85 | 4  | 1  | 7  | 3  | 8   | 65  | 8   |
| 8   | f1_may_2 | .     | -100000330.98 | 14 | 17 | 10 | 1  | -50 | 335 | 40  |
| 9   | f2_apr_1 | .     | -100000288.35 | 6  | 3  | 4  | 1  | 14  | 20  | 14  |
| 10  | f2_apr_2 | .     | -100000397.11 | 16 | 19 | 18 | 2  | -63 | 280 | 46  |
| 11  | f2_mar_1 | .     | -100000286.75 | 5  | 10 | 22 | 1  | 12  | 255 | 11  |
| 12  | f2_mar_2 | .     | -100000380.75 | 15 | 20 | 19 | 9  | 44  | 600 | 43  |
| 13  | f2_may_1 | .     | -100000304.85 | 7  | 4  | 9  | 2  | 18  | 115 | 18  |
| 14  | f2_may_2 | .     | -100000356.98 | 17 | 19 | 14 | 2  | -64 | 370 | 50  |
| 15  | fact1_1  | 1000  | -100000198.75 | 1  | 2  | 3  | 19 | -1  | 290 | -1  |
| 16  | fact1_2  | 1000  | -100000213.10 | 11 | 13 | 17 | 1  | -36 | 200 | -33 |
| 17  | fact2_1  | 850   | -100000198.75 | 10 | 21 | 5  | 2  | -66 | 45  | -33 |
| 18  | fact2_2  | 1500  | -100000198.75 | 20 | 21 | 15 | 10 | -68 | 150 | -65 |
| 19  | shop1_1  | -900  | -99999999.00  | 8  | 22 | 2  | 21 | 0   | 0   | 21  |
| 20  | shop1_2  | -900  | -99999854.92  | 18 | 16 | 12 | 1  | 57  | 400 | 53  |
| 21  | shop2_1  | -900  | -100000005.85 | 9  | 7  | 21 | 1  | 32  | 150 | 27  |
| 22  | shop2_2  | -1450 | -99999837.92  | 19 | 15 | 16 | 8  | 62  | 110 | 59  |

### Example 7.6: Adding Side Constraints, Using a Warm Start

The manufacturer of Gizmo chips, which are parts needed to make televisions, can supply only 2600 chips to factory 1 and 3750 chips to factory 2 in time for production in each of the months of March and April. However, Gizmo chips will not be in short supply in May. Three chips are required to make each 19-inch TV while the 25-inch TVs require four chips each. To limit the production of televisions produced at factory 1 in March so that the TVs have the correct number of chips, a side constraint called FACT1 MAR GIZMO is used. The form of this constraint is

```
3 * prod f1 19 mar + 4 * prod f1 25 mar <= 2600
```

“prod f1 19 mar” is the name of the arc directed from the node fact1\_1 toward node f1\_mar\_1 and, in the previous constraint, designates the flow assigned to this arc. The **ARCDATA=** and **ARCOUT=** data sets have arc names in a variable called **\_name\_**.

The other side constraints (shown below) are called FACT2 MAR GIZMO , FACT1 APL GIZMO, and FACT2 APL GIZMO.

```
3 * prod f2 19 mar + 4 * prod f2 25 mar <= 3750
3 * prod f1 19 apl + 4 * prod f1 25 apl <= 2600
3 * prod f2 19 apl + 4 * prod f2 25 apl <= 3750
```

To maintain customer goodwill, the total number of backorders is not to exceed 50 sets. The side constraint TOTAL BACKORDER that models this restriction is:

```
back f1 19 apl + back f1 25 apl +
back f2 19 apl + back f2 25 apl +
back f1 19 may + back f1 25 may +
back f2 19 may + back f2 25 may <= 50
```

The `sparse CONDATA=` data set format is used. All side constraints are less than or equal type. Because this is the default type value for the `DEFCONTYPE=` option, type information is not necessary in the following `CONDATA=CON3`. Also, `DEFCONTYPE= <=` does not have to be specified in the PROC NETFLOW statement that follows. Notice that the `_column_` variable value CHIP/BO LIMIT indicates that an observation of the CON3 data set contains rhs information. Therefore, specify `RHSOBS='CHIP/BO LIMIT'`.

```
title 'Adding Side Constraints and Using a Warm Start';
title2 'Production Planning/Inventory/Distribution';
data con3;
  input _column_ &$14. _row_ &$15. _coef_ ;
  datalines;
prod f1 19 mar FACT1 MAR GIZMO 3
prod f1 25 mar FACT1 MAR GIZMO 4
CHIP/BO LIMIT FACT1 MAR GIZMO 2600
prod f2 19 mar FACT2 MAR GIZMO 3
prod f2 25 mar FACT2 MAR GIZMO 4
CHIP/BO LIMIT FACT2 MAR GIZMO 3750
prod f1 19 apl FACT1 APL GIZMO 3
prod f1 25 apl FACT1 APL GIZMO 4
CHIP/BO LIMIT FACT1 APL GIZMO 2600
prod f2 19 apl FACT2 APL GIZMO 3
prod f2 25 apl FACT2 APL GIZMO 4
CHIP/BO LIMIT FACT2 APL GIZMO 3750
back f1 19 apl TOTAL BACKORDER 1
back f1 25 apl TOTAL BACKORDER 1
back f2 19 apl TOTAL BACKORDER 1
back f2 25 apl TOTAL BACKORDER 1
back f1 19 may TOTAL BACKORDER 1
back f1 25 may TOTAL BACKORDER 1
back f2 19 may TOTAL BACKORDER 1
back f2 25 may TOTAL BACKORDER 1
CHIP/BO LIMIT TOTAL BACKORDER 50
;
```

The four pairs of data sets that follow can be used as `ARCDATA=` and `NODEDATA=` data sets in the following PROC NETFLOW run. The set used depends on which cost information the arcs are to have and whether a warm start is to be used.

```

ARCDATA=arc0      NODEDATA=node0
ARCDATA=arc1      NODEDATA=node2
ARCDATA=arc2      NODEDATA=node2
ARCDATA=arc3      NODEDATA=node3

```

arc0, node0, arc1, and node2 were created in [Example 7.4](#). The first two data sets are the original input data sets. arc1 and node2 were the **ARCOUT=** and **NODEOUT=** data sets of a PROC NETFLOW run with **FUTURE1** specified. Now, if you use arc1 and node2 as the **ARCDATA=** data set and **NODEDATA=** data set in a PROC NETFLOW run, you can specify **WARM**, as these data sets contain additional information describing a warm start.

In [Example 7.5](#), arc2 was created by modifying arc1 to reflect different arc costs. arc2 and node2 can also be used as the **ARCDATA=** and **NODEDATA=** data sets in a PROC NETFLOW run. Again, specify **WARM**, as these data sets contain additional information describing a warm start. This start, however, contains the optimal basis using the original costs.

If you are going to continue optimization using the changed arc costs, it is probably best to use arc3 and node3 as the **ARCDATA=** and **NODEDATA=** data sets. These data sets, created in [Example 7.6](#) by PROC NETFLOW when the **FUTURE1** option was specified, contain an optimal basis that can be used as a warm start.

PROC NETFLOW is used to find the changed cost network solution that obeys the chip limit and backorder side constraints. The **FUTURE2** option is specified in case further processing is required. An explicit **ID** list has also been specified so that the variables oldcost, oldfc and oldflow do not appear in the subsequent output data sets.

```

proc netflow
  nodedata=node3 arcdata=arc3 warm
  condata=con3 sparsesecondata rhsobs='CHIP/BO LIMIT'
  future2 dualout=dual4 conout=con4;
    id diagonal factory key_id mth_made;
  run;
  quit;

proc print data=con4 heading=h width=min;
sum _fcost_;
var _tail_ _head_ _cost_ _capac_ _lo_ _name_ _supply_ _demand_ _flow_ _fcost_;
run;

proc print data=con4 heading=h width=min;
var _rcost_ _anumb_ _tnumb_ _status_ diagonal factory key_id mth_made;
run;

proc print data=dual4;
  run;

```

The following messages appear on the SAS log:

```
NOTE: The following 3 variables in ARCDATA do not belong to any SAS variable
      list. These will be ignored.
      oldcost
      oldfc
      oldflow
NOTE: Number of nodes= 21 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 5 .
NOTE: The greater of total supply and total demand= 4350 .
NOTE: Number of iterations performed (neglecting any constraints)= 1 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum (neglecting any constraints) found.
NOTE: Minimal total cost= -1285086.45 .
NOTE: Number of <= side constraints= 5 .
NOTE: Number of == side constraints= 0 .
NOTE: Number of >= side constraints= 0 .
NOTE: Number of arc and nonarc variable side constraint coefficients= 16 .
NOTE: Number of iterations, optimizing with constraints= 14 .
NOTE: Of these, 1 were degenerate.
NOTE: Optimum reached.
NOTE: Minimal total cost= -1282708.625 .
NOTE: The data set WORK.CON4 has 68 observations and 18 variables.
NOTE: The data set WORK.DUAL4 has 27 observations and 14 variables.
```

## Output 7.6.1 CONOUT=CON4

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |          |         |          |      |                |
|--|----------|----------|---------|----------|------|----------------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_  | _lo_ | _name_         |
| 1  | fact1_1  | EXCESS_  | 0.00    | 99999999 | 0    |                |
| 2  | fact2_1  | EXCESS_  | 0.00    | 99999999 | 0    |                |
| 3  | fact1_2  | EXCESS_  | 0.00    | 99999999 | 0    |                |
| 4  | fact2_2  | EXCESS_  | 0.00    | 99999999 | 0    |                |
| 5  | fact1_1  | f1_apr_1 | 78.60   | 600      | 50   | prod f1 19 apl |
| 6  | f1_mar_1 | f1_apr_1 | 15.00   | 50       | 0    |                |
| 7  | f1_may_1 | f1_apr_1 | 33.60   | 20       | 0    | back f1 19 may |
| 8  | f2_apr_1 | f1_apr_1 | 11.00   | 40       | 0    |                |
| 9  | fact1_2  | f1_apr_2 | 174.50  | 550      | 50   | prod f1 25 apl |
| 10   | f1_mar_2 | f1_apr_2 | 20.00   | 40       | 0    |                |
| 11   | f1_may_2 | f1_apr_2 | 49.20   | 15       | 0    | back f1 25 may |
| 12   | f2_apr_2 | f1_apr_2 | 21.00   | 25       | 0    |                |
| 13   | fact1_1  | f1_mar_1 | 127.90  | 500      | 50   | prod f1 19 mar |
| 14   | f1_apr_1 | f1_mar_1 | 33.60   | 20       | 0    | back f1 19 apl |
| 15   | f2_mar_1 | f1_mar_1 | 10.00   | 40       | 0    |                |
| 16   | fact1_2  | f1_mar_2 | 217.90  | 400      | 40   | prod f1 25 mar |
| 17   | f1_apr_2 | f1_mar_2 | 38.40   | 30       | 0    | back f1 25 apl |
| 18   | f2_mar_2 | f1_mar_2 | 20.00   | 25       | 0    |                |
| 19   | fact1_1  | f1_may_1 | 90.10   | 400      | 50   |                |
| 20   | f1_apr_1 | f1_may_1 | 12.00   | 50       | 0    |                |
| 21   | f2_may_1 | f1_may_1 | 13.00   | 40       | 0    |                |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_  |      |                |
| 1  | 1000     | 200      | 5.000   | 0.00     |      |                |
| 2  | 850      | 200      | 45.000  | 0.00     |      |                |
| 3  | 1000     | 200      | 0.000   | 0.00     |      |                |
| 4  | 1500     | 200      | 150.000 | 0.00     |      |                |
| 5  | 1000     | .        | 533.333 | 41920.00 |      |                |
| 6  | .        | .        | 0.000   | 0.00     |      |                |
| 7  | .        | .        | 0.000   | 0.00     |      |                |
| 8  | .        | .        | 0.000   | 0.00     |      |                |
| 9  | 1000     | .        | 250.000 | 43625.00 |      |                |
| 10   | .        | .        | 0.000   | 0.00     |      |                |
| 11   | .        | .        | 0.000   | 0.00     |      |                |
| 12   | .        | .        | 0.000   | 0.00     |      |                |
| 13   | 1000     | .        | 333.333 | 42633.33 |      |                |
| 14   | .        | .        | 20.000  | 672.00   |      |                |
| 15   | .        | .        | 40.000  | 400.00   |      |                |
| 16   | 1000     | .        | 400.000 | 87160.00 |      |                |
| 17   | .        | .        | 30.000  | 1152.00  |      |                |
| 18   | .        | .        | 25.000  | 500.00   |      |                |
| 19   | 1000     | .        | 128.333 | 11562.83 |      |                |
| 20   | .        | .        | 0.000   | 0.00     |      |                |
| 21   | .        | .        | 0.000   | 0.00     |      |                |



Output 7.6.1 continued

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |          |         |           |      |                |
|--|----------|----------|---------|-----------|------|----------------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_   | _lo_ | _name_         |
| 22   | fact1_2  | f1_may_2 | 113.30  | 350       | 40   |                |
| 23   | f1_apr_2 | f1_may_2 | 18.00   | 40        | 0    |                |
| 24   | f2_may_2 | f1_may_2 | 13.00   | 25        | 0    |                |
| 25   | f1_apr_1 | f2_apr_1 | 11.00   | 99999999  | 0    |                |
| 26   | fact2_1  | f2_apr_1 | 62.40   | 480       | 35   | prod f2 19 apl |
| 27   | f2_mar_1 | f2_apr_1 | 18.00   | 30        | 0    |                |
| 28   | f2_may_1 | f2_apr_1 | 30.00   | 15        | 0    | back f2 19 may |
| 29   | f1_apr_2 | f2_apr_2 | 23.00   | 99999999  | 0    |                |
| 30   | fact2_2  | f2_apr_2 | 196.70  | 680       | 35   | prod f2 25 apl |
| 31   | f2_mar_2 | f2_apr_2 | 28.00   | 50        | 0    |                |
| 32   | f2_may_2 | f2_apr_2 | 64.80   | 15        | 0    | back f2 25 may |
| 33   | f1_mar_1 | f2_mar_1 | 11.00   | 99999999  | 0    |                |
| 34   | fact2_1  | f2_mar_1 | 88.00   | 450       | 35   | prod f2 19 mar |
| 35   | f2_apr_1 | f2_mar_1 | 20.40   | 15        | 0    | back f2 19 apl |
| 36   | f1_mar_2 | f2_mar_2 | 23.00   | 99999999  | 0    |                |
| 37   | fact2_2  | f2_mar_2 | 182.00  | 650       | 35   | prod f2 25 mar |
| 38   | f2_apr_2 | f2_mar_2 | 37.20   | 15        | 0    | back f2 25 apl |
| 39   | f1_may_1 | f2_may_1 | 16.00   | 99999999  | 0    |                |
| 40   | fact2_1  | f2_may_1 | 128.80  | 250       | 35   |                |
| 41   | f2_apr_1 | f2_may_1 | 20.00   | 30        | 0    |                |
| 42   | f1_may_2 | f2_may_2 | 26.00   | 99999999  | 0    |                |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_   |      |                |
| 22   | 1000     | .        | 350.000 | 39655.00  |      |                |
| 23   | .        | .        | 0.000   | 0.00      |      |                |
| 24   | .        | .        | 0.000   | 0.00      |      |                |
| 25   | .        | .        | 13.333  | 146.67    |      |                |
| 26   | 850      | .        | 480.000 | 29952.00  |      |                |
| 27   | .        | .        | 0.000   | 0.00      |      |                |
| 28   | .        | .        | 0.000   | 0.00      |      |                |
| 29   | .        | .        | 0.000   | 0.00      |      |                |
| 30   | 1500     | .        | 577.500 | 113594.25 |      |                |
| 31   | .        | .        | 0.000   | 0.00      |      |                |
| 32   | .        | .        | 0.000   | 0.00      |      |                |
| 33   | .        | .        | 0.000   | 0.00      |      |                |
| 34   | 850      | .        | 290.000 | 25520.00  |      |                |
| 35   | .        | .        | 0.000   | 0.00      |      |                |
| 36   | .        | .        | 0.000   | 0.00      |      |                |
| 37   | 1500     | .        | 650.000 | 118300.00 |      |                |
| 38   | .        | .        | 0.000   | 0.00      |      |                |
| 39   | .        | .        | 115.000 | 1840.00   |      |                |
| 40   | 850      | .        | 35.000  | 4508.00   |      |                |
| 41   | .        | .        | 0.000   | 0.00      |      |                |
| 42   | .        | .        | 350.000 | 9100.00   |      |                |

## Output 7.6.1 continued

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |          |         |            |      |        |
|--|----------|----------|---------|------------|------|--------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_    | _lo_ | _name_ |
| 43   | fact2_2  | f2_may_2 | 181.40  | 550        | 35   |        |
| 44   | f2_apr_2 | f2_may_2 | 38.00   | 50         | 0    |        |
| 45   | f1_mar_1 | shop1_1  | -327.65 | 250        | 0    |        |
| 46   | f1_apr_1 | shop1_1  | -300.00 | 250        | 0    |        |
| 47   | f1_may_1 | shop1_1  | -285.00 | 250        | 0    |        |
| 48   | f2_mar_1 | shop1_1  | -297.40 | 250        | 0    |        |
| 49   | f2_apr_1 | shop1_1  | -290.00 | 250        | 0    |        |
| 50   | f2_may_1 | shop1_1  | -292.00 | 250        | 0    |        |
| 51   | f1_mar_2 | shop1_2  | -559.76 | 99999999   | 0    |        |
| 52   | f1_apr_2 | shop1_2  | -524.28 | 99999999   | 0    |        |
| 53   | f1_may_2 | shop1_2  | -475.02 | 99999999   | 0    |        |
| 54   | f2_mar_2 | shop1_2  | -567.83 | 500        | 0    |        |
| 55   | f2_apr_2 | shop1_2  | -542.19 | 500        | 0    |        |
| 56   | f2_may_2 | shop1_2  | -491.56 | 500        | 0    |        |
| 57   | f1_mar_1 | shop2_1  | -362.74 | 250        | 0    |        |
| 58   | f1_apr_1 | shop2_1  | -300.00 | 250        | 0    |        |
| 59   | f1_may_1 | shop2_1  | -245.00 | 250        | 0    |        |
| 60   | f2_mar_1 | shop2_1  | -272.70 | 250        | 0    |        |
| 61   | f2_apr_1 | shop2_1  | -312.00 | 250        | 0    |        |
| 62   | f2_may_1 | shop2_1  | -299.00 | 250        | 0    |        |
| 63   | f1_mar_2 | shop2_2  | -623.89 | 99999999   | 0    |        |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_    |      |        |
| 43   | 1500     | .        | 122.500 | 22221.50   |      |        |
| 44   | .        | .        | 0.000   | 0.00       |      |        |
| 45   | .        | 900      | 143.333 | -46963.17  |      |        |
| 46   | .        | 900      | 250.000 | -75000.00  |      |        |
| 47   | .        | 900      | 13.333  | -3800.00   |      |        |
| 48   | .        | 900      | 250.000 | -74350.00  |      |        |
| 49   | .        | 900      | 243.333 | -70566.67  |      |        |
| 50   | .        | 900      | 0.000   | 0.00       |      |        |
| 51   | .        | 900      | 0.000   | 0.00       |      |        |
| 52   | .        | 900      | 0.000   | 0.00       |      |        |
| 53   | .        | 900      | 0.000   | 0.00       |      |        |
| 54   | .        | 900      | 500.000 | -283915.00 |      |        |
| 55   | .        | 900      | 400.000 | -216876.00 |      |        |
| 56   | .        | 900      | 0.000   | 0.00       |      |        |
| 57   | .        | 900      | 250.000 | -90685.00  |      |        |
| 58   | .        | 900      | 250.000 | -75000.00  |      |        |
| 59   | .        | 900      | 0.000   | 0.00       |      |        |
| 60   | .        | 900      | 0.000   | 0.00       |      |        |
| 61   | .        | 900      | 250.000 | -78000.00  |      |        |
| 62   | .        | 900      | 150.000 | -44850.00  |      |        |
| 63   | .        | 1450     | 455.000 | -283869.95 |      |        |

**Output 7.6.1** *continued*

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |          |         |             |      |        |
|--|----------|----------|---------|-------------|------|--------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_     | _lo_ | _name_ |
| 64   | f1_apr_2 | shop2_2  | -549.68 | 99999999    | 0    |        |
| 65   | f1_may_2 | shop2_2  | -460.00 | 99999999    | 0    |        |
| 66   | f2_mar_2 | shop2_2  | -542.83 | 500         | 0    |        |
| 67   | f2_apr_2 | shop2_2  | -559.19 | 500         | 0    |        |
| 68   | f2_may_2 | shop2_2  | -519.06 | 500         | 0    |        |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_     |      |        |
| 64   | .        | 1450     | 220.000 | -120929.60  |      |        |
| 65   | .        | 1450     | 0.000   | 0.00        |      |        |
| 66   | .        | 1450     | 125.000 | -67853.75   |      |        |
| 67   | .        | 1450     | 177.500 | -99256.23   |      |        |
| 68   | .        | 1450     | 472.500 | -245255.85  |      |        |
|  |          |          |         | =====       |      |        |
|  |          |          |         | -1282708.63 |      |        |

## Output 7.6.2 CONOUT=CON4 (continued)

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |         |            |            |          |
|--|----------|---------|------------|------------|----------|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_    | _STATUS_   |          |
| 1  | .        | 65      | 1          | KEY_ARC    | BASIC    |
| 2  | .        | 66      | 10         | KEY_ARC    | BASIC    |
| 3  | 30.187   | 67      | 11         | LOWERBD    | NONBASIC |
| 4  | .        | 68      | 20         | KEY_ARC    | BASIC    |
| 5  | .        | 4       | 1          | KEY_ARC    | BASIC    |
| 6  | 63.650   | 5       | 2          | LOWERBD    | NONBASIC |
| 7  | 54.650   | 6       | 4          | LOWERBD    | NONBASIC |
| 8  | 22.000   | 7       | 6          | LOWERBD    | NONBASIC |
| 9  | .        | 36      | 11         | KEY_ARC    | BASIC    |
| 10   | 94.210   | 37      | 12         | LOWERBD    | NONBASIC |
| 11   | 7.630    | 38      | 14         | LOWERBD    | NONBASIC |
| 12   | 30.510   | 39      | 16         | LOWERBD    | NONBASIC |
| 13   | .        | 1       | 1          | KEY_ARC    | BASIC    |
| 14   | .        | 2       | 3          | NONKEY ARC | BASIC    |
| 15   | -34.750  | 3       | 5          | UPPERBD    | NONBASIC |
| 16   | -31.677  | 33      | 11         | UPPERBD    | NONBASIC |
| 17   | -20.760  | 34      | 13         | UPPERBD    | NONBASIC |
| 18   | -61.060  | 35      | 15         | UPPERBD    | NONBASIC |
| 19   | .        | 8       | 1          | KEY_ARC    | BASIC    |
| 20   | 6.000    | 9       | 3          | LOWERBD    | NONBASIC |
| 21   | 29.000   | 10      | 7          | LOWERBD    | NONBASIC |
| Obs  | diagonal | factory | key_id     | mth_made   |          |
| 1  | .        | .       |            |            |          |
| 2  | .        | .       |            |            |          |
| 3  | .        | .       |            |            |          |
| 4  | .        | .       |            |            |          |
| 5  | 19       | 1       | production | April      |          |
| 6  | 19       | 1       | storage    | March      |          |
| 7  | 19       | 1       | backorder  | May        |          |
| 8  | 19       | .       | f2_to_1    | April      |          |
| 9  | 25       | 1       | production | April      |          |
| 10   | 25       | 1       | storage    | March      |          |
| 11   | 25       | 1       | backorder  | May        |          |
| 12   | 25       | .       | f2_to_1    | April      |          |
| 13   | 19       | 1       | production | March      |          |
| 14   | 19       | 1       | backorder  | April      |          |
| 15   | 19       | .       | f2_to_1    | March      |          |
| 16   | 25       | 1       | production | March      |          |
| 17   | 25       | 1       | backorder  | April      |          |
| 18   | 25       | .       | f2_to_1    | March      |          |
| 19   | 19       | 1       | production | May        |          |
| 20   | 19       | 1       | storage    | April      |          |
| 21   | 19       | .       | f2_to_1    | May        |          |

## Output 7.6.2 continued

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |         |            |                  |
|--|----------|---------|------------|------------------|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_    | _STATUS_         |
| 22   | -11.913  | 40      | 11         | UPPERBD NONBASIC |
| 23   | 74.620   | 41      | 13         | LOWERBD NONBASIC |
| 24   | 39.000   | 42      | 17         | LOWERBD NONBASIC |
| 25   | .        | 14      | 3          | KEY_ARC BASIC    |
| 26   | -14.077  | 15      | 10         | UPPERBD NONBASIC |
| 27   | 10.900   | 16      | 5          | LOWERBD NONBASIC |
| 28   | 56.050   | 17      | 7          | LOWERBD NONBASIC |
| 29   | 13.490   | 46      | 13         | LOWERBD NONBASIC |
| 30   | .        | 47      | 20         | KEY_ARC BASIC    |
| 31   | 11.640   | 48      | 15         | LOWERBD NONBASIC |
| 32   | 39.720   | 49      | 17         | LOWERBD NONBASIC |
| 33   | 55.750   | 11      | 2          | LOWERBD NONBASIC |
| 34   | .        | 12      | 10         | KEY_ARC BASIC    |
| 35   | 42.550   | 13      | 6          | LOWERBD NONBASIC |
| 36   | 104.060  | 43      | 12         | LOWERBD NONBASIC |
| 37   | -23.170  | 44      | 20         | UPPERBD NONBASIC |
| 38   | 68.610   | 45      | 16         | LOWERBD NONBASIC |
| 39   | .        | 18      | 4          | KEY_ARC BASIC    |
| 40   | 22.700   | 19      | 10         | LOWERBD NONBASIC |
| 41   | 9.000    | 20      | 6          | LOWERBD NONBASIC |
| 42   | .        | 50      | 14         | KEY_ARC BASIC    |
| Obs  | diagonal | factory | key_id     | mth_made         |
| 22   | 25       | 1       | production | May              |
| 23   | 25       | 1       | storage    | April            |
| 24   | 25       | .       | f2_to_1    | May              |
| 25   | 19       | .       | f1_to_2    | April            |
| 26   | 19       | 2       | production | April            |
| 27   | 19       | 2       | storage    | March            |
| 28   | 19       | 2       | backorder  | May              |
| 29   | 25       | .       | f1_to_2    | April            |
| 30   | 25       | 2       | production | April            |
| 31   | 25       | 2       | storage    | March            |
| 32   | 25       | 2       | backorder  | May              |
| 33   | 19       | .       | f1_to_2    | March            |
| 34   | 19       | 2       | production | March            |
| 35   | 19       | 2       | backorder  | April            |
| 36   | 25       | .       | f1_to_2    | March            |
| 37   | 25       | 2       | production | March            |
| 38   | 25       | 2       | backorder  | April            |
| 39   | 19       | .       | f1_to_2    | May              |
| 40   | 19       | 2       | production | May              |
| 41   | 19       | 2       | storage    | April            |
| 42   | 25       | .       | f1_to_2    | May              |

## Output 7.6.2 continued

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |         |            |                  |
|--|----------|---------|------------|------------------|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_    | _STATUS_         |
| 43   | .        | 51      | 20         | NONKEY ARC BASIC |
| 44   | 78.1300  | 52      | 16         | LOWERBD NONBASIC |
| 45   | .        | 21      | 2          | KEY_ARC BASIC    |
| 46   | -21.0000 | 22      | 3          | UPPERBD NONBASIC |
| 47   | .        | 23      | 4          | NONKEY ARC BASIC |
| 48   | -14.5000 | 24      | 5          | UPPERBD NONBASIC |
| 49   | .        | 25      | 6          | NONKEY ARC BASIC |
| 50   | 9.0000   | 26      | 7          | LOWERBD NONBASIC |
| 51   | 47.1300  | 53      | 12         | LOWERBD NONBASIC |
| 52   | 8.4000   | 54      | 13         | LOWERBD NONBASIC |
| 53   | 1.0400   | 55      | 14         | LOWERBD NONBASIC |
| 54   | -42.0000 | 56      | 15         | UPPERBD NONBASIC |
| 55   | .        | 57      | 16         | KEY_ARC BASIC    |
| 56   | 10.5000  | 58      | 17         | LOWERBD NONBASIC |
| 57   | -37.0900 | 27      | 2          | UPPERBD NONBASIC |
| 58   | -23.0000 | 28      | 3          | UPPERBD NONBASIC |
| 59   | 38.0000  | 29      | 4          | LOWERBD NONBASIC |
| 60   | 8.2000   | 30      | 5          | LOWERBD NONBASIC |
| 61   | -24.0000 | 31      | 6          | UPPERBD NONBASIC |
| 62   | .        | 32      | 7          | KEY_ARC BASIC    |
| 63   | .        | 59      | 12         | KEY_ARC BASIC    |
| Obs  | diagonal | factory | key_id     | mth_made         |
| 43   | 25       | 2       | production | May              |
| 44   | 25       | 2       | storage    | April            |
| 45   | 19       | 1       | sales      | March            |
| 46   | 19       | 1       | sales      | April            |
| 47   | 19       | 1       | sales      | May              |
| 48   | 19       | 2       | sales      | March            |
| 49   | 19       | 2       | sales      | April            |
| 50   | 19       | 2       | sales      | May              |
| 51   | 25       | 1       | sales      | March            |
| 52   | 25       | 1       | sales      | April            |
| 53   | 25       | 1       | sales      | May              |
| 54   | 25       | 2       | sales      | March            |
| 55   | 25       | 2       | sales      | April            |
| 56   | 25       | 2       | sales      | May              |
| 57   | 19       | 1       | sales      | March            |
| 58   | 19       | 1       | sales      | April            |
| 59   | 19       | 1       | sales      | May              |
| 60   | 19       | 2       | sales      | March            |
| 61   | 19       | 2       | sales      | April            |
| 62   | 19       | 2       | sales      | May              |
| 63   | 25       | 1       | sales      | March            |

**Output 7.6.2** *continued*

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |         |         |          |          |
|--|----------|---------|---------|----------|----------|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_ | _STATUS_ |          |
| 64   | .        | 60      | 13      | KEY_ARC  | BASIC    |
| 65   | 33.0600  | 61      | 14      | LOWERBD  | NONBASIC |
| 66   | .        | 62      | 15      | KEY_ARC  | BASIC    |
| 67   | .        | 63      | 16      | KEY_ARC  | BASIC    |
| 68   | .        | 64      | 17      | KEY_ARC  | BASIC    |
| Obs  | diagonal | factory | key_id  | mth_made |          |
| 64   | 25       | 1       | sales   | April    |          |
| 65   | 25       | 1       | sales   | May      |          |
| 66   | 25       | 2       | sales   | March    |          |
| 67   | 25       | 2       | sales   | April    |          |
| 68   | 25       | 2       | sales   | May      |          |

## Output 7.6.3 DUALOUT=DUAL4

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |          |          |               |         |        |        |         |
|--|----------|----------|---------------|---------|--------|--------|---------|
| Obs  | _node_   | _supdem_ | _DUAL_        | _NNUMB_ | _PRED_ | _TRAV_ | _SCESS_ |
| 1  | _ROOT_   | 238      | 0.00          | 22      | 0      | 8      | 5       |
| 2  | _EXCESS_ | -200     | -100000193.90 | 21      | 1      | 20     | 13      |
| 3  | f1_apr_1 | .        | -100000278.00 | 3       | 1      | 6      | 2       |
| 4  | f1_apr_2 | .        | -100000405.92 | 13      | 19     | 11     | 2       |
| 5  | f1_mar_1 | .        | -100000326.65 | 2       | 8      | 1      | 20      |
| 6  | f1_mar_2 | .        | -100000480.13 | 12      | 19     | 13     | 1       |
| 7  | f1_may_1 | .        | -100000284.00 | 4       | 1      | 7      | 3       |
| 8  | f1_may_2 | .        | -100000349.30 | 14      | 17     | 15     | 1       |
| 9  | f2_apr_1 | .        | -100000289.00 | 6       | 3      | 4      | 1       |
| 10   | f2_apr_2 | .        | -100000415.43 | 16      | 20     | 18     | 9       |
| 11   | f2_mar_1 | .        | -100000281.90 | 5       | 10     | 3      | 1       |
| 12   | f2_mar_2 | .        | -100000399.07 | 15      | 19     | 10     | 1       |
| 13   | f2_may_1 | .        | -100000300.00 | 7       | 4      | 9      | 2       |
| 14   | f2_may_2 | .        | -100000375.30 | 17      | 19     | 14     | 2       |
| 15   | fact1_1  | 1000     | -100000193.90 | 1       | 2      | 21     | 19      |
| 16   | fact1_2  | 1000     | -100000224.09 | 11      | 13     | 17     | 1       |
| 17   | fact2_1  | 850      | -100000193.90 | 10      | 21     | 5      | 2       |
| 18   | fact2_2  | 1500     | -100000193.90 | 20      | 21     | 16     | 10      |
| 19   | shop1_1  | -900     | -99999999.00  | 8       | 22     | 2      | 21      |
| 20   | shop1_2  | -900     | -99999873.24  | 18      | 16     | 19     | 1       |
| 21   | shop2_1  | -900     | -100000001.00 | 9       | 7      | 22     | 1       |
| Obs  | _ARCID_  | _FLOW_   | _FBQ_         | _VALUE_ | _RHS_  | _TYPE_ | _row_   |
| 1  | 3        | 166.000  | -69           | 0       | 75     |        |         |
| 2  | 65       | 5.000    | 65            | .       | .      |        |         |
| 3  | 4        | 483.333  | 4             | .       | .      |        |         |
| 4  | -60      | 220.000  | 36            | .       | .      |        |         |
| 5  | -21      | 143.333  | 1             | .       | .      |        |         |
| 6  | -59      | 455.000  | 33            | .       | .      |        |         |
| 7  | 8        | 78.333   | 8             | .       | .      |        |         |
| 8  | -50      | 350.000  | 40            | .       | .      |        |         |
| 9  | 14       | 13.333   | 14            | .       | .      |        |         |
| 10   | 47       | 542.500  | 46            | .       | .      |        |         |
| 11   | 12       | 255.000  | 11            | .       | .      |        |         |
| 12   | -62      | 125.000  | 43            | .       | .      |        |         |
| 13   | 18       | 115.000  | 18            | .       | .      |        |         |
| 14   | -64      | 472.500  | 50            | .       | .      |        |         |
| 15   | -1       | 283.333  | -1            | .       | .      |        |         |
| 16   | -36      | 200.000  | -33           | .       | .      |        |         |
| 17   | -66      | 45.000   | -33           | .       | .      |        |         |
| 18   | -68      | 150.000  | -65           | .       | .      |        |         |
| 19   | 0        | 0.000    | 21            | .       | .      |        |         |
| 20   | 57       | 400.000  | 53            | .       | .      |        |         |
| 21   | 32       | 150.000  | 27            | .       | .      |        |         |



## Output 7.6.3 continued

| Adding Side Constraints and Using a Warm Start<br>Production Planning/Inventory/Distribution |         |          |              |         |        |        |                 |
|--|---------|----------|--------------|---------|--------|--------|-----------------|
| Obs  | _node_  | _supdem_ | _DUAL_       | _NNUB_  | _PRED_ | _TRAV_ | _SCESS_         |
| 22   | shop2_2 | -1450    | -99999856.24 | 19      | 16     | 12     | 7               |
| 23   |         | .        | -1.83        | 2       | 8      | .      | .               |
| 24   |         | .        | -1.62        | 0       | 8      | .      | .               |
| 25   |         | .        | -6.21        | 3       | 17     | .      | .               |
| 26   |         | .        | 0.00         | 1       | 1      | .      | 1               |
| 27   |         | .        | -15.05       | 4       | 2      | .      | .               |
| Obs  | _ARCID_ | _FLOW_   | _FBQ_        | _VALUE_ | _RHS_  | _TYPE_ | _row_           |
| 22   | 63      | 177.500  | 59           | .       | .      |        |                 |
| 23   | 25      | 243.333  | .            | 2600    | 2600   | LE     | FACT1 APL GIZMO |
| 24   | 23      | 13.333   | .            | 2600    | 2600   | LE     | FACT1 MAR GIZMO |
| 25   | 51      | 87.500   | .            | 3750    | 3750   | LE     | FACT2 APL GIZMO |
| 26   | .       | 280.000  | .            | 3470    | 3750   | LE     | FACT2 MAR GIZMO |
| 27   | 2       | 20.000   | .            | 50      | 50     | LE     | TOTAL BACKORDER |

## Example 7.7: Using a Constrained Solution Warm Start

Suppose the 25-inch screen TVs produced at factory 1 in May can be sold at either shop with an increased profit of 40 dollars each. What is the new optimal solution? Because only arc costs have been changed, information about the present solution in `DUALOUT=dual4` and `CONOUT=con4` can be used as a warm start in the following PROC NETFLOW run. It is still necessary to specify `CONDATA=con3` `SPARSECONDATA` `RHSOBS='CHIP/BO LIMIT'`, since the `CONDATA=` data set is always read.

```

title 'Using a Constrained Solution Warm Start';
title2 'Production Planning/Inventory/Distribution';
data new_con4;
  set con4;
  oldcost=_cost_;
  oldflow=_flow_;
  oldfc=_fcost_;
  if _tail_='f1_may_2'
    & (_head_='shop1_2' | _head_='shop2_2')
    then _cost_=_cost_-40;
run;

proc netflow
  warm
  arcdata=new_con4
  dualin=dual4
  condata=con3
  sparsecondata
  rhsobs='CHIP/BO LIMIT'
  dualout=dual5

```

```

        conout=con5;
run;
quit;

proc print data=con5 heading=h width=min;
sum _fcost_;
var _tail_ _head_ _capac_ _lo_ _supply_ _demand_ _name_ _cost_ _flow_ _fcost_;
run;

proc print data=con5 heading=h width=min;
sum oldfc;
var oldcost oldflow oldfc diagonal factory key_id mth_made _anumb_ _tnumb_;
run;

proc print data=dual5;
run;

```

The following messages appear on the SAS log:

```

NOTE: The following 1 variables in NODEDATA do not belong to any SAS variable
list. These will be ignored.
      _VALUE_
NOTE: Number of nodes= 21 .
NOTE: Number of supply nodes= 4 .
NOTE: Number of demand nodes= 5 .
NOTE: The greater of total supply and total demand= 4350 .
NOTE: Number of <= side constraints= 5 .
NOTE: Number of == side constraints= 0 .
NOTE: Number of >= side constraints= 0 .
NOTE: Number of arc and nonarc variable side constraint coefficients= 16 .
NOTE: Number of iterations, optimizing with constraints= 6 .
NOTE: Of these, 0 were degenerate.
NOTE: Optimum reached.
NOTE: Minimal total cost= -1295661.8 .
NOTE: The data set WORK.CON5 has 68 observations and 21 variables.
NOTE: The data set WORK.DUAL5 has 25 observations and 14 variables.

```

## Output 7.7.1 CONOUT=CON5

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |                |          |          |          |          |          |
|---|----------------|----------|----------|----------|----------|----------|
| Obs   | _tail_         | _head_   | _capac_  | _lo_     | _SUPPLY_ | _DEMAND_ |
| 1   | fact1_1        | _EXCESS_ | 99999999 | 0        | 1000     | 200      |
| 2   | fact2_1        | _EXCESS_ | 99999999 | 0        | 850      | 200      |
| 3   | fact1_2        | _EXCESS_ | 99999999 | 0        | 1000     | 200      |
| 4   | fact2_2        | _EXCESS_ | 99999999 | 0        | 1500     | 200      |
| 5   | fact1_1        | f1_apr_1 | 600      | 50       | 1000     | .        |
| 6   | f1_mar_1       | f1_apr_1 | 50       | 0        | .        | .        |
| 7   | f1_may_1       | f1_apr_1 | 20       | 0        | .        | .        |
| 8   | f2_apr_1       | f1_apr_1 | 40       | 0        | .        | .        |
| 9   | fact1_2        | f1_apr_2 | 550      | 50       | 1000     | .        |
| 10  | f1_mar_2       | f1_apr_2 | 40       | 0        | .        | .        |
| 11  | f1_may_2       | f1_apr_2 | 15       | 0        | .        | .        |
| 12  | f2_apr_2       | f1_apr_2 | 25       | 0        | .        | .        |
| 13  | fact1_1        | f1_mar_1 | 500      | 50       | 1000     | .        |
| 14  | f1_apr_1       | f1_mar_1 | 20       | 0        | .        | .        |
| 15  | f2_mar_1       | f1_mar_1 | 40       | 0        | .        | .        |
| 16  | fact1_2        | f1_mar_2 | 400      | 40       | 1000     | .        |
| 17  | f1_apr_2       | f1_mar_2 | 30       | 0        | .        | .        |
| 18  | f2_mar_2       | f1_mar_2 | 25       | 0        | .        | .        |
| 19  | fact1_1        | f1_may_1 | 400      | 50       | 1000     | .        |
| 20  | f1_apr_1       | f1_may_1 | 50       | 0        | .        | .        |
| 21  | f2_may_1       | f1_may_1 | 40       | 0        | .        | .        |
| Obs   | _name_         | _cost_   | _FLOW_   | _FCOST_  |          |          |
| 1   |                | 0.00     | 5.000    | 0.00     |          |          |
| 2   |                | 0.00     | 45.000   | 0.00     |          |          |
| 3   |                | 0.00     | 0.000    | 0.00     |          |          |
| 4   |                | 0.00     | 150.000  | 0.00     |          |          |
| 5   | prod f1 19 apl | 78.60    | 533.333  | 41920.00 |          |          |
| 6   |                | 15.00    | 0.000    | 0.00     |          |          |
| 7   | back f1 19 may | 33.60    | 0.000    | 0.00     |          |          |
| 8   |                | 11.00    | 0.000    | 0.00     |          |          |
| 9   | prod f1 25 apl | 174.50   | 250.000  | 43625.00 |          |          |
| 10  |                | 20.00    | 0.000    | 0.00     |          |          |
| 11  | back f1 25 may | 49.20    | 0.000    | 0.00     |          |          |
| 12  |                | 21.00    | 0.000    | 0.00     |          |          |
| 13  | prod f1 19 mar | 127.90   | 333.333  | 42633.33 |          |          |
| 14  | back f1 19 apl | 33.60    | 20.000   | 672.00   |          |          |
| 15  |                | 10.00    | 40.000   | 400.00   |          |          |
| 16  | prod f1 25 mar | 217.90   | 400.000  | 87160.00 |          |          |
| 17  | back f1 25 apl | 38.40    | 30.000   | 1152.00  |          |          |
| 18  |                | 20.00    | 25.000   | 500.00   |          |          |
| 19  |                | 90.10    | 128.333  | 11562.83 |          |          |
| 20  |                | 12.00    | 0.000    | 0.00     |          |          |
| 21  |                | 13.00    | 0.000    | 0.00     |          |          |

## Output 7.7.1 continued

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |                |          |          |           |          |          |
|---|----------------|----------|----------|-----------|----------|----------|
| Obs   | _tail_         | _head_   | _capac_  | _lo_      | _SUPPLY_ | _DEMAND_ |
| 22  | fact1_2        | f1_may_2 | 350      | 40        | 1000     | .        |
| 23  | f1_apr_2       | f1_may_2 | 40       | 0         | .        | .        |
| 24  | f2_may_2       | f1_may_2 | 25       | 0         | .        | .        |
| 25  | f1_apr_1       | f2_apr_1 | 99999999 | 0         | .        | .        |
| 26  | fact2_1        | f2_apr_1 | 480      | 35        | 850      | .        |
| 27  | f2_mar_1       | f2_apr_1 | 30       | 0         | .        | .        |
| 28  | f2_may_1       | f2_apr_1 | 15       | 0         | .        | .        |
| 29  | f1_apr_2       | f2_apr_2 | 99999999 | 0         | .        | .        |
| 30  | fact2_2        | f2_apr_2 | 680      | 35        | 1500     | .        |
| 31  | f2_mar_2       | f2_apr_2 | 50       | 0         | .        | .        |
| 32  | f2_may_2       | f2_apr_2 | 15       | 0         | .        | .        |
| 33  | f1_mar_1       | f2_mar_1 | 99999999 | 0         | .        | .        |
| 34  | fact2_1        | f2_mar_1 | 450      | 35        | 850      | .        |
| 35  | f2_apr_1       | f2_mar_1 | 15       | 0         | .        | .        |
| 36  | f1_mar_2       | f2_mar_2 | 99999999 | 0         | .        | .        |
| 37  | fact2_2        | f2_mar_2 | 650      | 35        | 1500     | .        |
| 38  | f2_apr_2       | f2_mar_2 | 15       | 0         | .        | .        |
| 39  | f1_may_1       | f2_may_1 | 99999999 | 0         | .        | .        |
| 40  | fact2_1        | f2_may_1 | 250      | 35        | 850      | .        |
| 41  | f2_apr_1       | f2_may_1 | 30       | 0         | .        | .        |
| 42  | f1_may_2       | f2_may_2 | 99999999 | 0         | .        | .        |
| Obs   | _name_         | _cost_   | _FLOW_   | _FCOST_   |          |          |
| 22  |                | 113.30   | 350.000  | 39655.00  |          |          |
| 23  |                | 18.00    | 0.000    | 0.00      |          |          |
| 24  |                | 13.00    | 0.000    | 0.00      |          |          |
| 25  |                | 11.00    | 13.333   | 146.67    |          |          |
| 26  | prod f2 19 apl | 62.40    | 480.000  | 29952.00  |          |          |
| 27  |                | 18.00    | 0.000    | 0.00      |          |          |
| 28  | back f2 19 may | 30.00    | 0.000    | 0.00      |          |          |
| 29  |                | 23.00    | 0.000    | 0.00      |          |          |
| 30  | prod f2 25 apl | 196.70   | 550.000  | 108185.00 |          |          |
| 31  |                | 28.00    | 0.000    | 0.00      |          |          |
| 32  | back f2 25 may | 64.80    | 0.000    | 0.00      |          |          |
| 33  |                | 11.00    | 0.000    | 0.00      |          |          |
| 34  | prod f2 19 mar | 88.00    | 290.000  | 25520.00  |          |          |
| 35  | back f2 19 apl | 20.40    | 0.000    | 0.00      |          |          |
| 36  |                | 23.00    | 0.000    | 0.00      |          |          |
| 37  | prod f2 25 mar | 182.00   | 650.000  | 118300.00 |          |          |
| 38  | back f2 25 apl | 37.20    | 0.000    | 0.00      |          |          |
| 39  |                | 16.00    | 115.000  | 1840.00   |          |          |
| 40  |                | 128.80   | 35.000   | 4508.00   |          |          |
| 41  |                | 20.00    | 0.000    | 0.00      |          |          |
| 42  |                | 26.00    | 0.000    | 0.00      |          |          |

## Output 7.7.1 continued

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |          |          |          |            |          |          |
|---|----------|----------|----------|------------|----------|----------|
| Obs   | _tail_   | _head_   | _capac_  | _lo_       | _SUPPLY_ | _DEMAND_ |
| 43  | fact2_2  | f2_may_2 | 550      | 35         | 1500     | .        |
| 44  | f2_apr_2 | f2_may_2 | 50       | 0          | .        | .        |
| 45  | f1_mar_1 | shop1_1  | 250      | 0          | .        | 900      |
| 46  | f1_apr_1 | shop1_1  | 250      | 0          | .        | 900      |
| 47  | f1_may_1 | shop1_1  | 250      | 0          | .        | 900      |
| 48  | f2_mar_1 | shop1_1  | 250      | 0          | .        | 900      |
| 49  | f2_apr_1 | shop1_1  | 250      | 0          | .        | 900      |
| 50  | f2_may_1 | shop1_1  | 250      | 0          | .        | 900      |
| 51  | f1_mar_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 52  | f1_apr_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 53  | f1_may_2 | shop1_2  | 99999999 | 0          | .        | 900      |
| 54  | f2_mar_2 | shop1_2  | 500      | 0          | .        | 900      |
| 55  | f2_apr_2 | shop1_2  | 500      | 0          | .        | 900      |
| 56  | f2_may_2 | shop1_2  | 500      | 0          | .        | 900      |
| 57  | f1_mar_1 | shop2_1  | 250      | 0          | .        | 900      |
| 58  | f1_apr_1 | shop2_1  | 250      | 0          | .        | 900      |
| 59  | f1_may_1 | shop2_1  | 250      | 0          | .        | 900      |
| 60  | f2_mar_1 | shop2_1  | 250      | 0          | .        | 900      |
| 61  | f2_apr_1 | shop2_1  | 250      | 0          | .        | 900      |
| 62  | f2_may_1 | shop2_1  | 250      | 0          | .        | 900      |
| 63  | f1_mar_2 | shop2_2  | 99999999 | 0          | .        | 1450     |
| Obs   | _name_   | _cost_   | _FLOW_   | _FCOST_    |          |          |
| 43  |          | 181.40   | 150.000  | 27210.00   |          |          |
| 44  |          | 38.00    | 0.000    | 0.00       |          |          |
| 45  |          | -327.65  | 143.333  | -46963.17  |          |          |
| 46  |          | -300.00  | 250.000  | -75000.00  |          |          |
| 47  |          | -285.00  | 13.333   | -3800.00   |          |          |
| 48  |          | -297.40  | 250.000  | -74350.00  |          |          |
| 49  |          | -290.00  | 243.333  | -70566.67  |          |          |
| 50  |          | -292.00  | 0.000    | 0.00       |          |          |
| 51  |          | -559.76  | 0.000    | 0.00       |          |          |
| 52  |          | -524.28  | 0.000    | 0.00       |          |          |
| 53  |          | -515.02  | 350.000  | -180257.00 |          |          |
| 54  |          | -567.83  | 500.000  | -283915.00 |          |          |
| 55  |          | -542.19  | 50.000   | -27109.50  |          |          |
| 56  |          | -491.56  | 0.000    | 0.00       |          |          |
| 57  |          | -362.74  | 250.000  | -90685.00  |          |          |
| 58  |          | -300.00  | 250.000  | -75000.00  |          |          |
| 59  |          | -245.00  | 0.000    | 0.00       |          |          |
| 60  |          | -272.70  | 0.000    | 0.00       |          |          |
| 61  |          | -312.00  | 250.000  | -78000.00  |          |          |
| 62  |          | -299.00  | 150.000  | -44850.00  |          |          |
| 63  |          | -623.89  | 455.000  | -283869.95 |          |          |

Output 7.7.1 *continued*

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |          |         |          |             |          |          |
|---|----------|---------|----------|-------------|----------|----------|
| Obs   | _tail_   | _head_  | _capac_  | _lo_        | _SUPPLY_ | _DEMAND_ |
| 64  | f1_apr_2 | shop2_2 | 99999999 | 0           | .        | 1450     |
| 65  | f1_may_2 | shop2_2 | 99999999 | 0           | .        | 1450     |
| 66  | f2_mar_2 | shop2_2 | 500      | 0           | .        | 1450     |
| 67  | f2_apr_2 | shop2_2 | 500      | 0           | .        | 1450     |
| 68  | f2_may_2 | shop2_2 | 500      | 0           | .        | 1450     |
| Obs   | _name_   | _cost_  | _FLOW_   | _FCOST_     |          |          |
| 64  |          | -549.68 | 220.000  | -120929.60  |          |          |
| 65  |          | -500.00 | 0.000    | 0.00        |          |          |
| 66  |          | -542.83 | 125.000  | -67853.75   |          |          |
| 67  |          | -559.19 | 500.000  | -279595.00  |          |          |
| 68  |          | -519.06 | 150.000  | -77859.00   |          |          |
|   |          |         |          | =====       |          |          |
|   |          |         |          | -1295661.80 |          |          |

**Output 7.7.2** CONOUT=CON5 (continued)

Using a Constrained Solution Warm Start  
Production Planning/Inventory/Distribution

| Obs | oldcost | oldflow | oldfc    | diagonal | factory |
|-----|---------|---------|----------|----------|---------|
| 1   | 0.00    | 5.000   | 0.00     | .        | .       |
| 2   | 0.00    | 45.000  | 0.00     | .        | .       |
| 3   | 0.00    | 0.000   | 0.00     | .        | .       |
| 4   | 0.00    | 150.000 | 0.00     | .        | .       |
| 5   | 78.60   | 533.333 | 41920.00 | 19       | 1       |
| 6   | 15.00   | 0.000   | 0.00     | 19       | 1       |
| 7   | 33.60   | 0.000   | 0.00     | 19       | 1       |
| 8   | 11.00   | 0.000   | 0.00     | 19       | .       |
| 9   | 174.50  | 250.000 | 43625.00 | 25       | 1       |
| 10  | 20.00   | 0.000   | 0.00     | 25       | 1       |
| 11  | 49.20   | 0.000   | 0.00     | 25       | 1       |
| 12  | 21.00   | 0.000   | 0.00     | 25       | .       |
| 13  | 127.90  | 333.333 | 42633.33 | 19       | 1       |
| 14  | 33.60   | 20.000  | 672.00   | 19       | 1       |
| 15  | 10.00   | 40.000  | 400.00   | 19       | .       |
| 16  | 217.90  | 400.000 | 87160.00 | 25       | 1       |
| 17  | 38.40   | 30.000  | 1152.00  | 25       | 1       |
| 18  | 20.00   | 25.000  | 500.00   | 25       | .       |
| 19  | 90.10   | 128.333 | 11562.83 | 19       | 1       |
| 20  | 12.00   | 0.000   | 0.00     | 19       | 1       |
| 21  | 13.00   | 0.000   | 0.00     | 19       | .       |

| Obs | key_id     | mth_made | _ANUMB_ | _TNUMB_ |
|-----|------------|----------|---------|---------|
| 1   |            |          | 65      | 1       |
| 2   |            |          | 66      | 10      |
| 3   |            |          | 67      | 11      |
| 4   |            |          | 68      | 20      |
| 5   | production | April    | 4       | 1       |
| 6   | storage    | March    | 5       | 2       |
| 7   | backorder  | May      | 6       | 4       |
| 8   | f2_to_1    | April    | 7       | 6       |
| 9   | production | April    | 36      | 11      |
| 10  | storage    | March    | 37      | 12      |
| 11  | backorder  | May      | 38      | 14      |
| 12  | f2_to_1    | April    | 39      | 16      |
| 13  | production | March    | 1       | 1       |
| 14  | backorder  | April    | 2       | 3       |
| 15  | f2_to_1    | March    | 3       | 5       |
| 16  | production | March    | 33      | 11      |
| 17  | backorder  | April    | 34      | 13      |
| 18  | f2_to_1    | March    | 35      | 15      |
| 19  | production | May      | 8       | 1       |
| 20  | storage    | April    | 9       | 3       |
| 21  | f2_to_1    | May      | 10      | 7       |

## Output 7.7.2 continued

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |            |           |           |          |         |
|---|------------|-----------|-----------|----------|---------|
| Obs   | oldcost    | oldflow   | oldfc     | diagonal | factory |
| 22  | 113.30     | 350.000   | 39655.00  | 25       | 1       |
| 23  | 18.00      | 0.000     | 0.00      | 25       | 1       |
| 24  | 13.00      | 0.000     | 0.00      | 25       | .       |
| 25  | 11.00      | 13.333    | 146.67    | 19       | .       |
| 26  | 62.40      | 480.000   | 29952.00  | 19       | 2       |
| 27  | 18.00      | 0.000     | 0.00      | 19       | 2       |
| 28  | 30.00      | 0.000     | 0.00      | 19       | 2       |
| 29  | 23.00      | 0.000     | 0.00      | 25       | .       |
| 30  | 196.70     | 577.500   | 113594.25 | 25       | 2       |
| 31  | 28.00      | 0.000     | 0.00      | 25       | 2       |
| 32  | 64.80      | 0.000     | 0.00      | 25       | 2       |
| 33  | 11.00      | 0.000     | 0.00      | 19       | .       |
| 34  | 88.00      | 290.000   | 25520.00  | 19       | 2       |
| 35  | 20.40      | 0.000     | 0.00      | 19       | 2       |
| 36  | 23.00      | 0.000     | 0.00      | 25       | .       |
| 37  | 182.00     | 650.000   | 118300.00 | 25       | 2       |
| 38  | 37.20      | 0.000     | 0.00      | 25       | 2       |
| 39  | 16.00      | 115.000   | 1840.00   | 19       | .       |
| 40  | 128.80     | 35.000    | 4508.00   | 19       | 2       |
| 41  | 20.00      | 0.000     | 0.00      | 19       | 2       |
| 42  | 26.00      | 350.000   | 9100.00   | 25       | .       |
| Obs   | key_id     | mt_h_made | _ANUMB_   | _TNUMB_  |         |
| 22  | production | May       | 40        | 11       |         |
| 23  | storage    | April     | 41        | 13       |         |
| 24  | f2_to_1    | May       | 42        | 17       |         |
| 25  | f1_to_2    | April     | 14        | 3        |         |
| 26  | production | April     | 15        | 10       |         |
| 27  | storage    | March     | 16        | 5        |         |
| 28  | backorder  | May       | 17        | 7        |         |
| 29  | f1_to_2    | April     | 46        | 13       |         |
| 30  | production | April     | 47        | 20       |         |
| 31  | storage    | March     | 48        | 15       |         |
| 32  | backorder  | May       | 49        | 17       |         |
| 33  | f1_to_2    | March     | 11        | 2        |         |
| 34  | production | March     | 12        | 10       |         |
| 35  | backorder  | April     | 13        | 6        |         |
| 36  | f1_to_2    | March     | 43        | 12       |         |
| 37  | production | March     | 44        | 20       |         |
| 38  | backorder  | April     | 45        | 16       |         |
| 39  | f1_to_2    | May       | 18        | 4        |         |
| 40  | production | May       | 19        | 10       |         |
| 41  | storage    | April     | 20        | 6        |         |
| 42  | f1_to_2    | May       | 50        | 14       |         |



## Output 7.7.2 continued

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |            |          |            |          |         |
|---|------------|----------|------------|----------|---------|
| Obs   | oldcost    | oldflow  | oldfc      | diagonal | factory |
| 43  | 181.40     | 122.500  | 22221.50   | 25       | 2       |
| 44  | 38.00      | 0.000    | 0.00       | 25       | 2       |
| 45  | -327.65    | 143.333  | -46963.17  | 19       | 1       |
| 46  | -300.00    | 250.000  | -75000.00  | 19       | 1       |
| 47  | -285.00    | 13.333   | -3800.00   | 19       | 1       |
| 48  | -297.40    | 250.000  | -74350.00  | 19       | 2       |
| 49  | -290.00    | 243.333  | -70566.67  | 19       | 2       |
| 50  | -292.00    | 0.000    | 0.00       | 19       | 2       |
| 51  | -559.76    | 0.000    | 0.00       | 25       | 1       |
| 52  | -524.28    | 0.000    | 0.00       | 25       | 1       |
| 53  | -475.02    | 0.000    | 0.00       | 25       | 1       |
| 54  | -567.83    | 500.000  | -283915.00 | 25       | 2       |
| 55  | -542.19    | 400.000  | -216876.00 | 25       | 2       |
| 56  | -491.56    | 0.000    | 0.00       | 25       | 2       |
| 57  | -362.74    | 250.000  | -90685.00  | 19       | 1       |
| 58  | -300.00    | 250.000  | -75000.00  | 19       | 1       |
| 59  | -245.00    | 0.000    | 0.00       | 19       | 1       |
| 60  | -272.70    | 0.000    | 0.00       | 19       | 2       |
| 61  | -312.00    | 250.000  | -78000.00  | 19       | 2       |
| 62  | -299.00    | 150.000  | -44850.00  | 19       | 2       |
| 63  | -623.89    | 455.000  | -283869.95 | 25       | 1       |
| Obs   | key_id     | mth_made | _ANUMB_    | _TNUMB_  |         |
| 43  | production | May      | 51         | 20       |         |
| 44  | storage    | April    | 52         | 16       |         |
| 45  | sales      | March    | 21         | 2        |         |
| 46  | sales      | April    | 22         | 3        |         |
| 47  | sales      | May      | 23         | 4        |         |
| 48  | sales      | March    | 24         | 5        |         |
| 49  | sales      | April    | 25         | 6        |         |
| 50  | sales      | May      | 26         | 7        |         |
| 51  | sales      | March    | 53         | 12       |         |
| 52  | sales      | April    | 54         | 13       |         |
| 53  | sales      | May      | 55         | 14       |         |
| 54  | sales      | March    | 56         | 15       |         |
| 55  | sales      | April    | 57         | 16       |         |
| 56  | sales      | May      | 58         | 17       |         |
| 57  | sales      | March    | 27         | 2        |         |
| 58  | sales      | April    | 28         | 3        |         |
| 59  | sales      | May      | 29         | 4        |         |
| 60  | sales      | March    | 30         | 5        |         |
| 61  | sales      | April    | 31         | 6        |         |
| 62  | sales      | May      | 32         | 7        |         |
| 63  | sales      | March    | 59         | 12       |         |

## Output 7.7.2 continued

Using a Constrained Solution Warm Start  
 Production Planning/Inventory/Distribution

| Obs | oldcost | oldflow | oldfc       | diagonal | factory |
|-----|---------|---------|-------------|----------|---------|
| 64  | -549.68 | 220.000 | -120929.60  | 25       | 1       |
| 65  | -460.00 | 0.000   | 0.00        | 25       | 1       |
| 66  | -542.83 | 125.000 | -67853.75   | 25       | 2       |
| 67  | -559.19 | 177.500 | -99256.23   | 25       | 2       |
| 68  | -519.06 | 472.500 | -245255.85  | 25       | 2       |
|     |         |         | =====       |          |         |
|     |         |         | -1282708.63 |          |         |

| Obs | key_id | mth_made | _ANUMB_ | _TNUMB_ |
|-----|--------|----------|---------|---------|
| 64  | sales  | April    | 60      | 13      |
| 65  | sales  | May      | 61      | 14      |
| 66  | sales  | March    | 62      | 15      |
| 67  | sales  | April    | 63      | 16      |
| 68  | sales  | May      | 64      | 17      |

## Output 7.7.3 DUALOUT=DUAL5

| Using a Constrained Solution Warm Start<br>Production Planning/Inventory/Distribution |          |          |               |         |        |        |                 |
|---|----------|----------|---------------|---------|--------|--------|-----------------|
| Obs   | _node_   | _supdem_ | _DUAL_        | _NNUMB_ | _PRED_ | _TRAV_ | _SCESS_         |
| 1   | f1_apr_1 | .        | -100000278.00 | 3       | 1      | 6      | 2               |
| 2   | f1_apr_2 | .        | -100000405.92 | 13      | 19     | 11     | 2               |
| 3   | f1_mar_1 | .        | -100000326.65 | 2       | 8      | 1      | 20              |
| 4   | f1_mar_2 | .        | -100000480.13 | 12      | 19     | 13     | 1               |
| 5   | f1_may_1 | .        | -100000284.00 | 4       | 1      | 7      | 3               |
| 6   | f1_may_2 | .        | -100000363.43 | 14      | 18     | 10     | 1               |
| 7   | f2_apr_1 | .        | -100000289.00 | 6       | 3      | 4      | 1               |
| 8   | f2_apr_2 | .        | -100000390.60 | 16      | 20     | 18     | 3               |
| 9   | f2_mar_1 | .        | -100000281.90 | 5       | 10     | 3      | 1               |
| 10  | f2_mar_2 | .        | -100000399.07 | 15      | 19     | 16     | 1               |
| 11  | f2_may_1 | .        | -100000300.00 | 7       | 4      | 9      | 2               |
| 12  | f2_may_2 | .        | -100000375.30 | 17      | 20     | 19     | 6               |
| 13  | fact1_1  | 1000     | -100000193.90 | 1       | 2      | 21     | 19              |
| 14  | fact1_2  | 1000     | -100000224.09 | 11      | 13     | 15     | 1               |
| 15  | fact2_1  | 850      | -100000193.90 | 10      | 21     | 5      | 2               |
| 16  | fact2_2  | 1500     | -100000193.90 | 20      | 21     | 17     | 10              |
| 17  | shop1_1  | -900     | -99999999.00  | 8       | 22     | 2      | 21              |
| 18  | shop1_2  | -900     | -99999848.41  | 18      | 16     | 14     | 2               |
| 19  | shop2_1  | -900     | -100000001.00 | 9       | 7      | 22     | 1               |
| 20  | shop2_2  | -1450    | -99999856.24  | 19      | 17     | 12     | 5               |
| 21  | .        | .        | -1.83         | 2       | 8      | .      | .               |
| 22  | .        | .        | -1.62         | 0       | 8      | .      | .               |
| 23  | .        | .        | 0.00          | 3       | 3      | .      | 3               |
| 24  | .        | .        | 0.00          | 1       | 1      | .      | 1               |
| 25  | .        | .        | -15.05        | 4       | 2      | .      | .               |
| Obs   | _ARCID_  | _FLOW_   | _FBQ_         | _VALUE_ | _RHS_  | _TYPE_ | _row_           |
| 1   | 4        | 483.333  | 4             | .       | .      |        |                 |
| 2   | -60      | 220.000  | 36            | .       | .      |        |                 |
| 3   | -21      | 143.333  | 1             | .       | .      |        |                 |
| 4   | -59      | 455.000  | 33            | .       | .      |        |                 |
| 5   | 8        | 78.333   | 8             | .       | .      |        |                 |
| 6   | -55      | 350.000  | 40            | .       | .      |        |                 |
| 7   | 14       | 13.333   | 14            | .       | .      |        |                 |
| 8   | 47       | 515.000  | 46            | .       | .      |        |                 |
| 9   | 12       | 255.000  | 11            | .       | .      |        |                 |
| 10  | -62      | 125.000  | 43            | .       | .      |        |                 |
| 11  | 18       | 115.000  | 18            | .       | .      |        |                 |
| 12  | 51       | 115.000  | 50            | .       | .      |        |                 |
| 13  | -1       | 283.333  | -1            | .       | .      |        |                 |
| 14  | -36      | 200.000  | -33           | .       | .      |        |                 |
| 15  | -66      | 45.000   | -33           | .       | .      |        |                 |
| 16  | -68      | 150.000  | -65           | .       | .      |        |                 |
| 17  | 0        | 0.000    | 21            | .       | .      |        |                 |
| 18  | 57       | 50.000   | 53            | .       | .      |        |                 |
| 19  | 32       | 150.000  | 27            | .       | .      |        |                 |
| 20  | 64       | 150.000  | 59            | .       | .      |        |                 |
| 21  | 25       | 243.333  | .             | 2600    | 2600   | LE     | FACT1 APL GIZMO |
| 22  | 23       | 13.333   | .             | 2600    | 2600   | LE     | FACT1 MAR GIZMO |
| 23  | .        | 110.000  | .             | 3640    | 3750   | LE     | FACT2 APL GIZMO |
| 24  | .        | 280.000  | .             | 3470    | 3750   | LE     | FACT2 MAR GIZMO |
| 25  | 2        | 20.000   | .             | 50      | 50     | LE     | TOTAL BACKORDER |

### Example 7.8: Nonarc Variables in the Side Constraints

Notice in `DUALOUT=dual5` from [Example 7.7](#) the `FACT2 MAR GIZMO` constraint (observation 24) has a `_VALUE_` of 3470, which is not equal to the `_RHS_` of this constraint. Not all of the 3750 chips that can be supplied to factory 2 for March production are used. It is suggested that all the possible chips be obtained in March and those not used be saved for April production. Because chips must be kept in an air-controlled environment, it costs 1 dollar to store each chip purchased in March until April. The maximum number of chips that can be stored in this environment at each factory is 150. In addition, a search of the parts inventory at factory 1 turned up 15 chips available for their March production.

Nonarc variables are used in the side constraints that handle the limitations of supply of Gizmo chips. A nonarc variable called “f1 unused chips” has as a value the number of chips that are not used at factory 1 in March. Another nonarc variable, “f2 unused chips”, has as a value the number of chips that are not used at factory 2 in March. “f1 chips from mar” has as a value the number of chips left over from March used for production at factory 1 in April. Similarly, “f2 chips from mar” has as a value the number of chips left over from March used for April production at factory 2 in April. The last two nonarc variables have objective function coefficients of 1 and upper bounds of 150. The Gizmo side constraints are

```
3*prod f1 19 mar + 4*prod f1 25 mar + f1 unused chips = 2615
3*prod f2 19 apl + 4*prod f2 25 apl + f2 unused chips = 3750
3*prod f1 19 apl + 4*prod f1 25 apl - f1 chips from mar = 2600
3*prod f2 19 apl + 4*prod f2 25 apl - f2 chips from mar = 3750
f1 unused chips + f2 unused chips -
f1 chips from mar - f2 chips from mar >= 0
```

The last side constraint states that the number of chips not used in March is not less than the number of chips left over from March and used in April. Here, this constraint is called `CHIP LEFTOVER`.

The following SAS code creates a new data set containing constraint data. It seems that most of the constraints are now equalities, so you specify `DEFCONTYPE=EQ` in the `PROC NETFLOW` statements from now on and provide constraint type data for constraints that are not “equal to” type, using the default `TYPEOBS` value `_TYPE_` as the `_COLUMN_` variable value to indicate observations that contain constraint type data. Also, from now on, the default `RHSOBS` value is used.

```
title 'Nonarc Variables in the Side Constraints';
title2 'Production Planning/Inventory/Distribution';
data con6;
  input _column_ &$17. _row_ &$15. _coef_ ;
  datalines;
prod f1 19 mar      FACT1 MAR GIZMO  3
prod f1 25 mar      FACT1 MAR GIZMO  4
f1 unused chips     FACT1 MAR GIZMO  1
_RHS_               FACT1 MAR GIZMO 2615
prod f2 19 mar      FACT2 MAR GIZMO  3
prod f2 25 mar      FACT2 MAR GIZMO  4
f2 unused chips     FACT2 MAR GIZMO  1
_RHS_               FACT2 MAR GIZMO 3750
prod f1 19 apl      FACT1 APL GIZMO  3
prod f1 25 apl      FACT1 APL GIZMO  4
f1 chips from mar   FACT1 APL GIZMO -1
```

```

_RHS_          FACT1 APL GIZMO 2600
prod f2 19 apl  FACT2 APL GIZMO 3
prod f2 25 apl  FACT2 APL GIZMO 4
f2 chips from mar FACT2 APL GIZMO -1
_RHS_          FACT2 APL GIZMO 3750
f1 unused chips  CHIP LEFTOVER 1
f2 unused chips  CHIP LEFTOVER 1
f1 chips from mar CHIP LEFTOVER -1
f2 chips from mar CHIP LEFTOVER -1
_TYPE_          CHIP LEFTOVER 1
back f1 19 apl   TOTAL BACKORDER 1
back f1 25 apl   TOTAL BACKORDER 1
back f2 19 apl   TOTAL BACKORDER 1
back f2 25 apl   TOTAL BACKORDER 1
back f1 19 may   TOTAL BACKORDER 1
back f1 25 may   TOTAL BACKORDER 1
back f2 19 may   TOTAL BACKORDER 1
back f2 25 may   TOTAL BACKORDER 1
_TYPE_          TOTAL BACKORDER -1
_RHS_          TOTAL BACKORDER 50
;

```

The nonarc variables “f1 chips from mar” and “f2 chips from mar” have objective function coefficients of 1 and upper bounds of 150. There are various ways in which this information can be furnished to PROC NETFLOW. If there were a **TYPE** list variable in the **CONDATA=** data set, observations could be in the form

| <u>COLUMN</u>     | <u>TYPE</u> | <u>ROW</u> | <u>COEF</u> |
|-------------------|-------------|------------|-------------|
| f1 chips from mar | objfn       | .          | 1           |
| f1 chips from mar | upperbd     | .          | 150         |
| f2 chips from mar | objfn       | .          | 1           |
| f2 chips from mar | upperbd     | .          | 150         |

It is desirable to assign **ID** list variable values to all the nonarc variables:

```

data arc6;
  set con5;
  drop oldcost oldfc oldflow _flow_ _fcost_ _status_ _rcost_;
data arc6_b;
  length key_id $10;
  input _name_ &$17. _cost_ _capac_ factory key_id $ ;
  datalines;
f1 unused chips      .      . 1 chips
f2 unused chips      .      . 2 chips
f1 chips from mar    1 150 1 chips
f2 chips from mar    1 150 2 chips
;

proc append force nowarn
  base=arc6 data=arc6_b;
run;

proc netflow
  nodedata=node0 arcdata=arc6

```

```
condata=con6 defcontype=eq sparsecondata  
dualout=dual7 conout=con7;  
run;  
  
print nonarcs/short;
```

The following messages appear on the SAS log:

```
NOTE: Number of nodes= 21 .  
NOTE: Number of supply nodes= 4 .  
NOTE: Number of demand nodes= 5 .  
NOTE: Total supply= 4350 , total demand= 4350 .  
NOTE: Number of arcs= 68 .  
NOTE: Number of nonarc variables= 4 .  
NOTE: Number of iterations performed (neglecting any constraints)= 69 .  
NOTE: Of these, 1 were degenerate.  
NOTE: Optimum (neglecting any constraints) found.  
NOTE: Minimal total cost= -1295730.8 .  
NOTE: Number of <= side constraints= 1 .  
NOTE: Number of == side constraints= 4 .  
NOTE: Number of >= side constraints= 1 .  
NOTE: Number of arc and nonarc variable side constraint coefficients= 24 .  
NOTE: Number of iterations, optimizing with constraints= 13 .  
NOTE: Of these, 2 were degenerate.  
NOTE: Optimum reached.  
NOTE: Minimal total cost= -1295542.742 .  
NOTE: The data set WORK.CON7 has 68 observations and 18 variables.  
NOTE: The data set WORK.DUAL7 has 26 observations and 14 variables.
```

The output in [Output 7.8.1](#) is produced by

```
print nonarcs/short ;
```

**Output 7.8.1** Output of PRINT NONARCS/SHORT;

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |                   |        |          |      |         |
|--|-------------------|--------|----------|------|---------|
| The NETFLOW Procedure  |                   |        |          |      |         |
| _N_  | _name_            | _cost_ | _capac_  | _lo_ | _VALUE_ |
| 1  | f1 chips from mar | 1      | 150      | 0    | 20      |
| 2  | f1 unused chips   | 0      | 99999999 | 0    | 0       |
| 3  | f2 chips from mar | 1      | 150      | 0    | 0       |
| 4  | f2 unused chips   | 0      | 99999999 | 0    | 280     |

The optimal solution data sets, `CONOUT=CON7` in [Output 7.8.2](#) and [Output 7.8.3](#) and `DUALOUT=DUAL7` in [Output 7.8.4](#) follow.

```
proc print data=con7;
  sum _fcost_;
proc print data=dual7;
```

## Output 7.8.2 CONOUT=CON7

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |          |         |          |      |                |
|--|----------|----------|---------|----------|------|----------------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_  | _lo_ | _name_         |
| 1  | fact1_1  | f1_apr_1 | 78.60   | 600      | 50   | prod f1 19 apl |
| 2  | f1_mar_1 | f1_apr_1 | 15.00   | 50       | 0    |                |
| 3  | f1_may_1 | f1_apr_1 | 33.60   | 20       | 0    | back f1 19 may |
| 4  | f2_apr_1 | f1_apr_1 | 11.00   | 40       | 0    |                |
| 5  | fact1_2  | f1_apr_2 | 174.50  | 550      | 50   | prod f1 25 apl |
| 6  | f1_mar_2 | f1_apr_2 | 20.00   | 40       | 0    |                |
| 7  | f1_may_2 | f1_apr_2 | 49.20   | 15       | 0    | back f1 25 may |
| 8  | f2_apr_2 | f1_apr_2 | 21.00   | 25       | 0    |                |
| 9  | fact1_1  | f1_mar_1 | 127.90  | 500      | 50   | prod f1 19 mar |
| 10   | f1_apr_1 | f1_mar_1 | 33.60   | 20       | 0    | back f1 19 apl |
| 11   | f2_mar_1 | f1_mar_1 | 10.00   | 40       | 0    |                |
| 12   | fact1_2  | f1_mar_2 | 217.90  | 400      | 40   | prod f1 25 mar |
| 13   | f1_apr_2 | f1_mar_2 | 38.40   | 30       | 0    | back f1 25 apl |
| 14   | f2_mar_2 | f1_mar_2 | 20.00   | 25       | 0    |                |
| 15   | fact1_1  | f1_may_1 | 90.10   | 400      | 50   |                |
| 16   | f1_apr_1 | f1_may_1 | 12.00   | 50       | 0    |                |
| 17   | f2_may_1 | f1_may_1 | 13.00   | 40       | 0    |                |
| 18   | fact1_2  | f1_may_2 | 113.30  | 350      | 40   |                |
| 19   | f1_apr_2 | f1_may_2 | 18.00   | 40       | 0    |                |
| 20   | f2_may_2 | f1_may_2 | 13.00   | 25       | 0    |                |
| 21   | f1_apr_1 | f2_apr_1 | 11.00   | 99999999 | 0    |                |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_  |      |                |
| 1  | 1000     | .        | 540.000 | 42444.00 |      |                |
| 2  | .        | .        | 0.000   | 0.00     |      |                |
| 3  | .        | .        | 0.000   | 0.00     |      |                |
| 4  | .        | .        | 0.000   | 0.00     |      |                |
| 5  | 1000     | .        | 250.000 | 43625.00 |      |                |
| 6  | .        | .        | 0.000   | 0.00     |      |                |
| 7  | .        | .        | 0.000   | 0.00     |      |                |
| 8  | .        | .        | 25.000  | 525.00   |      |                |
| 9  | 1000     | .        | 338.333 | 43272.83 |      |                |
| 10   | .        | .        | 20.000  | 672.00   |      |                |
| 11   | .        | .        | 40.000  | 400.00   |      |                |
| 12   | 1000     | .        | 400.000 | 87160.00 |      |                |
| 13   | .        | .        | 30.000  | 1152.00  |      |                |
| 14   | .        | .        | 25.000  | 500.00   |      |                |
| 15   | 1000     | .        | 116.667 | 10511.67 |      |                |
| 16   | .        | .        | 0.000   | 0.00     |      |                |
| 17   | .        | .        | 0.000   | 0.00     |      |                |
| 18   | 1000     | .        | 350.000 | 39655.00 |      |                |
| 19   | .        | .        | 0.000   | 0.00     |      |                |
| 20   | .        | .        | 0.000   | 0.00     |      |                |
| 21   | .        | .        | 20.000  | 220.00   |      |                |



## Output 7.8.2 continued

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |          |         |           |      |                |
|--|----------|----------|---------|-----------|------|----------------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_   | _lo_ | _name_         |
| 22   | fact2_1  | f2_apr_1 | 62.40   | 480       | 35   | prod f2 19 apl |
| 23   | f2_mar_1 | f2_apr_1 | 18.00   | 30        | 0    |                |
| 24   | f2_may_1 | f2_apr_1 | 30.00   | 15        | 0    | back f2 19 may |
| 25   | f1_apr_2 | f2_apr_2 | 23.00   | 99999999  | 0    |                |
| 26   | fact2_2  | f2_apr_2 | 196.70  | 680       | 35   | prod f2 25 apl |
| 27   | f2_mar_2 | f2_apr_2 | 28.00   | 50        | 0    |                |
| 28   | f2_may_2 | f2_apr_2 | 64.80   | 15        | 0    | back f2 25 may |
| 29   | f1_mar_1 | f2_mar_1 | 11.00   | 99999999  | 0    |                |
| 30   | fact2_1  | f2_mar_1 | 88.00   | 450       | 35   | prod f2 19 mar |
| 31   | f2_apr_1 | f2_mar_1 | 20.40   | 15        | 0    | back f2 19 apl |
| 32   | f1_mar_2 | f2_mar_2 | 23.00   | 99999999  | 0    |                |
| 33   | fact2_2  | f2_mar_2 | 182.00  | 650       | 35   | prod f2 25 mar |
| 34   | f2_apr_2 | f2_mar_2 | 37.20   | 15        | 0    | back f2 25 apl |
| 35   | f1_may_1 | f2_may_1 | 16.00   | 99999999  | 0    |                |
| 36   | fact2_1  | f2_may_1 | 128.80  | 250       | 35   |                |
| 37   | f2_apr_1 | f2_may_1 | 20.00   | 30        | 0    |                |
| 38   | f1_may_2 | f2_may_2 | 26.00   | 99999999  | 0    |                |
| 39   | fact2_2  | f2_may_2 | 181.40  | 550       | 35   |                |
| 40   | f2_apr_2 | f2_may_2 | 38.00   | 50        | 0    |                |
| 41   | f1_mar_1 | shop1_1  | -327.65 | 250       | 0    |                |
| 42   | f1_apr_1 | shop1_1  | -300.00 | 250       | 0    |                |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_   |      |                |
| 22   | 850      | .        | 480.000 | 29952.00  |      |                |
| 23   | .        | .        | 0.000   | 0.00      |      |                |
| 24   | .        | .        | 0.000   | 0.00      |      |                |
| 25   | .        | .        | 0.000   | 0.00      |      |                |
| 26   | 1500     | .        | 577.500 | 113594.25 |      |                |
| 27   | .        | .        | 0.000   | 0.00      |      |                |
| 28   | .        | .        | 0.000   | 0.00      |      |                |
| 29   | .        | .        | 0.000   | 0.00      |      |                |
| 30   | 850      | .        | 290.000 | 25520.00  |      |                |
| 31   | .        | .        | 0.000   | 0.00      |      |                |
| 32   | .        | .        | 0.000   | 0.00      |      |                |
| 33   | 1500     | .        | 650.000 | 118300.00 |      |                |
| 34   | .        | .        | 0.000   | 0.00      |      |                |
| 35   | .        | .        | 115.000 | 1840.00   |      |                |
| 36   | 850      | .        | 35.000  | 4508.00   |      |                |
| 37   | .        | .        | 0.000   | 0.00      |      |                |
| 38   | .        | .        | 0.000   | 0.00      |      |                |
| 39   | 1500     | .        | 122.500 | 22221.50  |      |                |
| 40   | .        | .        | 0.000   | 0.00      |      |                |
| 41   | .        | 900      | 148.333 | -48601.42 |      |                |
| 42   | .        | 900      | 250.000 | -75000.00 |      |                |

## Output 7.8.2 continued

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |          |         |            |      |        |
|--|----------|----------|---------|------------|------|--------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_    | _lo_ | _name_ |
| 43   | f1_may_1 | shop1_1  | -285.00 | 250        | 0    |        |
| 44   | f2_mar_1 | shop1_1  | -297.40 | 250        | 0    |        |
| 45   | f2_apr_1 | shop1_1  | -290.00 | 250        | 0    |        |
| 46   | f2_may_1 | shop1_1  | -292.00 | 250        | 0    |        |
| 47   | f1_mar_2 | shop1_2  | -559.76 | 99999999   | 0    |        |
| 48   | f1_apr_2 | shop1_2  | -524.28 | 99999999   | 0    |        |
| 49   | f1_may_2 | shop1_2  | -515.02 | 99999999   | 0    |        |
| 50   | f2_mar_2 | shop1_2  | -567.83 | 500        | 0    |        |
| 51   | f2_apr_2 | shop1_2  | -542.19 | 500        | 0    |        |
| 52   | f2_may_2 | shop1_2  | -491.56 | 500        | 0    |        |
| 53   | f1_mar_1 | shop2_1  | -362.74 | 250        | 0    |        |
| 54   | f1_apr_1 | shop2_1  | -300.00 | 250        | 0    |        |
| 55   | f1_may_1 | shop2_1  | -245.00 | 250        | 0    |        |
| 56   | f2_mar_1 | shop2_1  | -272.70 | 250        | 0    |        |
| 57   | f2_apr_1 | shop2_1  | -312.00 | 250        | 0    |        |
| 58   | f2_may_1 | shop2_1  | -299.00 | 250        | 0    |        |
| 59   | f1_mar_2 | shop2_2  | -623.89 | 99999999   | 0    |        |
| 60   | f1_apr_2 | shop2_2  | -549.68 | 99999999   | 0    |        |
| 61   | f1_may_2 | shop2_2  | -500.00 | 99999999   | 0    |        |
| 62   | f2_mar_2 | shop2_2  | -542.83 | 500        | 0    |        |
| 63   | f2_apr_2 | shop2_2  | -559.19 | 500        | 0    |        |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_    |      |        |
| 43   | .        | 900      | 1.667   | -475.00    |      |        |
| 44   | .        | 900      | 250.000 | -74350.00  |      |        |
| 45   | .        | 900      | 250.000 | -72500.00  |      |        |
| 46   | .        | 900      | 0.000   | 0.00       |      |        |
| 47   | .        | 900      | 0.000   | 0.00       |      |        |
| 48   | .        | 900      | 0.000   | 0.00       |      |        |
| 49   | .        | 900      | 347.500 | -178969.45 |      |        |
| 50   | .        | 900      | 500.000 | -283915.00 |      |        |
| 51   | .        | 900      | 52.500  | -28464.98  |      |        |
| 52   | .        | 900      | 0.000   | 0.00       |      |        |
| 53   | .        | 900      | 250.000 | -90685.00  |      |        |
| 54   | .        | 900      | 250.000 | -75000.00  |      |        |
| 55   | .        | 900      | 0.000   | 0.00       |      |        |
| 56   | .        | 900      | 0.000   | 0.00       |      |        |
| 57   | .        | 900      | 250.000 | -78000.00  |      |        |
| 58   | .        | 900      | 150.000 | -44850.00  |      |        |
| 59   | .        | 1450     | 455.000 | -283869.95 |      |        |
| 60   | .        | 1450     | 245.000 | -134671.60 |      |        |
| 61   | .        | 1450     | 2.500   | -1250.00   |      |        |
| 62   | .        | 1450     | 125.000 | -67853.75  |      |        |
| 63   | .        | 1450     | 500.000 | -279595.00 |      |        |

**Output 7.8.2** *continued*

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |          |         |             |      |                   |
|--|----------|----------|---------|-------------|------|-------------------|
| Obs  | _tail_   | _head_   | _cost_  | _capac_     | _lo_ | _name_            |
| 64   | f2_may_2 | shop2_2  | -519.06 | 500         | 0    |                   |
| 65   |          |          | 1.00    | 150         | 0    | f1 chips from mar |
| 66   |          |          | 0.00    | 99999999    | 0    | f1 unused chips   |
| 67   |          |          | 1.00    | 150         | 0    | f2 chips from mar |
| 68   |          |          | 0.00    | 99999999    | 0    | f2 unused chips   |
| Obs  | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_     |      |                   |
| 64   | .        | 1450     | 122.500 | -63584.85   |      |                   |
| 65   | .        | .        | 20.000  | 20.00       |      |                   |
| 66   | .        | .        | 0.000   | 0.00        |      |                   |
| 67   | .        | .        | 0.000   | 0.00        |      |                   |
| 68   | .        | .        | 280.000 | 0.00        |      |                   |
|  |          |          |         | =====       |      |                   |
|  |          |          |         | -1295542.74 |      |                   |

**Output 7.8.3** CONOUT=CON7 (continued)

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |         |            |                  |
|--|----------|---------|------------|------------------|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_    | _STATUS_         |
| 1  | .        | 5       | 1          | KEY_ARC BASIC    |
| 2  | 66.150   | 6       | 7          | LOWERBD NONBASIC |
| 3  | 42.580   | 7       | 8          | LOWERBD NONBASIC |
| 4  | 22.000   | 8       | 9          | LOWERBD NONBASIC |
| 5  | .        | 19      | 4          | KEY_ARC BASIC    |
| 6  | 94.210   | 20      | 11         | LOWERBD NONBASIC |
| 7  | .        | 21      | 12         | NONKEY ARC BASIC |
| 8  | -1.510   | 22      | 13         | UPPERBD NONBASIC |
| 9  | .        | 9       | 1          | KEY_ARC BASIC    |
| 10   | -17.070  | 10      | 6          | UPPERBD NONBASIC |
| 11   | -34.750  | 11      | 14         | UPPERBD NONBASIC |
| 12   | -28.343  | 23      | 4          | UPPERBD NONBASIC |
| 13   | -35.330  | 24      | 10         | UPPERBD NONBASIC |
| 14   | -61.060  | 25      | 15         | UPPERBD NONBASIC |
| 15   | .        | 12      | 1          | KEY_ARC BASIC    |
| 16   | 3.500    | 13      | 6          | LOWERBD NONBASIC |
| 17   | 29.000   | 14      | 16         | LOWERBD NONBASIC |
| 18   | -15.520  | 26      | 4          | UPPERBD NONBASIC |
| 19   | 67.680   | 27      | 10         | LOWERBD NONBASIC |
| 20   | 32.060   | 28      | 17         | LOWERBD NONBASIC |
| 21   | .        | 15      | 6          | KEY_ARC BASIC    |
| Obs  | diagonal | factory | key_id     | mth_made         |
| 1  | 19       | 1       | production | April            |
| 2  | 19       | 1       | storage    | March            |
| 3  | 19       | 1       | backorder  | May              |
| 4  | 19       | .       | f2_to_1    | April            |
| 5  | 25       | 1       | production | April            |
| 6  | 25       | 1       | storage    | March            |
| 7  | 25       | 1       | backorder  | May              |
| 8  | 25       | .       | f2_to_1    | April            |
| 9  | 19       | 1       | production | March            |
| 10   | 19       | 1       | backorder  | April            |
| 11   | 19       | .       | f2_to_1    | March            |
| 12   | 25       | 1       | production | March            |
| 13   | 25       | 1       | backorder  | April            |
| 14   | 25       | .       | f2_to_1    | March            |
| 15   | 19       | 1       | production | May              |
| 16   | 19       | 1       | storage    | April            |
| 17   | 19       | .       | f2_to_1    | May              |
| 18   | 25       | 1       | production | May              |
| 19   | 25       | 1       | storage    | April            |
| 20   | 25       | .       | f2_to_1    | May              |
| 21   | 19       | .       | f1_to_2    | April            |

## Output 7.8.3 continued

Nonarc Variables in the Side Constraints  
Production Planning/Inventory/Distribution

| Obs | _RCOST_ | _ANUMB_ | _TNUMB_ | _STATUS_         |
|-----|---------|---------|---------|------------------|
| 22  | -35.592 | 16      | 3       | UPPERBD NONBASIC |
| 23  | 13.400  | 17      | 14      | LOWERBD NONBASIC |
| 24  | 43.980  | 18      | 16      | LOWERBD NONBASIC |
| 25  | 45.510  | 29      | 10      | LOWERBD NONBASIC |
| 26  | .       | 30      | 5       | KEY_ARC BASIC    |
| 27  | 43.660  | 31      | 15      | LOWERBD NONBASIC |
| 28  | 57.170  | 32      | 17      | LOWERBD NONBASIC |
| 29  | 55.750  | 33      | 7       | LOWERBD NONBASIC |
| 30  | .       | 34      | 3       | KEY_ARC BASIC    |
| 31  | 25.480  | 35      | 9       | LOWERBD NONBASIC |
| 32  | 104.060 | 36      | 11      | LOWERBD NONBASIC |
| 33  | -23.170 | 37      | 5       | UPPERBD NONBASIC |
| 34  | 22.020  | 38      | 13      | LOWERBD NONBASIC |
| 35  | .       | 39      | 8       | KEY_ARC BASIC    |
| 36  | 22.700  | 40      | 3       | LOWERBD NONBASIC |
| 37  | 6.500   | 41      | 9       | LOWERBD NONBASIC |
| 38  | 6.940   | 42      | 12      | LOWERBD NONBASIC |
| 39  | .       | 43      | 5       | KEY_ARC BASIC    |
| 40  | 46.110  | 44      | 13      | LOWERBD NONBASIC |
| 41  | .       | 45      | 7       | KEY_ARC BASIC    |
| 42  | -23.500 | 46      | 6       | UPPERBD NONBASIC |

| Obs | diagonal | factory | key_id     | mth_made |
|-----|----------|---------|------------|----------|
| 22  | 19       | 2       | production | April    |
| 23  | 19       | 2       | storage    | March    |
| 24  | 19       | 2       | backorder  | May      |
| 25  | 25       | .       | fl_to_2    | April    |
| 26  | 25       | 2       | production | April    |
| 27  | 25       | 2       | storage    | March    |
| 28  | 25       | 2       | backorder  | May      |
| 29  | 19       | .       | fl_to_2    | March    |
| 30  | 19       | 2       | production | March    |
| 31  | 19       | 2       | backorder  | April    |
| 32  | 25       | .       | fl_to_2    | March    |
| 33  | 25       | 2       | production | March    |
| 34  | 25       | 2       | backorder  | April    |
| 35  | 19       | .       | fl_to_2    | May      |
| 36  | 19       | 2       | production | May      |
| 37  | 19       | 2       | storage    | April    |
| 38  | 25       | .       | fl_to_2    | May      |
| 39  | 25       | 2       | production | May      |
| 40  | 25       | 2       | storage    | April    |
| 41  | 19       | 1       | sales      | March    |
| 42  | 19       | 1       | sales      | April    |

Output 7.8.3 continued

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |         |         |                  |          |         |        |          |  |
|--|----------|---------|---------|------------------|----------|---------|--------|----------|--|
| Obs  | _RCOST_  | _ANUMB_ | _TNUMB_ | _STATUS_         | diagonal | factory | key_id | mth_made |  |
| 43   | .        | 47      | 8       | NONKEY ARC BASIC | 19       | 1       | sales  | May      |  |
| 44   | -14.5000 | 48      | 14      | UPPERBD NONBASIC | 19       | 2       | sales  | March    |  |
| 45   | -2.5000  | 49      | 9       | UPPERBD NONBASIC | 19       | 2       | sales  | April    |  |
| 46   | 9.0000   | 50      | 16      | LOWERBD NONBASIC | 19       | 2       | sales  | May      |  |
| 47   | 79.1500  | 51      | 11      | LOWERBD NONBASIC | 25       | 1       | sales  | March    |  |
| 48   | 40.4200  | 52      | 10      | LOWERBD NONBASIC | 25       | 1       | sales  | April    |  |
| 49   | .        | 53      | 12      | KEY_ARC BASIC    | 25       | 1       | sales  | May      |  |
| 50   | -9.9800  | 54      | 15      | UPPERBD NONBASIC | 25       | 2       | sales  | March    |  |
| 51   | .        | 55      | 13      | KEY_ARC BASIC    | 25       | 2       | sales  | April    |  |
| 52   | 42.5200  | 56      | 17      | LOWERBD NONBASIC | 25       | 2       | sales  | May      |  |
| 53   | -37.0900 | 57      | 7       | UPPERBD NONBASIC | 19       | 1       | sales  | March    |  |
| 54   | -25.5000 | 58      | 6       | UPPERBD NONBASIC | 19       | 1       | sales  | April    |  |
| 55   | 38.0000  | 59      | 8       | LOWERBD NONBASIC | 19       | 1       | sales  | May      |  |
| 56   | 8.2000   | 60      | 14      | LOWERBD NONBASIC | 19       | 2       | sales  | March    |  |
| 57   | -26.5000 | 61      | 9       | UPPERBD NONBASIC | 19       | 2       | sales  | April    |  |
| 58   | .        | 62      | 16      | KEY_ARC BASIC    | 19       | 2       | sales  | May      |  |
| 59   | .        | 63      | 11      | KEY_ARC BASIC    | 25       | 1       | sales  | March    |  |
| 60   | .        | 64      | 10      | KEY_ARC BASIC    | 25       | 1       | sales  | April    |  |
| 61   | .        | 65      | 12      | NONKEY ARC BASIC | 25       | 1       | sales  | May      |  |
| 62   | .        | 66      | 15      | KEY_ARC BASIC    | 25       | 2       | sales  | March    |  |
| 63   | -32.0200 | 67      | 13      | UPPERBD NONBASIC | 25       | 2       | sales  | April    |  |
| 64   | .        | 68      | 17      | KEY_ARC BASIC    | 25       | 2       | sales  | May      |  |
| 65   | .        | -2      | .       | NONKEY BASIC     | .        | 1       | chips  |          |  |
| 66   | 1.6167   | 0       | .       | LOWERBD NONBASIC | .        | 1       | chips  |          |  |
| 67   | 2.7975   | -3      | .       | LOWERBD NONBASIC | .        | 2       | chips  |          |  |
| 68   | .        | -1      | .       | NONKEY BASIC     | .        | 2       | chips  |          |  |

## Output 7.8.4 DUALOUT=DUAL7

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |          |          |               |         |        |        |         |
|--|----------|----------|---------------|---------|--------|--------|---------|
| Obs  | _node_   | _supdem_ | _DUAL_        | _NNUMB_ | _PRED_ | _TRAV_ | _SCESS_ |
| 1  | f1_apr_1 | .        | -100000275.50 | 6       | 1      | 9      | 2       |
| 2  | f1_apr_2 | .        | -100000405.92 | 10      | 21     | 4      | 2       |
| 3  | f1_mar_1 | .        | -100000326.65 | 7       | 18     | 1      | 20      |
| 4  | f1_mar_2 | .        | -100000480.13 | 11      | 21     | 15     | 1       |
| 5  | f1_may_1 | .        | -100000284.00 | 8       | 1      | 16     | 3       |
| 6  | f1_may_2 | .        | -100000356.24 | 12      | 19     | 6      | 1       |
| 7  | f2_apr_1 | .        | -100000286.50 | 9       | 6      | 8      | 1       |
| 8  | f2_apr_2 | .        | -100000383.41 | 13      | 5      | 19     | 3       |
| 9  | f2_mar_1 | .        | -100000281.90 | 14      | 3      | 5      | 1       |
| 10   | f2_mar_2 | .        | -100000399.07 | 15      | 21     | 10     | 1       |
| 11   | f2_may_1 | .        | -100000300.00 | 16      | 8      | 20     | 2       |
| 12   | f2_may_2 | .        | -100000375.30 | 17      | 5      | 21     | 6       |
| 13   | fact1_1  | 1000     | -100000193.90 | 1       | 7      | 2      | 19      |
| 14   | fact1_2  | 1000     | -100000227.42 | 4       | 10     | 13     | 1       |
| 15   | fact2_1  | 850      | -100000193.90 | 3       | 2      | 14     | 2       |
| 16   | fact2_2  | 1500     | -100000193.90 | 5       | 2      | 17     | 10      |
| 17   | shop1_1  | -900     | -99999999.00  | 18      | 22     | 7      | 21      |
| 18   | shop1_2  | -900     | -99999841.22  | 19      | 13     | 12     | 2       |
| 19   | shop2_1  | -900     | -100000001.00 | 20      | 16     | 22     | 1       |
| 20   | shop2_2  | -1450    | -99999856.24  | 21      | 17     | 11     | 5       |
| 21   | .        | .        | 0.00          | 4       | 4      | .      | 4       |

| Obs | _ARCID_ | _FLOW_  | _FBQ_ | _VALUE_ | _RHS_ | _TYPE_ | _row_         |
|-----|---------|---------|-------|---------|-------|--------|---------------|
| 1   | 5       | 490.000 | 5     | .       | .     |        |               |
| 2   | -64     | 245.000 | 19    | .       | .     |        |               |
| 3   | -45     | 148.333 | 9     | .       | .     |        |               |
| 4   | -63     | 455.000 | 23    | .       | .     |        |               |
| 5   | 12      | 66.667  | 12    | .       | .     |        |               |
| 6   | -53     | 347.500 | 26    | .       | .     |        |               |
| 7   | 15      | 20.000  | 15    | .       | .     |        |               |
| 8   | 30      | 542.500 | 29    | .       | .     |        |               |
| 9   | 34      | 255.000 | 33    | .       | .     |        |               |
| 10  | -66     | 125.000 | 36    | .       | .     |        |               |
| 11  | 39      | 115.000 | 39    | .       | .     |        |               |
| 12  | 43      | 87.500  | 42    | .       | .     |        |               |
| 13  | -9      | 288.333 | -1    | .       | .     |        |               |
| 14  | -19     | 200.000 | -5    | .       | .     |        |               |
| 15  | -2      | 45.000  | -5    | .       | .     |        |               |
| 16  | -4      | 150.000 | -5    | .       | .     |        |               |
| 17  | 0       | 0.000   | 45    | .       | .     |        |               |
| 18  | 55      | 52.500  | 51    | .       | .     |        |               |
| 19  | 62      | 150.000 | 57    | .       | .     |        |               |
| 20  | 68      | 122.500 | 63    | .       | .     |        |               |
| 21  | .       | 260.000 | .     | 260     | 0     | GE     | CHIP LEFTOVER |

Output 7.8.4 continued

| Nonarc Variables in the Side Constraints<br>Production Planning/Inventory/Distribution |         |          |        |         |        |        |                 |
|--|---------|----------|--------|---------|--------|--------|-----------------|
| Obs  | _node_  | _supdem_ | _DUAL_ | _NNUMB_ | _PRED_ | _TRAV_ | _SCESS_         |
| 22   |         | .        | -1.00  | 2       | 2      | .      | .               |
| 23   |         | .        | -1.62  | 0       | 18     | .      | .               |
| 24   |         | .        | 1.80   | 3       | 21     | .      | .               |
| 25   |         | .        | 0.00   | 1       | 1      | .      | .               |
| 26   |         | .        | -0.48  | 5       | 10     | .      | .               |
| Obs  | _ARCID_ | _FLOW_   | _FBQ_  | _VALUE_ | _RHS_  | _TYPE_ | _row_           |
| 22   | -2      | 20.000   | .      | 2600    | 2600   | EQ     | FACT1 APL GIZMO |
| 23   | 47      | 1.667    | .      | 2615    | 2615   | EQ     | FACT1 MAR GIZMO |
| 24   | 65      | 2.500    | .      | 3750    | 3750   | EQ     | FACT2 APL GIZMO |
| 25   | -1      | 280.000  | .      | 3750    | 3750   | EQ     | FACT2 MAR GIZMO |
| 26   | 21      | 0.000    | .      | 50      | 50     | LE     | TOTAL BACKORDER |

The optimal value of the nonarc variable “f2 unused chips” is 280. This means that although there are 3750 chips that can be used at factory 2 in March, only 3470 are used. As the optimal value of “f1 unused chips” is zero, all chips available for production in March at factory 1 are used. The nonarc variable “f2 chips from mar” also has zero optimal value. This means that the April production at factory 2 does not need any chips that could have been held in inventory since March. However, the nonarc variable “f1 chips from mar” has value of 20. Thus, 3490 chips should be ordered for factory 2 in March. Twenty of these chips should be held in inventory until April, then sent to factory 1.

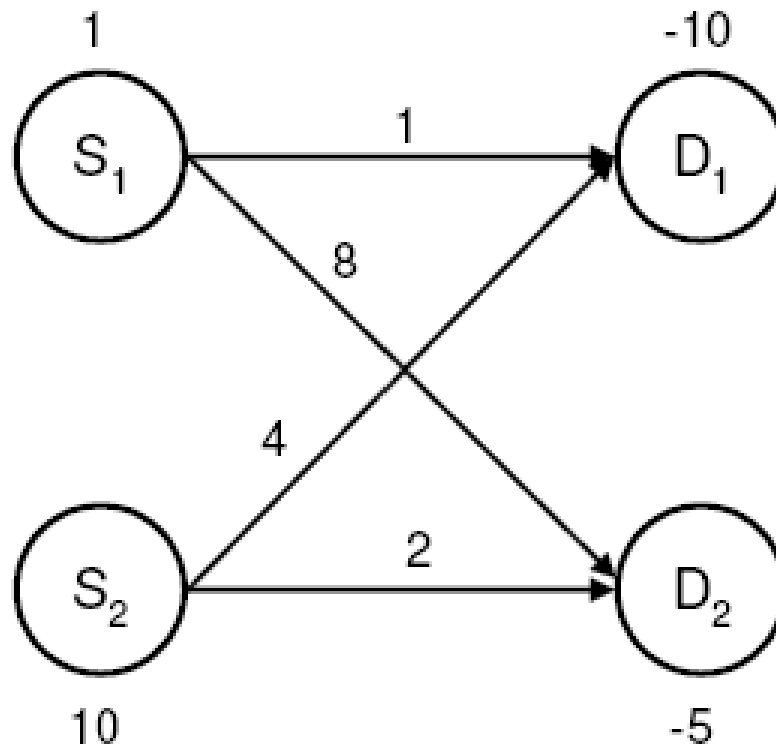
### Example 7.9: Pure Networks: Using the EXCESS= Option

In this example we illustrate the use of the EXCESS= option for various scenarios in pure networks. Consider a simple network as shown in [Output 7.9.1](#). The positive numbers on the nodes correspond to supply and the negative numbers correspond to demand. The numbers on the arcs indicate costs.

#### Transportation Problem, Total Supply < Total Demand

We first analyze a simple transportation problem where total demand exceeds total supply, as seen in [Output 7.9.1](#). The EXCESS=SLACKS option is illustrated first.



**Output 7.9.1** Transportation Problem

The following SAS code creates the input data sets.

```

data parcs;
    input _from_ $ _to_ $ _cost_;
datalines;
s1 d1 1
s1 d2 8
s2 d1 4
s2 d2 2
;

data S1eD;
    input _node_ $ _sd_;
datalines;
s1 1
s2 10
d1 -10
d2 -5
;
  
```

You can solve the problem using the following call to PROC NETFLOW:

```
title1 'The NETFLOW Procedure';
proc netflow
  excess    = slacks
  arcdata   = parcs
  nodedata  = S1eD
  conout    = solex1;
run;
```

Since the EXCESS=SLACKS option is specified, the interior point method is used for optimization. Accordingly, the CONOUT= data set is specified. The optimal solution is displayed in [Output 7.9.2](#).

**Output 7.9.2** Supply < Demand

| The NETFLOW Procedure |        |      |        |          |      |          |          |        |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|--------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 1        | 10       | 1      | 1       |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 10       | 10       | 5      | 20      |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 1        | 5        | 0      | 0       |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 10       | 5        | 5      | 10      |

The solution with the THRUNET option specified is displayed in [Output 7.9.3](#).

```
title1 'The NETFLOW Procedure';
proc netflow
  thrunet
  excess    = slacks
  arcdata   = parcs
  nodedata  = S1eD
  conout    = solex1t;
run;
```

**Output 7.9.3** Supply < Demand, THRUNET Specified

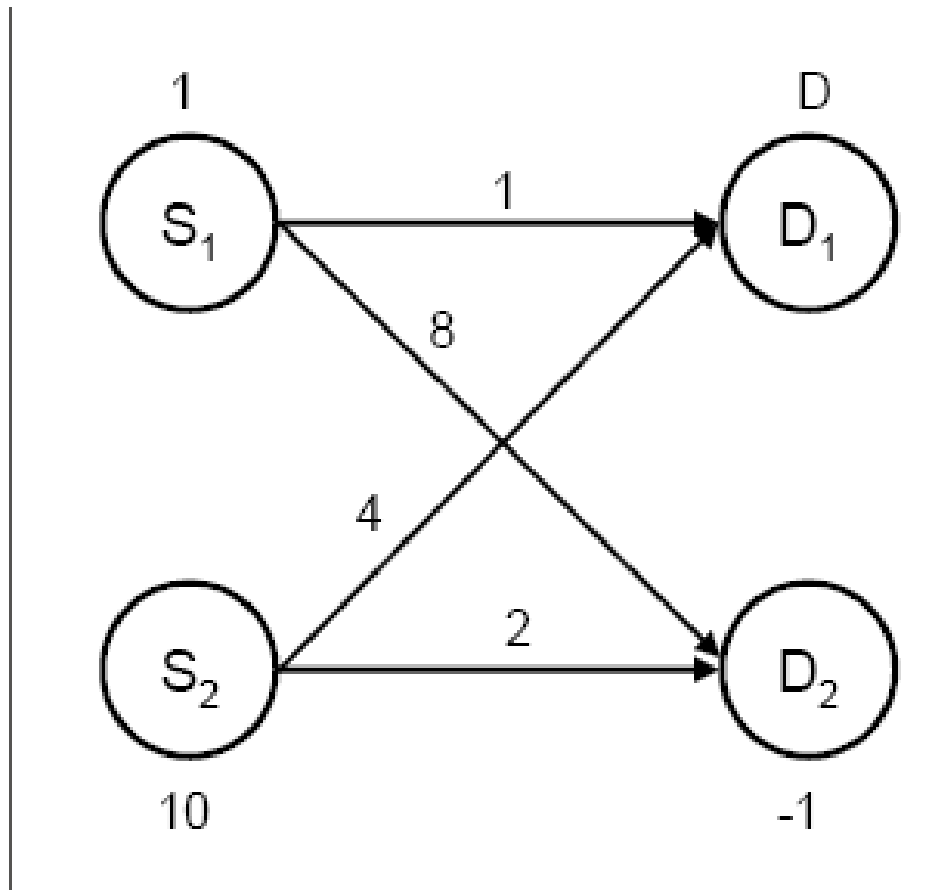
| The NETFLOW Procedure |        |      |        |          |      |          |          |        |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|--------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 1        | 10       | 5      | 5       |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 10       | 10       | 5      | 20      |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 1        | 5        | 0      | 0       |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 10       | 5        | 5      | 10      |

**NOTE:** If you want to use the network simplex solver instead, you need to specify the EXCESS=ARCS option and, accordingly, the ARCOUT= data set.

## Missing D Demand

As shown in [Output 7.9.4](#), node  $D_1$  has a missing D demand value.

**Output 7.9.4** Missing D Demand



The following code creates the node data set:

```

data node_missingD1;
    input _node_ $ _sd_;
    missing D;
datalines;
s1 1
s2 10
d1 D
d2 -1
;

```

You can use the following call to PROC NETFLOW to solve the problem:

```

title1 'The NETFLOW Procedure';
proc netflow
    excess    = slacks
    arcdata   = parcs
    nodedata  = node_missingD1
    conout    = solex1b;
run;

```

The optimal solution is displayed in [Output 7.9.5](#). As you can see, the flow balance at nodes with nonmissing `supdem` values is maintained. In other words, if a node has a nonmissing supply (demand) value, then the sum of flows out of (into) that node is equal to its `supdem` value.

**Output 7.9.5** THRUNET Not Specified

| The NETFLOW Procedure |        |      |        |          |      |          |          |        |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|--------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 1        | D        | 1      | 1       |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 10       | D        | 9      | 36      |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 1        | 1        | 0      | 0       |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 10       | 1        | 1      | 2       |

### Missing D Demand, THRUNET Specified

Consider the previous example, but with the THRUNET option specified.

```

title1 'The NETFLOW Procedure';
proc netflow
  thrUNET
  excess    = slacks
  arcdata   = parcs
  nodedata  = node_missingD1
  conout    = solex1c;
run;

```

The optimal solution is displayed in [Output 7.9.6](#). By specifying the THRUNET option, we have actually obtained the minimum-cost flow through the network, while maintaining flow balance at the nodes with nonmissing supply values.

**Output 7.9.6** Missing D Demand, THRUNET Specified

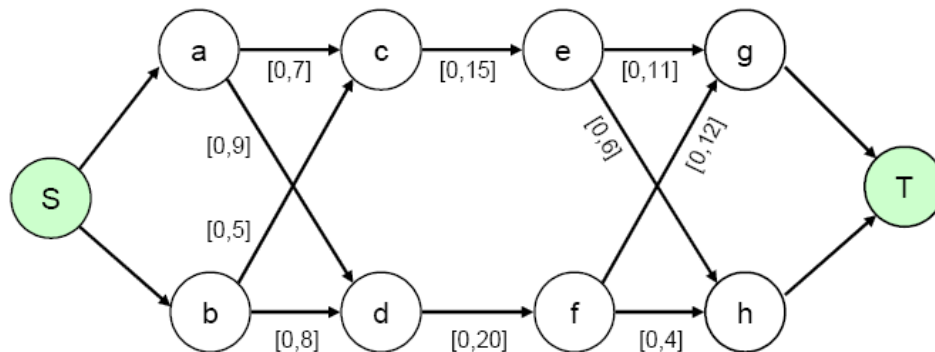
| The NETFLOW Procedure |        |      |        |          |      |          |          |        |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|--------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 1        | D        | 1      | 1       |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 10       | D        | 0      | 0       |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 1        | 1        | 0      | 0       |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 10       | 1        | 10     | 20      |

**NOTE:** The case with missing S supply values is similar to the case with missing D demand values.

## Example 7.10: Maximum Flow Problem

Consider the maximum flow problem depicted in [Output 7.10.1](#). The maximum flow between nodes S and T is to be determined. The minimum arc flow and arc capacities are specified as lower and upper bounds in square brackets, respectively.

**Output 7.10.1** Maximum Flow Problem Example



You can solve the problem using either EXCESS=ARCS or EXCESS=SLACKS. Consider using the EXCESS=ARCS option first. You can use the following SAS code to create the input data set:

```

data arcs;
  input _from_ $ _to_ $ _cost_ _capac_;
datalines;
S a . .
S b . .
a c 1 7
b c 2 9
a d 3 5
b d 4 8
c e 5 15
d f 6 20
e g 7 11
f g 8 6
e h 9 12
f h 10 4
g T . .
h T . .
;

```

You can use the following call to PROC NETFLOW to solve the problem:

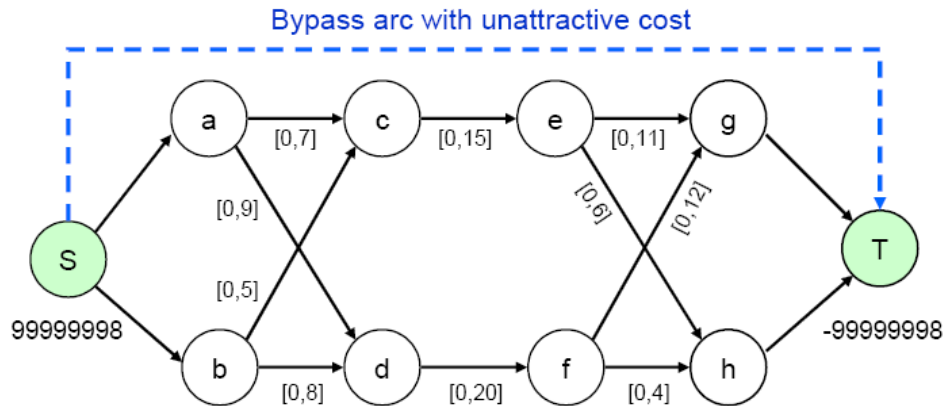
```

title1 'The NETFLOW Procedure';
proc netflow
  intpoint
  maxflow
  excess = arcs
  arcdata = arcs
  source = S    sink = T
  conout  = gout3;
run;

```

With the EXCESS=ARCS option specified, the problem gets transformed internally to the one depicted in [Output 7.10.2](#). Note that there is an additional arc from the source node to the sink node.

**Output 7.10.2** Maximum Flow Problem, EXCESS=ARCS Option Specified



The output SAS data set is displayed in [Output 7.10.3](#).

**Output 7.10.3** Maximum Flow Problem, EXCESS=ARCS Option Specified

| The NETFLOW Procedure |        |      |        |          |      |          |          |         |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _capac_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | g      | T    | 0      | 99999999 | 0    | .        | 99999998 | 16.9996 | 0.0000  |
| 2                     | h      | T    | 0      | 99999999 | 0    | .        | 99999998 | 8.0004  | 0.0000  |
| 3                     | S      | a    | 0      | 99999999 | 0    | 99999998 | .        | 11.9951 | 0.0000  |
| 4                     | S      | b    | 0      | 99999999 | 0    | 99999998 | .        | 13.0049 | 0.0000  |
| 5                     | a      | c    | 1      | 7        | 0    | .        | .        | 6.9952  | 6.9952  |
| 6                     | b      | c    | 2      | 9        | 0    | .        | .        | 8.0048  | 16.0097 |
| 7                     | a      | d    | 3      | 5        | 0    | .        | .        | 4.9999  | 14.9998 |
| 8                     | b      | d    | 4      | 8        | 0    | .        | .        | 5.0001  | 20.0002 |
| 9                     | c      | e    | 5      | 15       | 0    | .        | .        | 15.0000 | 75.0000 |
| 10                    | d      | f    | 6      | 20       | 0    | .        | .        | 10.0000 | 60.0000 |
| 11                    | e      | g    | 7      | 11       | 0    | .        | .        | 10.9996 | 76.9975 |
| 12                    | f      | g    | 8      | 6        | 0    | .        | .        | 6.0000  | 48.0000 |
| 13                    | e      | h    | 9      | 12       | 0    | .        | .        | 4.0004  | 36.0032 |
| 14                    | f      | h    | 10     | 4        | 0    | .        | .        | 4.0000  | 40.0000 |

You can solve the same maximum flow problem, but this time with EXCESS=SLACKS specified. The SAS code is as follows:

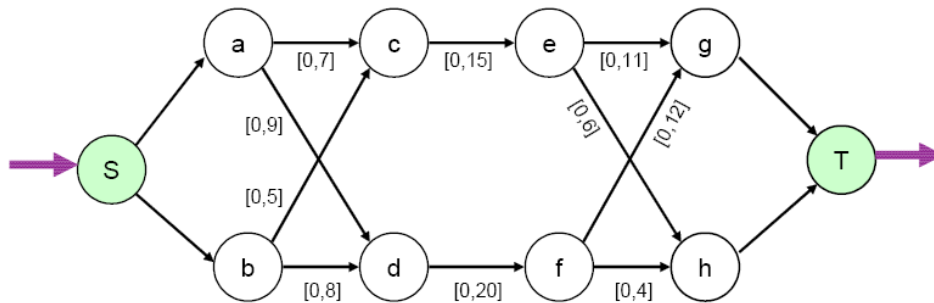
```

title1 'The NETFLOW Procedure';
proc netflow
  intpoint
  excess = slacks
  arcdata = arcs
  source = S    sink = T
  maxflow
  conout = gout3b;
run;

```

With the EXCESS=SLACKS option specified, the problem gets transformed internally to the one depicted in Figure 7.10.4. Note that the source node and sink node each have a single-ended “excess” arc attached to them.

**Output 7.10.4** Maximum Flow Problem, EXCESS=SLACKS Option Specified



The solution, as displayed in Output 7.10.5, is the same as before. Note that the `_SUPPLY_` value of the source node Y has changed from 99999998 to missing S, and the `_DEMAND_` value of the sink node Z has changed from -99999998 to missing D.

**Output 7.10.5** Maximal Flow Problem

| The NETFLOW Procedure |        |      |        |          |      |          |          |         |         |
|-----------------------|--------|------|--------|----------|------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _capac_  | _LO_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | g      | T    | 0      | 99999999 | 0    | .        | D        | 16.9993 | 0.0000  |
| 2                     | h      | T    | 0      | 99999999 | 0    | .        | D        | 8.0007  | 0.0000  |
| 3                     | S      | a    | 0      | 99999999 | 0    | S        | .        | 11.9867 | 0.0000  |
| 4                     | S      | b    | 0      | 99999999 | 0    | S        | .        | 13.0133 | 0.0000  |
| 5                     | a      | c    | 1      | 7        | 0    | .        | .        | 6.9868  | 6.9868  |
| 6                     | b      | c    | 2      | 9        | 0    | .        | .        | 8.0132  | 16.0264 |
| 7                     | a      | d    | 3      | 5        | 0    | .        | .        | 4.9999  | 14.9998 |
| 8                     | b      | d    | 4      | 8        | 0    | .        | .        | 5.0001  | 20.0002 |
| 9                     | c      | e    | 5      | 15       | 0    | .        | .        | 15.0000 | 75.0000 |
| 10                    | d      | f    | 6      | 20       | 0    | .        | .        | 10.0000 | 60.0000 |
| 11                    | e      | g    | 7      | 11       | 0    | .        | .        | 10.9993 | 76.9953 |
| 12                    | f      | g    | 8      | 6        | 0    | .        | .        | 6.0000  | 48.0000 |
| 13                    | e      | h    | 9      | 12       | 0    | .        | .        | 4.0007  | 36.0061 |
| 14                    | f      | h    | 10     | 4        | 0    | .        | .        | 4.0000  | 40.0000 |

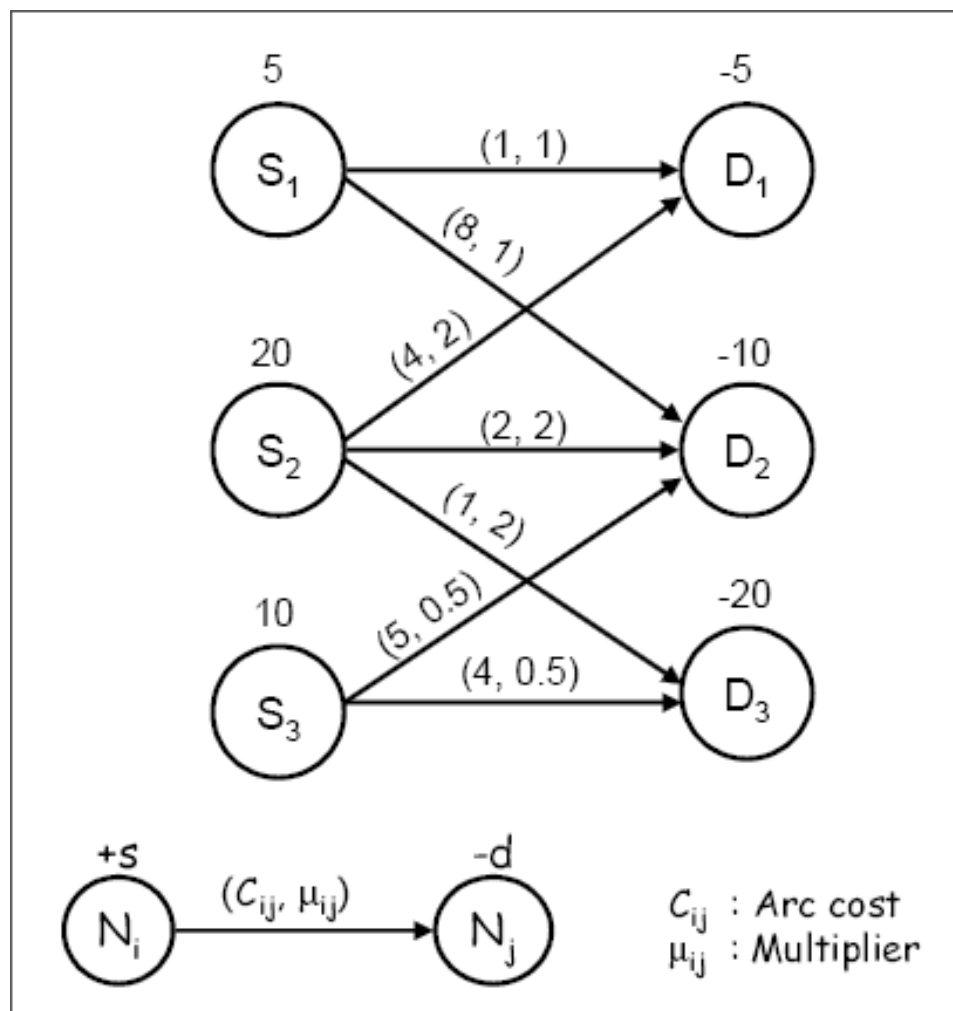
### Example 7.11: Generalized Networks: Using the EXCESS= Option

For generalized networks you can specify either EXCESS=SUPPLY or EXCESS=DEMAND to indicate which nodal flow conservation constraints have slack variables associated with them. The default option is EXCESS=NONE.

#### Using the EXCESS=SUPPLY Option

Consider the simple network shown in [Output 7.11.1](#). As you can see, the sum of positive supdem values (35) is equal to the absolute sum of the negative ones. However, the arcs connecting the supply and demand nodes have varying arc multipliers. Let us now solve the problem using the EXCESS=SUPPLY option.

**Output 7.11.1** Generalized Network: Supply = Demand



You can use the following SAS code to create the input data sets:



```

data garcs;
    input _from_ $ _to_ $ _cost_ _mult_;
datalines;
s1 d1 1 .
s1 d2 8 .
s2 d1 4 2
s2 d2 2 2
s2 d3 1 2
s3 d2 5 0.5
s3 d3 4 0.5
;

data gnodes;
    input _node_ $ _sd_ ;
datalines;
s1 5
s2 20
s3 10
d1 -5
d2 -10
d3 -20
;

```

To solve the problem, use the following call to PROC NETFLOW:

```

title1 'The NETFLOW Procedure';
proc netflow
    arcdata = garcs
    nodedata = gnodes
    excess = supply
    conout = gnetout;
run;

```

The optimal solution is displayed in [Output 7.11.2](#).

**Output 7.11.2** Optimal Solution Obtained Using the EXCESS=SUPPLY Option

| The NETFLOW Procedure |        |      |        |          |      |        |          |          |        |         |
|-----------------------|--------|------|--------|----------|------|--------|----------|----------|--------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _mult_ | _SUPPLY_ | _DEMAND_ | _FLOW_ | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 1.0    | 5        | 5        | 5      | 5       |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 2.0    | 20       | 5        | 0      | 0       |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 1.0    | 5        | 10       | 0      | 0       |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 2.0    | 20       | 10       | 5      | 10      |
| 5                     | s3     | d2   | 5      | 99999999 | 0    | 0.5    | 10       | 10       | 0      | 0       |
| 6                     | s2     | d3   | 1      | 99999999 | 0    | 2.0    | 20       | 20       | 10     | 10      |
| 7                     | s3     | d3   | 4      | 99999999 | 0    | 0.5    | 10       | 20       | 0      | 0       |

**NOTE:** If you do not specify the EXCESS= option, or if you specify the EXCESS=DEMAND option, the procedure will declare the problem infeasible. Therefore, in case of real-life problems, you would need to have a little more detail about how the arc multipliers end up affecting the network — whether they tend to create excess demand or excess supply.

### Using the EXCESS=DEMAND Option

Consider the previous example but with a slight modification: the arcs out of node  $S_1$  have multipliers of 0.5, and the arcs out of node  $S_2$  have multipliers of 1. You can use the following SAS code to create the input arc data set:

```
data garcs1;
    input _from_ $ _to_ $ _cost_ _mult_;
datalines;
s1 d1 1 0.5
s1 d2 8 0.5
s2 d1 4 .
s2 d2 2 .
s2 d3 1 .
s3 d2 5 0.5
s3 d3 4 0.5
;
```

Note that the node data set remains unchanged. You can use the following call to PROC NETFLOW to solve the problem:

```
title1 'The NETFLOW Procedure';
proc netflow
    arcdata = garcs1
    nodedata = gnodes
    excess = demand
    conout = gnetout1;
run;
```

The optimal solution is displayed in [Output 7.11.3](#).

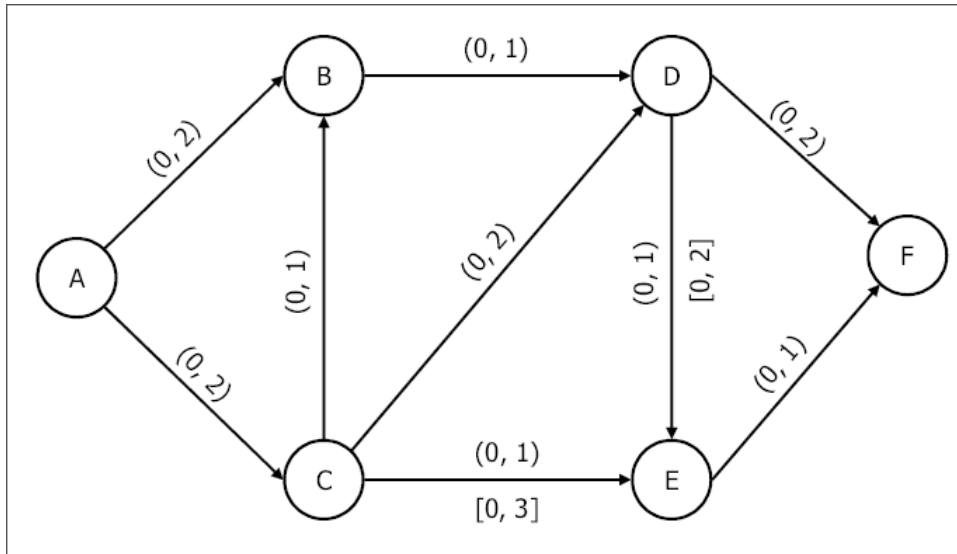
**Output 7.11.3** Optimal Solution Obtained Using the EXCESS=DEMAND Option

| The NETFLOW Procedure |        |      |        |          |      |        |          |          |         |         |
|-----------------------|--------|------|--------|----------|------|--------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _mult_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | s1     | d1   | 1      | 99999999 | 0    | 0.5    | 5        | 5        | 5.0000  | 5.0000  |
| 2                     | s2     | d1   | 4      | 99999999 | 0    | 1.0    | 20       | 5        | 0.0000  | 0.0000  |
| 3                     | s1     | d2   | 8      | 99999999 | 0    | 0.5    | 5        | 10       | 0.0000  | 0.0000  |
| 4                     | s2     | d2   | 2      | 99999999 | 0    | 1.0    | 20       | 10       | 5.0000  | 10.0000 |
| 5                     | s3     | d2   | 5      | 99999999 | 0    | 0.5    | 10       | 10       | 0.0000  | 0.0000  |
| 6                     | s2     | d3   | 1      | 99999999 | 0    | 1.0    | 20       | 20       | 15.0000 | 15.0000 |
| 7                     | s3     | d3   | 4      | 99999999 | 0    | 0.5    | 10       | 20       | 10.0000 | 40.0000 |

## Example 7.12: Generalized Networks: Maximum Flow Problem

Consider the generalized network displayed in [Output 7.12.1](#). Lower and upper bounds of the flow are displayed in parentheses above the arc, and cost and multiplier, where applicable, are indicated in square brackets below the arc.

**Output 7.12.1** Generalized Maximum Flow Problem



You can enter the data for the problem using the following SAS code:

```
data garcsM;
  input _from_ $ _to_ $ _upper_ _mult_;
datalines;
A B 2 .
A C 2 .
C B 1 .
B D 1 .
C D 2 .
C E 1 3
D E 1 2
E F 5 .
D F 2 .
;
```

Use the following call to PROC NETFLOW:

```
title1 'The NETFLOW Procedure';
proc netflow
  arcdata = garcsM
  maxflow
  source  = A  sink = F
  conout  = gmfput;
run;
```

The optimal solution is displayed in [Output 7.12.2](#).

**Output 7.12.2** Generalized Maximum Flow Problem: Optimal Solution

| The NETFLOW Procedure |        |      |        |         |      |        |          |          |         |         |
|-----------------------|--------|------|--------|---------|------|--------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _COST_ | _upper_ | _LO_ | _mult_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | A      | B    | 0      | 2       | 0    | 1      | S        | .        | 1.00000 | 0       |
| 2                     | C      | B    | 0      | 1       | 0    | 1      | .        | .        | 0.00000 | 0       |
| 3                     | A      | C    | 0      | 2       | 0    | 1      | S        | .        | 2.00000 | 0       |
| 4                     | B      | D    | 0      | 1       | 0    | 1      | .        | .        | 1.00000 | 0       |
| 5                     | C      | D    | 0      | 2       | 0    | 1      | .        | .        | 1.00000 | 0       |
| 6                     | C      | E    | 0      | 1       | 0    | 3      | .        | .        | 1.00000 | 0       |
| 7                     | D      | E    | 0      | 1       | 0    | 2      | .        | .        | 1.00000 | 0       |
| 8                     | E      | F    | 0      | 5       | 0    | 1      | .        | D        | 5.00000 | 0       |
| 9                     | D      | F    | 0      | 2       | 0    | 1      | .        | D        | 1.00000 | 0       |

### Example 7.13: Machine Loading Problem

Machine loading problems arise in a variety of applications. Consider a simple instance as described in Ahuja, Magnanti, and Orlin (1993). Assume you need to schedule the production of three products,  $P1 - P3$ , on four machines,  $M1 - M4$ . Suppose that machine 1 and machine 2 are each available for 40 hours and machine 3 and machine 4 are each available for 50 hours. Also, any of the machines can produce any product. The per-unit processing time and production cost for each product on each machine are indicated in [Table 7.14](#).

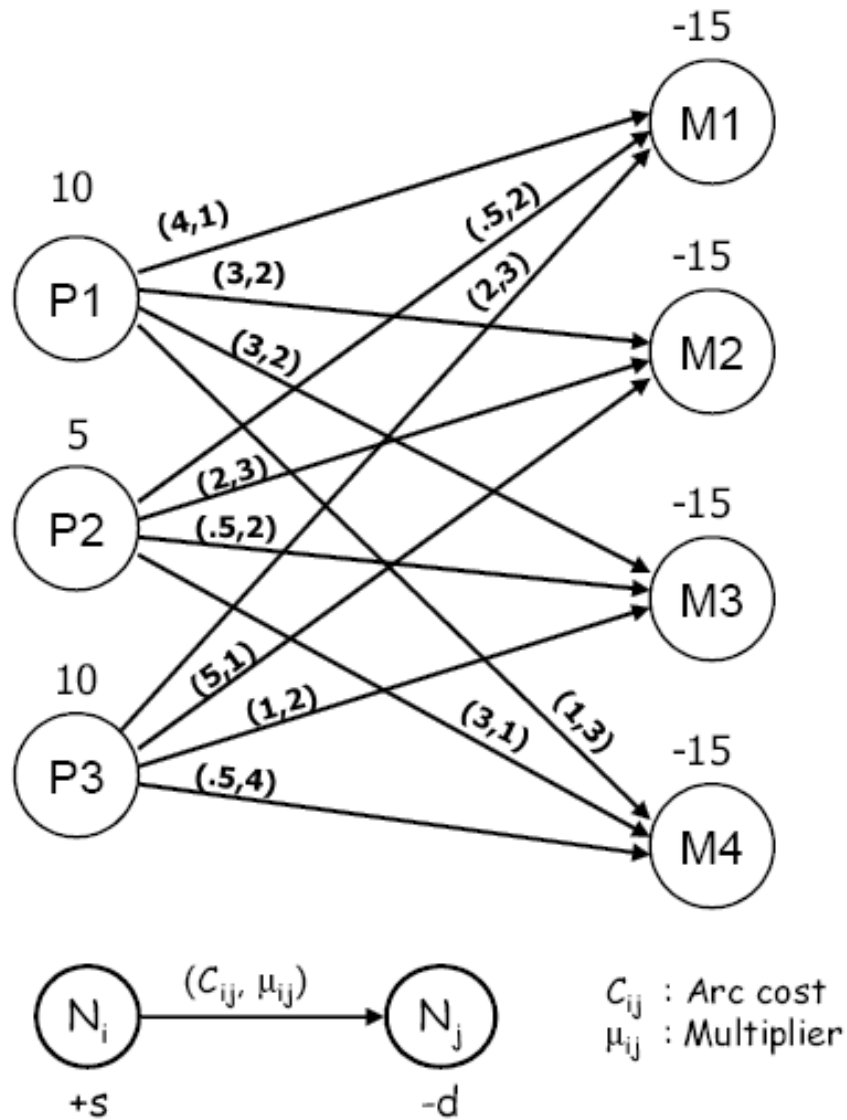
**Table 7.14** Processing Times and Production Costs

|           | M1 | M2 | M3 | M4 |
|-----------|----|----|----|----|
| <b>P1</b> | 1  | 2  | 2  | 3  |
| <b>P2</b> | 2  | 3  | 2  | 1  |
| <b>P3</b> | 3  | 1  | 2  | 4  |

|           | M1  | M2 | M3  | M4 |
|-----------|-----|----|-----|----|
| <b>P1</b> | 4   | 3  | 3   | 1  |
| <b>P2</b> | 0.5 | 2  | 0.5 | 3  |
| <b>P3</b> | 2   | 5  | 1   | 5  |

The problem is to satisfy the demands for the three products at minimum cost.

You can model this problem as a generalized network as shown in [Output 7.13.1](#). The network has three product nodes with demands indicated by positive `supdem` values and four machine nodes with availabilities (in hours) indicated by negative `supdem` values. The multiplier on an arc between a machine and a product indicates the hours of machine capacity needed to produce one unit of the product.

**Output 7.13.1** Machine Loading Problem

You can create the input data sets with the following SAS code:

```
data mlarcs;
  input _from_ $ _to_ $ _cost_ _mult_;
datalines;
P1 M1 4 .
P1 M2 3 2
P1 M3 3 2
P1 M4 1 3
P2 M1 .5 2
P2 M2 2 3
P2 M3 .5 2
P2 M4 3 1
P3 M1 2 3
```

```

P3  M2    5    .
P3  M3    1    2
P3  M4    .5    4
;

data mlnodes;
    input _node_ $ _sd_;
datalines;
P1    10
P2     5
P3    10
M1   -40
M2   -40
M3   -50
M4   -50
;

```

You can solve the problem using the following call to PROC NETFLOW:

```

title1 'The NETFLOW Procedure';
proc netflow
    excess    = demand
    arcdata   = mlarcs
    nodedata  = mlnodes
    conout    = mlsol;
run;

```

The optimal solution, as displayed in [Output 7.13.2](#), can be interpreted as follows:

- Product 1: 10 units on machine 4
- Product 2: 3 units on machine 1, and 2 units on machine 3
- Product 3: 5 units on machine 3, and 5 units on machine 4

**Output 7.13.2** Optimum Solution to the Machine Loading Problem

| The NETFLOW Procedure |        |      |        |          |      |        |          |          |         |         |
|-----------------------|--------|------|--------|----------|------|--------|----------|----------|---------|---------|
| Obs                   | _from_ | _to_ | _cost_ | _CAPAC_  | _LO_ | _mult_ | _SUPPLY_ | _DEMAND_ | _FLOW_  | _FCOST_ |
| 1                     | P1     | M1   | 4.0    | 99999999 | 0    | 1      | 10       | 40       | 0.00000 | 0.00000 |
| 2                     | P2     | M1   | 0.5    | 99999999 | 0    | 2      | 5        | 40       | 3.67856 | 1.83928 |
| 3                     | P3     | M1   | 2.0    | 99999999 | 0    | 3      | 10       | 40       | 0.00000 | 0.00000 |
| 4                     | P1     | M2   | 3.0    | 99999999 | 0    | 2      | 10       | 40       | 0.00000 | 0.00000 |
| 5                     | P2     | M2   | 2.0    | 99999999 | 0    | 3      | 5        | 40       | 0.00000 | 0.00000 |
| 6                     | P3     | M2   | 5.0    | 99999999 | 0    | 1      | 10       | 40       | 0.00000 | 0.00000 |
| 7                     | P1     | M3   | 3.0    | 99999999 | 0    | 2      | 10       | 50       | 0.00000 | 0.00000 |
| 8                     | P2     | M3   | 0.5    | 99999999 | 0    | 2      | 5        | 50       | 1.32144 | 0.66072 |
| 9                     | P3     | M3   | 1.0    | 99999999 | 0    | 2      | 10       | 50       | 5.00000 | 5.00000 |
| 10                    | P1     | M4   | 1.0    | 99999999 | 0    | 3      | 10       | 50       | 10.0000 | 10.0000 |
| 11                    | P2     | M4   | 3.0    | 99999999 | 0    | 1      | 5        | 50       | 0.00000 | 0.00000 |
| 12                    | P3     | M4   | 0.5    | 99999999 | 0    | 4      | 10       | 50       | 5.00000 | 2.50000 |

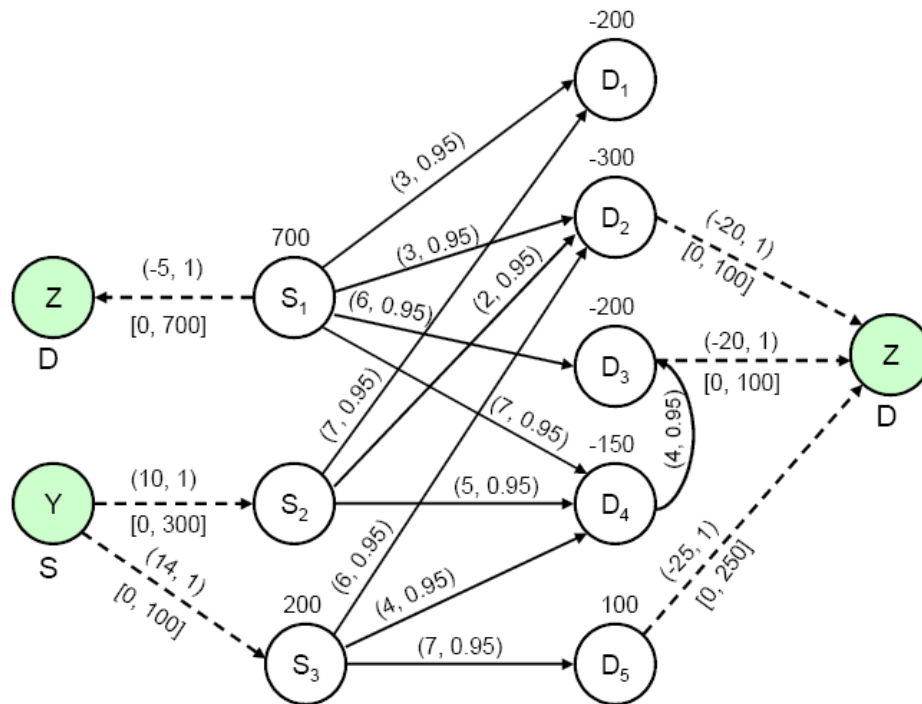
### Example 7.14: Generalized Networks: Distribution Problem

Consider a distribution problem (from Jensen and Bard 2003) with three supply plants ( $S_1 - S_3$ ) and five demand points ( $D_1 - D_5$ ). Further information about the problem is as follows:

- $S_1$  To be closed. Entire inventory must be shipped or sold to scrap. The scrap value is \$5 per unit.
- $S_2$  Maximum production of 300 units with manufacturing cost of \$10 per unit.
- $S_3$  The production in regular time amounts to 200 units and must be shipped. An additional 100 units can be produced using overtime at \$14 per unit.
- $D_1$  Fixed demand of 200 units must be met.
- $D_2$  Contracted demand of 300 units. An additional 100 units can be sold at \$20 per unit.
- $D_3$  Minimum demand of 200 units. An additional 100 units can be sold at \$20 per unit. Additional units can be procured from  $D_4$  at \$4 per unit. There is a 5% “shipping loss” on the arc connecting these two nodes.
- $D_4$  Fixed demand of 150 units must be met.
- $D_5$  100 units left over from previous shipments. No firm demand, but up to 250 units can be sold at \$25 per unit.

Additionally, there is a 5% “shipping loss” on each of the arcs between supply and demand nodes.

You can model this scenario as a generalized network. Since there are both fixed and varying supply and demand suprem values, you can transform this to a case where you need to address missing supply and demand simultaneously. As seen from [Output 7.14.1](#), we have added two artificial nodes, Y and Z, with missing S supply value and missing D demand value, respectively. The extra production capability is depicted by arcs from node Y to the corresponding supply nodes, and the extra revenue generation capability of the demand points (and scrap revenue for  $S_1$ ) is depicted by arcs to node Z.

**Output 7.14.1** Distribution Problem

The following SAS data set has the complete information about the arc costs, multipliers, and node supdem values:

```
data dnodes;
    input _node_ $ _sd_ ;
    missing S D;
datalines;
S1    700
S2     0
S3    200
D1   -200
D2   -300
D3   -200
D4   -150
D5    100
Y      S
Z      D
;

data darcs;
    input _from_ $ _to_ $ _cost_ _capac_ _mult_;
datalines;
S1 D1    3    200  0.95
S1 D2    3    200  0.95
S1 D3    6    200  0.95
S1 D4    7    200  0.95
S2 D1    7    200  0.95
S2 D2    2    200  0.95
```





### Example 7.15: Converting to an MPS-Format SAS Data Set

This example demonstrates the use of the `MPSOUT=` option to convert a problem data set in PROC NETFLOW input format into an MPS-format SAS data set for use with the OPTLP procedure.

Suppose you want to solve a linear program with the following formulation:

$$\begin{array}{llllll}
 \min & 2x_1 & - & 3x_2 & - & 4x_3 \\
 \text{subject to} & & - & 2x_2 & - & 3x_3 & \geq & -5 \\
 & x_1 & + & x_2 & + & 2x_3 & \leq & 4 \\
 & x_1 & + & 2x_2 & + & 3x_3 & \geq & 7 \\
 & & & 0 & \leq & x_1 & \leq & 10 \\
 & & & 0 & \leq & x_2 & \leq & 15 \\
 & & & 0 & \leq & x_3 & \leq & 20
 \end{array}$$

You can save the LP in dense format by using the following DATA step:

```

data exdata;
  input x1 x2 x3 _type_ $ _rhs_;
datalines;
2 -3 -4 min .
. -2 -3 >= -5
1 1 2 <= 6
1 2 3 >= 7
10 15 20 upperbd .
;

```

If you decide to solve the problem by using the OPTLP procedure, you need to convert the data set `exdata` from dense format to MPS format. You can accomplish this by using the following statements:

```

/* convert to MPS format */

proc netflow condata=exdata mpsout=mpsdata bytes=100000;
run;

```

The MPS-format SAS data set mpsdata is shown in [Output 7.15.1](#).

**Output 7.15.1** Data Set mpsdata

| The NETFLOW Procedure |         |         |         |        |        |        |
|-----------------------|---------|---------|---------|--------|--------|--------|
| Obs                   | field1  | field2  | field3  | field4 | field5 | field6 |
| 1                     | NAME    |         | modname | .      |        | .      |
| 2                     | ROWS    |         |         | .      |        | .      |
| 3                     | MIN     | objfn   |         | .      |        | .      |
| 4                     | G       | _OBS2_  |         | .      |        | .      |
| 5                     | L       | _OBS3_  |         | .      |        | .      |
| 6                     | G       | _OBS4_  |         | .      |        | .      |
| 7                     | COLUMNS |         |         | .      |        | .      |
| 8                     |         | x1      | objfn   | 2      | _OBS3_ | 1      |
| 9                     |         | x1      | _OBS4_  | 1      |        | .      |
| 10                    |         | x2      | objfn   | -3     | _OBS2_ | -2     |
| 11                    |         | x2      | _OBS3_  | 1      | _OBS4_ | 2      |
| 12                    |         | x3      | objfn   | -4     | _OBS2_ | -3     |
| 13                    |         | x3      | _OBS3_  | 2      | _OBS4_ | 3      |
| 14                    | RHS     |         |         | .      |        | .      |
| 15                    |         |         | _OBS2_  | -5     | _OBS3_ | 6      |
| 16                    |         |         | _OBS4_  | 7      |        | .      |
| 17                    | BOUNDS  |         |         | .      |        | .      |
| 18                    | UP      | bdsvect | x1      | 10     |        | .      |
| 19                    | UP      | bdsvect | x2      | 15     |        | .      |
| 20                    | UP      | bdsvect | x3      | 20     |        | .      |
| 21                    | ENDATA  |         |         | .      |        | .      |

The constraint names `_OBS2_`, `_OBS3_`, and `_OBS4_` are generated by the NETFLOW procedure. If you want to provide your own constraint names, use the `ROW` list variable in the `CONOUT=` data set. If you specify the problem data in sparse format instead of dense format, the `MPSOUT=` option produces the same MPS-format SAS data set shown in the preceding output.

Now that the problem data are in MPS format, you can solve the problem by using the OPTLP procedure. For more information, see Chapter 10, “The OPTLP Procedure” (*SAS/OR User’s Guide: Mathematical Programming*).

## Example 7.16: Migration to OPTMODEL: Generalized Networks

The following example shows how to solve [Example 7.11](#) using PROC OPTMODEL. The input data sets are the same as in that example.

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called GENETOUT:

```
proc optmodel;
  set <str> NODES;
  num _sd_ {NODES} init 0;
  read data gnodes into NODES=[_node_] _sd_;
```

```

set <str,str> ARCS;
num _lo_ {ARCS} init 0;
num _capac_ {ARCS} init .;
num _cost_ {ARCS};
num _mult_ {ARCS} init 1;
read data garcs nomiss into ARCS=[_from_ _to_] _cost_ _mult_;
NODES = NODES union (union {<i,j> in ARCS} {i,j});

var Flow {<i,j> in ARCS} >= _lo_[i,j];
min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
    - sum {<j,(i)> in ARCS} _mult_[j,i] * Flow[j,i] = _sd_[i];

num infinity = min {r in {}} r;
/* change equality constraint to le constraint for supply nodes */
for {i in NODES: _sd_[i] > 0} balance[i].lb = -infinity;

solve;

num _supply_ {<i,j> in ARCS} = (if _sd_[i] ne 0 then _sd_[i] else .);
num _demand_ {<i,j> in ARCS} = (if _sd_[j] ne 0 then -_sd_[j] else .);
num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

create data gnetout from [_from_ _to_]
    _cost_ _capac_ _lo_ _mult_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;

```

To solve a generalized network flow problem, the usual balance constraint is altered to include the arc multiplier `_MULT_[I,J]` in the second sum. The balance constraint is initially declared as an equality, but to mimic the PROC NETFLOW EXCESS=SUPPLY option, the sense of this constraint is changed to “ $\leq$ ” by relaxing the constraint’s lower bound for supply nodes. The output data set contains the same optimal solution as [Output 7.11.2](#). The log is displayed in [Output 7.16.1](#).

## Output 7.16.1 OPTMODEL Log

```

NOTE: There were 6 observations read from the data set WORK.GNODES.
NOTE: There were 7 observations read from the data set WORK.GARCS.
NOTE: The problem has 7 variables (0 free, 0 fixed).
NOTE: The problem has 6 linear constraints (3 LE, 3 EQ, 0 GE, 0 range).
NOTE: The problem has 14 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 2 variables and 2 constraints.
NOTE: The OPTLP presolver removed 4 constraint coefficients.
NOTE: The presolved problem has 5 variables, 4 constraints, and 10 constraint
      coefficients.
NOTE: The DUAL SIMPLEX solver is called.
      Objective
      Phase Iteration Value
           2           1    25.000000
NOTE: Optimal.
NOTE: Objective = 25.
NOTE: The data set WORK.GNETOUT has 7 observations and 10 variables.

```

Now consider the previous example but with a slight modification to the arc multipliers, as in [Example 7.11](#).

```

data garcs1;
  input _from_ $ _to_ $ _cost_ _mult_;
  datalines;
s1 d1 1 0.5
s1 d2 8 0.5
s2 d1 4 .
s2 d2 2 .
s2 d3 1 .
s3 d2 5 0.5
s3 d3 4 0.5
;

```

The following PROC OPTMODEL statements are identical to the preceding statements, except for the balance constraint. It is still initially declared as an equality, but to mimic the PROC NETFLOW EXCESS=DEMAND option, the sense of this constraint is changed to “ $\geq$ ” by relaxing the constraint’s upper bound for demand nodes.

```

proc optmodel;
  set <str> NODES;
  num _sd_ {NODES} init 0;
  read data gnodes into NODES=[_node_] _sd_;

  set <str,str> ARCS;
  num _lo_ {ARCS} init 0;
  num _capac_ {ARCS} init .;
  num _cost_ {ARCS};
  num _mult_ {ARCS} init 1;
  read data garcs1 nomiss into ARCS=[_from_ _to_] _cost_ _mult_;
  NODES = NODES union (union {<i,j> in ARCS} {i,j});

```

```

var Flow {<i,j> in ARCS} >= _lo_[i,j];
for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
con balance {i in NODES}: sum {<i,j> in ARCS} Flow[i,j]
    - sum {<j,i> in ARCS} _mult_[j,i] * Flow[j,i] = _sd_[i];

num infinity = min {r in {}} r;
/* change equality constraint to ge constraint */
for {i in NODES: _sd_[i] < 0} balance[i].ub = infinity;

solve;

num _supply_ {<i,j> in ARCS} = (if _sd_[i] ne 0 then _sd_[i] else .);
num _demand_ {<i,j> in ARCS} = (if _sd_[j] ne 0 then -_sd_[j] else .);
num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

create data gnetout1 from [_from_ _to_]
    _cost_ _capac_ _lo_ _mult_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;

```

The output data set contains the same optimal solution as [Output 7.11.3](#). The log is displayed in [Output 7.16.2](#).

#### Output 7.16.2 OPTMODEL Log

```

NOTE: There were 6 observations read from the data set WORK.GNODES.
NOTE: There were 7 observations read from the data set WORK.GARCS1.
NOTE: The problem has 7 variables (0 free, 0 fixed).
NOTE: The problem has 6 linear constraints (0 LE, 3 EQ, 3 GE, 0 range).
NOTE: The problem has 14 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 2 variables and 2 constraints.
NOTE: The OPTLP presolver removed 4 constraint coefficients.
NOTE: The presolved problem has 5 variables, 4 constraints, and 10 constraint
coefficients.
NOTE: The DUAL SIMPLEX solver is called.

```

|       |           | Objective |
|-------|-----------|-----------|
| Phase | Iteration | Value     |
| 2     | 1         | 65.000000 |
| 2     | 2         | 70.000000 |

```

NOTE: Optimal.
NOTE: Objective = 70.
NOTE: The data set WORK.GNETOUT1 has 7 observations and 10 variables.

```

## Example 7.17: Migration to OPTMODEL: Maximum Flow

The following example shows how to solve [Example 7.10](#) using PROC OPTMODEL. The input data set is the same as in that example.

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called GOUT3:

```
proc optmodel;
  str source = 'S';
  str sink = 'T';

  set <str> NODES;
  num _supdem_ {i in NODES} = (if i in {source, sink} then . else 0);

  set <str,str> ARCS;
  num _lo_ {ARCS} init 0;
  num _capac_ {ARCS} init .;
  num _cost_ {ARCS} init 0;
  read data arcs nomiss into ARCS=[_from_ _to_] _cost_ _capac_;
  NODES = (union {<i,j> in ARCS} {i,j});

  var Flow {<i,j> in ARCS} >= _lo_[i,j];
  for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
  max obj = sum {<i,j> in ARCS: j = sink} Flow[i,j];
  con balance {i in NODES diff {source, sink}}:
    sum {<(i),j> in ARCS} Flow[i,j]
    - sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];

  solve;

  num _supply_ {<i,j> in ARCS} =
    (if _supdem_[i] ne 0 then _supdem_[i] else .);
  num _demand_ {<i,j> in ARCS} =
    (if _supdem_[j] ne 0 then -_supdem_[j] else .);
  num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

  create data gout3 from [_from_ _to_]
    _cost_ _capac_ _lo_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;
```

To solve a maximum flow problem, you solve a network flow problem that has a zero supply or demand at all nodes other than the source and sink nodes, as specified in the declaration of the `_SUPDEM_` numeric parameter and the balance constraint. The objective declaration uses the logical condition `J = SINK` to maximize the flow into the sink node. The output data set contains the same optimal solution as [Output 7.10.3](#). The log is displayed in [Output 7.17.1](#).

## Output 7.17.1 OPTMODEL Log

```

NOTE: There were 14 observations read from the data set WORK.ARCS.
NOTE: The problem has 14 variables (0 free, 0 fixed).
NOTE: The problem has 8 linear constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 24 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 10 variables and 6 constraints.
NOTE: The OPTLP presolver removed 20 constraint coefficients.
NOTE: The presolved problem has 4 variables, 2 constraints, and 4 constraint
      coefficients.
NOTE: The DUAL SIMPLEX solver is called.
      Objective
      Phase Iteration Value
          2           1  25.000000
          2           2  25.000000
NOTE: Optimal.
NOTE: Objective = 25.
NOTE: The data set WORK.GOUT3 has 14 observations and 9 variables.

```

**Example 7.18: Migration to OPTMODEL: Production, Inventory, Distribution**

The following example shows how to solve [Example 7.4](#) using PROC OPTMODEL. The input data sets are the same as in that example.

The following PROC OPTMODEL code read the data sets, build the linear programming model, solve the model, and output the optimal solution to SAS data sets called ARC1 and NODE2:

```

proc optmodel;
  set <str> NODES;
  num _supdem_ {NODES} init 0;
  read data node0 into NODES=[_node_] _supdem_;

  set <str,str> ARCS;
  num _lo_ {ARCS} init 0;
  num _capac_ {ARCS} init .;
  num _cost_ {ARCS};
  num diagonal {ARCS};
  num factory {ARCS};
  str key_id {ARCS};
  str mth_made {ARCS};
  str _name_ {ARCS};
  read data arc0 nomiss into ARCS=[_tail_ _head_] _lo_ _capac_ _cost_
    diagonal factory key_id mth_made _name_;
  NODES = NODES union (union {<i,j> in ARCS} {i,j});

  var Flow {<i,j> in ARCS} >= _lo_[i,j];
  for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
  min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
  con balance {i in NODES}:

```



```

sum {<(i),j> in ARCS} Flow[i,j]
- sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];

num infinity = min {r in {}} r;
num excess = sum {i in NODES} _supdem_[i];
if (excess > 0) then do;
    /* change equality constraint to le constraint for supply nodes */
    for {i in NODES: _supdem_[i] > 0} balance[i].lb = -infinity;
end;
else if (excess < 0) then do;
    /* change equality constraint to ge constraint for demand nodes */
    for {i in NODES: _supdem_[i] < 0} balance[i].ub = infinity;
end;

solve;

num _supply_ {<i,j> in ARCS} =
    (if _supdem_[i] ne 0 then _supdem_[i] else .);
num _demand_ {<i,j> in ARCS} =
    (if _supdem_[j] ne 0 then -_supdem_[j] else .);
num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

create data arc1 from [_tail_ _head_]
    _cost_ _capac_ _lo_ _name_ _supply_ _demand_ _flow_=Flow _fcost_
    _rcost_ =
        (if Flow[_tail_, _head_].rc ne 0 then Flow[_tail_, _head_].rc else .)
    _status_ = Flow.status diagonal factory key_id mth_made;
create data node2 from [_node_]
    _supdem_ = (if _supdem_[_node_] ne 0 then _supdem_[_node_] else .)
    _dual_ = balance.dual;
quit;

```

The statements use both single-dimensional (NODES) and multiple-dimensional (ARCS) index sets, which are populated from the corresponding data set variables in the READ DATA statements. The `_SUPDEM_`, `_LO_`, and `_CAPAC_` parameters are given initial values, and the `NOMISS` option in the READ DATA statement tells OPTMODEL to read only the nonmissing values from the input data set. The balance constraint is initially declared as an equality, but depending on the total supply or demand, the sense of this constraint is changed to “ $\leq$ ” or “ $\geq$ ” by relaxing the constraint’s lower or upper bound, respectively. The ARC1 output data set contains most of the same information as in [Example 7.4](#), including reduced cost, basis status, and dual values. The `_ANUMB_` and `_TNUMB_` values do not apply here.

The PROC PRINT statements are similar to [Example 7.4](#).

```

options ls=80 ps=54;
proc print data=arc1 heading=h width=min;
    var _tail_ _head_ _cost_ _capac_ _lo_ _name_
        _supply_ _demand_ _flow_ _fcost_;
    sum _fcost_;
run;
proc print data=arc1 heading=h width=min;
    var _rcost_ _status_ diagonal factory key_id mth_made;
run;
proc print data=node2;
run;

```

The output data sets contain the same optimal solution as [Output 7.4.1](#), [Output 7.4.2](#), and [Output 7.4.3](#). The log is displayed in [Output 7.18.1](#).

#### Output 7.18.1 OPTMODEL Log

```
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 64 observations read from the data set WORK.ARC0.
NOTE: The problem has 64 variables (0 free, 0 fixed).
NOTE: The problem has 20 linear constraints (4 LE, 16 EQ, 0 GE, 0 range).
NOTE: The problem has 128 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed 0 variables and 0 constraints.
NOTE: The OPTLP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 64 variables, 20 constraints, and 128
      constraint coefficients.
NOTE: The DUAL SIMPLEX solver is called.
      Objective
Phase Iteration Value
      2          1   -2952213
      2         30   -1281110
NOTE: Optimal.
NOTE: Objective = -1281110.35.
NOTE: The data set WORK.ARC1 has 64 observations and 16 variables.
NOTE: The data set WORK.NODE2 has 20 observations and 3 variables.
```

### Example 7.19: Migration to OPTMODEL: Shortest Path

The following example shows how to solve [Example 7.1](#) using PROC OPTMODEL. The input data set is the same as in that example.

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called SPATH:

```
proc optmodel;
  str sourcenode = 'Honolulu';
  str sinknode = 'Heathrow London';

  set <str> NODES;
  num _supdem_ {i in NODES} = (if i = sourcenode then 1
    else if i = sinknode then -1 else 0);

  set <str,str> ARCS;
  num _lo_ {ARCS} init 0;
  num _capac_ {ARCS} init .;
  num _cost_ {ARCS};
  read data aircost1 into ARCS=[ffrom tto] _cost_;
  NODES = (union {<i,j> in ARCS} {i,j});

  var Flow {<i,j> in ARCS} >= _lo_[i,j];
```

```

min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
con balance {i in NODES}: sum {<i,j> in ARCS} Flow[i,j]
    - sum {<j,i> in ARCS} Flow[j,i] = _supdem_[i];
solve;

num _supply_ {<i,j> in ARCS} =
    (if _supdem_[i] ne 0 then _supdem_[i] else .);
num _demand_ {<i,j> in ARCS} =
    (if _supdem_[j] ne 0 then -_supdem_[j] else .);
num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

create data spath from [ffrom tto]
    _cost_ _capac_ _lo_ _supply_ _demand_ _flow_=Flow _fcost_
    _rcost_ = (if Flow[ffrom,tto].rc ne 0 then Flow[ffrom,tto].rc else .)
    _status_ = Flow.status;
quit;

```

The statements use both single-dimensional (NODES) and multiple-dimensional (ARCS) index sets. The ARCS data set is populated from the `ffrom` and `tto` data set variables in the READ DATA statement. To solve a shortest path problem, you solve a minimum-cost network-flow problem that has a supply of one unit at the source node, a demand of one unit at the sink node, and zero supply or demand at all other nodes, as specified in the declaration of the `_SUPDEM_` numeric parameter. The `SPATH` output data set contains most of the same information as in [Example 7.1](#), including reduced cost and basis status. The `_ANUMB_` and `_TNUMB_` values do not apply here.

The PROC PRINT statements are similar to [Example 7.1](#).

```

proc print data=spath;
    sum _fcost_;
run;

```

The output data set contains the same optimal solution as [Output 7.1.1](#). The log is displayed in [Output 7.19.1](#).

#### Output 7.19.1 OPTMODEL Log

```

NOTE: There were 13 observations read from the data set WORK.AIRCOST1.
NOTE: The problem has 13 variables (0 free, 0 fixed).
NOTE: The problem has 8 linear constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 26 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The OPTLP presolver value AUTOMATIC is applied.
NOTE: The OPTLP presolver removed all variables and constraints.
NOTE: Optimal.
NOTE: Objective = 177.
NOTE: The data set WORK.SPATH has 13 observations and 11 variables.

```

---

## References

- Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993), *Network Flows: Theory, Algorithms, and Applications*, Englewood Cliffs, NJ: Prentice-Hall.
- Bland, R. G. (1977), “New Finite Pivoting Rules for the Simplex Method,” *Mathematics of Operations Research*, 2, 103–107.
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# Chapter 8

## The NLP Procedure

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## Overview: NLP Procedure

The NLP (nonlinear programming) procedure offers a set of optimization techniques for minimizing or maximizing a continuous nonlinear function  $f(x)$  of  $n$  decision variables,  $x = (x_1, \dots, x_n)^T$  with lower and upper bound, linear and nonlinear, equality and inequality constraints. This can be expressed as solving

$$\begin{aligned} \min_{x \in \mathcal{R}^n} \quad & f(x) \\ \text{subject to} \quad & c_i(x) = 0, \quad i = 1, \dots, m_e \\ & c_i(x) \geq 0, \quad i = m_e + 1, \dots, m \\ & l_i \leq x_i \leq u_i, \quad i = 1, \dots, n \end{aligned}$$

where  $f$  is the objective function, the  $c_i$ 's are the nonlinear functions, and the  $l_i$ 's and  $u_i$ 's are the lower and upper bounds. Problems of this type are found in many settings ranging from optimal control to maximum likelihood estimation.

The NLP procedure provides a number of algorithms for solving this problem that take advantage of a special structure on the objective function and constraints. One example is the quadratic programming problem,

$$\begin{aligned} \min (\max) \quad & f(x) = \frac{1}{2}x^T Gx + g^T x + b \\ \text{subject to} \quad & c_i(x) = 0, \quad i = 1, \dots, m_e \end{aligned}$$

where  $G$  is an  $n \times n$  symmetric matrix,  $g = (g_1, \dots, g_n)^T$  is a vector,  $b$  is a scalar, and the  $c_i(x)$ 's are linear functions.

Another example is the least squares problem:

$$\begin{aligned} \min \quad & f(x) = \frac{1}{2}\{f_1^2(x) + \dots + f_l^2(x)\} \\ \text{subject to} \quad & c_i(x) = 0, \quad i = 1, \dots, m_e \end{aligned}$$

where the  $c_i(x)$ 's are linear functions, and  $f_1(x), \dots, f_l(x)$  are nonlinear functions of  $x$ .

The following problems are handled by PROC NLP:

- quadratic programming with an option for sparse problems
- unconstrained minimization/maximization
- constrained minimization/maximization
- linear complementarity problem

The following optimization techniques are supported in PROC NLP:

- Quadratic Active Set Technique
- Trust Region Method
- Newton-Raphson Method with Line Search
- Newton-Raphson Method with Ridging
- Quasi-Newton Methods
- Double Dogleg Method
- Conjugate Gradient Methods
- Nelder-Mead Simplex Method
- Levenberg-Marquardt Method
- Hybrid Quasi-Newton Methods

These optimization techniques require a continuous objective function  $f$ , and all but one (NMSIMP) require continuous first-order derivatives of the objective function  $f$ . Some of the techniques also require continuous second-order derivatives. There are three ways to compute derivatives in PROC NLP:

- analytically (using a special derivative compiler), the default method
- via finite-difference approximations
- via user-supplied exact or approximate numerical functions

Nonlinear programs can be input into the procedure in various ways. The objective, constraint, and derivative functions are specified using the programming statements of PROC NLP. In addition, information in SAS data sets can be used to define the structure of objectives and constraints as well as specify constants used in objectives, constraints and derivatives.

PROC NLP uses data sets to input various pieces of information:

- The **DATA=** data set enables you to specify data shared by all functions involved in a least squares problem.
- The **INQUAD=** data set contains the arrays appearing in a quadratic programming problem.
- The **INEST=** data set specifies initial values for the decision variables, the values of constants that are referred to in the program statements, and simple boundary and general linear constraints.
- The **MODEL=** data set specifies a model (functions, constraints, derivatives) saved at a previous execution of the NLP procedure.

PROC NLP uses data sets to output various results:

- The **OUTEST=** data set saves the values of the decision variables, the derivatives, the solution, and the covariance matrix at the solution.
- The **OUT=** output data set contains variables generated in the program statements defining the objective function as well as selected variables of the **DATA=** input data set, if available.
- The **OUTMODEL=** data set saves the programming statements. It can be used to input a model in the **MODEL=** input data set.

---

## Getting Started: NLP Procedure

The NLP procedure solves general nonlinear programs. It has several optimizers that are tuned to best perform on a particular class of problems. Guidelines for choosing a particular optimizer for a problem can be found in the section “[Optimization Algorithms](#)” on page 627.

Regardless of the selected optimizer, it is necessary to specify an objective function and constraints that the optimal solution must satisfy. In PROC NLP, the objective function and the constraints are specified using SAS programming statements that are similar to those used in the SAS DATA step. Some of the differences are discussed in the section “[Program Statements](#)” on page 620 and in the section “[ARRAY Statement](#)” on page 607. As with any programming language, there are many different ways to specify the same problem. Some are more economical than others.



## Introductory Examples

The following introductory examples illustrate how to get started using the NLP procedure.

### An Unconstrained Problem

Consider the simple example of minimizing the Rosenbrock function (Rosenbrock 1960):

$$\begin{aligned} f(x) &= \frac{1}{2} \{100(x_2 - x_1^2)^2 + (1 - x_1)^2\} \\ &= \frac{1}{2} \{f_1^2(x) + f_2^2(x)\}, \quad x = (x_1, x_2) \end{aligned}$$

The minimum function value is  $f(x^*) = 0$  at  $x^* = (1, 1)$ . This problem does not have any constraints.

The following statements can be used to solve this problem:

```
proc nlp;
  min f;
  decvar x1 x2;
  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;
  f = .5 * (f1 * f1 + f2 * f2);
run;
```

The **MIN** statement identifies the symbol  $f$  that characterizes the objective function in terms of  $f_1$  and  $f_2$ , and the **DECVAR** statement names the decision variables  $x_1$  and  $x_2$ . Because there is no explicit optimizing algorithm option specified (**TECH=**), PROC NLP uses the Newton-Raphson method with ridging, the default algorithm when there are no constraints.

A better way to solve this problem is to take advantage of the fact that  $f$  is a sum of squares of  $f_1$  and  $f_2$  and to treat it as a least squares problem. Using the **LSQ** statement instead of the **MIN** statement tells the procedure that this is a least squares problem, which results in the use of one of the specialized algorithms for solving least squares problems (for example, Levenberg-Marquardt).

```
proc nlp;
  lsq f1 f2;
  decvar x1 x2;
  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;
run;
```

The **LSQ** statement results in the minimization of a function that is the sum of squares of functions that appear in the **LSQ** statement. The least squares specification is preferred because it enables the procedure to exploit the structure in the problem for numerical stability and performance.

PROC NLP displays the iteration history and the solution to this least squares problem as shown in [Figure 8.1](#). It shows that the solution has  $x_1 = 1$  and  $x_2 = 1$ . As expected in an unconstrained problem, the gradient at the solution is very close to 0.

Figure 8.1 Least Squares Minimization

```

PROC NLP: Least Squares Minimization

      Levenberg-Marquardt Optimization

      Scaling Update of More (1978)

      Parameter Estimates                2
      Functions (Observations)          2

      Optimization Start

Active Constraints              0  Objective Function      0.7264362643
Max Abs Gradient Element      20.201360396  Radius          359.91383645

      Iter      Rest      Func      Act      Objective  Obj Fun  Max Abs      Actual
      arts     Calls     Con      Function  Change  Gradient  Element  Over
      1         0         2         0         0.03373   0.6927   5.1950     0.954
      2         0         3         0      1.5777E-30  0.0337  1.78E-15     1.000

      Optimization Results

Iterations                2  Function Calls                4
Jacobian Calls            3  Active Constraints          0
Objective Function        1.577722E-30  Max Abs Gradient Element  1.776357E-15
Lambda                    0  Actual Over Pred Change      1
Radius                    0.5194962481

ABSGCONV convergence criterion satisfied.

PROC NLP: Least Squares Minimization

      Optimization Results
      Parameter Estimates

      N Parameter      Estimate      Gradient
      Objective
      Function

      1 x1              1.000000      1.776357E-15
      2 x2              1.000000              0

      Value of Objective Function = 1.577722E-30

```

## Boundary Constraints on the Decision Variables

Bounds on the decision variables can be used. Suppose, for example, that it is necessary to constrain the decision variables in the previous example to be less than 0.5. That can be done by adding a **BOUNDS** statement.

```
proc nlp;
  lsq f1 f2;
  decvar x1 x2;
  bounds x1-x2 <= .5;
  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;
run;
```

The solution in Figure 8.2 shows that the decision variables meet the constraint bounds.

**Figure 8.2** Least Squares with Bounds Solution

|                                      |          |                                   |                               |
|--------------------------------------|----------|-----------------------------------|-------------------------------|
| PROC NLP: Least Squares Minimization |          |                                   |                               |
| Value of Objective Function = 29.25  |          |                                   |                               |
| PROC NLP: Least Squares Minimization |          |                                   |                               |
| Optimization Results                 |          |                                   |                               |
| Parameter Estimates                  |          |                                   |                               |
| N Parameter                          | Estimate | Gradient<br>Objective<br>Function | Active<br>Bound<br>Constraint |
| 1 x1                                 | 0.500000 | -0.500000                         | Upper BC                      |
| 2 x2                                 | 0.250000 | 0                                 |                               |

## Linear Constraints on the Decision Variables

More general linear equality or inequality constraints of the form

$$\sum_{j=1}^n a_{ij} x_j \{ \leq \mid = \mid \geq \} b_i \quad \text{for } i = 1, \dots, m$$

can be specified in a **LINCON** statement. For example, suppose that in addition to the bounds constraints on the decision variables it is necessary to guarantee that the sum  $x_1 + x_2$  is less than or equal to 0.6. That can be achieved by adding a **LINCON** statement:

```
proc nlp;
  lsq f1 f2;
  decvar x1 x2;
  bounds x1-x2 <= .5;
  lincon x1 + x2 <= .6;
  f1 = 10 * (x2 - x1 * x1);
```

```
f2 = 1 - x1;
run;
```

The output in Figure 8.3 displays the iteration history and the convergence criterion.

**Figure 8.3** Least Squares with Bounds and Linear Constraints Iteration History

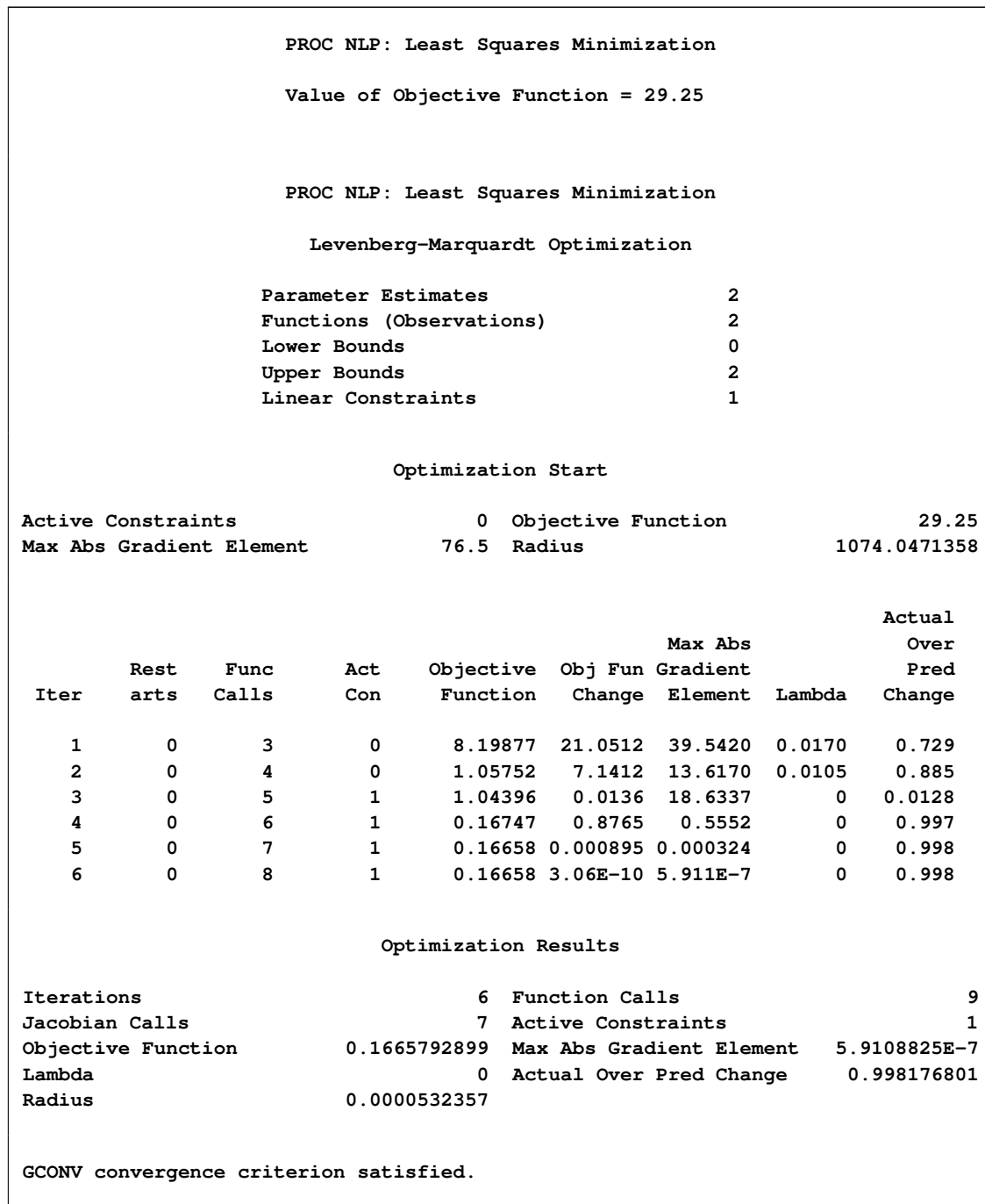


Figure 8.4 shows that the solution satisfies the linear constraint. Note that the procedure displays the active constraints (the constraints that are tight) at optimality.

**Figure 8.4** Least Squares with Bounds and Linear Constraints Solution

| PROC NLP: Least Squares Minimization     |  |                                   |
|--|--|-----------------------------------|
| Scaling Update of More (1978)            |  |                                   |
| PROC NLP: Least Squares Minimization     |  |                                   |
| Optimization Results                     |  |                                   |
| Parameter Estimates                      |  |                                   |
| N Parameter                              | Estimate                               | Gradient<br>Objective<br>Function |
| 1 x1                                     | 0.423645                               | -0.312000                         |
| 2 x2                                     | 0.176355                               | -0.312001                         |
| Linear Constraints Evaluated at Solution |  |                                   |
| 1 ACT                                    | 0 = 0.6000 - 1.0000 * x1 - 1.0000 * x2 |                                   |

### Nonlinear Constraints on the Decision Variables

More general nonlinear equality or inequality constraints can be specified using an **NLINCON** statement. Consider the least squares problem with the additional constraint

$$x_1^2 - 2x_2 \geq 0$$

This constraint is specified by a new function **c1** constrained to be greater than or equal to 0 in the **NLINCON** statement. The function **c1** is defined in the programming statements.

```
proc nlp tech=QUANEW;
  min f;
  decvar x1 x2;
  bounds x1-x2 <= .5;
  lincon x1 + x2 <= .6;
  nlincon c1 >= 0;

  c1 = x1 * x1 - 2 * x2;

  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;

  f = .5 * (f1 * f1 + f2 * f2);
run;
```

Figure 8.5 shows the iteration history, and Figure 8.6 shows the solution to this problem.

**Figure 8.5** Least Squares with Bounds, Linear and Nonlinear Constraints, Iteration History

| PROC NLP: Nonlinear Minimization                           |          |       |                   |                              |           |                  |          |  |
|--|----------|-------|-------------------|------------------------------|-----------|------------------|----------|--|
| Dual Quasi-Newton Optimization                             |          |       |                   |                              |           |                  |          |  |
| Modified VMCWD Algorithm of Powell (1978, 1982)            |          |       |                   |                              |           |                  |          |  |
| Dual Broyden - Fletcher - Goldfarb - Shanno Update (DBFGS) |          |       |                   |                              |           |                  |          |  |
| Lagrange Multiplier Update of Powell(1982)                 |          |       |                   |                              |           |                  |          |  |
| Parameter Estimates  |          |       | 2                 |                              |           |                  |          |  |
| Lower Bounds   |          |       | 0                 |                              |           |                  |          |  |
| Upper Bounds   |          |       | 2                 |                              |           |                  |          |  |
| Linear Constraints   |          |       | 1                 |                              |           |                  |          |  |
| Nonlinear Constraints                                      |          |       | 1                 |                              |           |                  |          |  |
| Optimization Start   |          |       |                   |                              |           |                  |          |  |
| Objective Function   |          |       | 29.25             | Maximum Constraint Violation |           | 0                |          |  |
| Maximum Gradient of the Lagran Func                        |          |       | 76.5              |                              |           |                  |          |  |
|  |          |       |                   |                              |           |                  |          |  |
|  |          |       | Maximum Predicted |                              |           | Maximum Gradient |          |  |
|  |          |       |                   |                              |           | Element          |          |  |
|  |          |       |                   |                              |           | of the           |          |  |
| Function   |          |       | Objective         | Constraint                   | Function  | Step             | Lagrange |  |
| Iter   | Restarts | Calls | Function          | Violation                    | Reduction | Size             | Function |  |
| 1  | 0        | 4     | 2.88501           | 0                            | 2.9362    | 1.000            | 20.961   |  |
| 2  | 0        | 5     | 0.91110           | 0                            | 0.5601    | 1.000            | 6.777    |  |
| 3  | 0        | 6     | 0.61803           | 0                            | 0.00743   | 1.000            | 1.148    |  |
| 4'   | 0        | 7     | 0.61090           | 0                            | 0.0709    | 1.000            | 1.194    |  |
| 5'   | 0        | 8     | 0.54427           | 0                            | 0.6015    | 1.000            | 0.988    |  |
| 6  | 0        | 10    | 0.49223           | 0                            | 0.3369    | 0.100            | 0.970    |  |
| 7  | 0        | 12    | 0.45729           | 0                            | 0.1848    | 0.114            | 1.332    |  |
| 8  | 0        | 14    | 0.40786           | 0                            | 0.0749    | 0.355            | 2.390    |  |
| 9  | 0        | 15    | 0.36176           | 0                            | 0.0556    | 1.000            | 1.129    |  |
| 10   | 0        | 16    | 0.33086           | 0                            | 0.00178   | 1.000            | 0.139    |  |
| 11   | 0        | 17    | 0.33017           | 0                            | 0.000290  | 1.000            | 0.0521   |  |
| 12   | 0        | 18    | 0.33004           | 0                            | 0.000012  | 1.000            | 0.00222  |  |
| 13   | 0        | 19    | 0.33003           | 0                            | 2.963E-8  | 1.000            | 0.00004  |  |

Figure 8.5 continued

| Optimization Results                |              |                              |              |
|-------------------------------------|--------------|------------------------------|--------------|
| Iterations                          | 13           | Function Calls               | 20           |
| Gradient Calls                      | 16           | Active Constraints           | 1            |
| Objective Function                  | 0.3300307304 | Maximum Constraint Violation | 0            |
| Maximum Projected Gradient          | 0.0000142688 | Value Lagrange Function      | 0.3300307155 |
| Maximum Gradient of the Lagran Func | 0.0000138527 | Slope of Search Direction    | -2.962973E-8 |

Figure 8.6 Least Squares with Bounds, Linear and Nonlinear Constraints, Solution

| PROC NLP: Nonlinear Minimization           |          |                                      |                            |
|--|----------|--------------------------------------|----------------------------|
| Optimization Results                       |          |                                      |                            |
| Parameter Estimates                        |          |                                      |                            |
| N Parameter                                | Estimate | Gradient Objective Function          | Gradient Lagrange Function |
| 1 x1                                       | 0.246953 | 0.753007                             | -0.000019007               |
| 2 x2                                       | 0.030493 | -3.049279                            | -0.000004694               |
| Value of Objective Function = 0.3300307281 |          |                                      |                            |
| Value of Lagrange Function = 0.3300307156  |          |                                      |                            |
| Linear Constraints Evaluated at Solution   |          |                                      |                            |
| 1  | 0.32255  | = 0.6000 - 1.0000 * x1 - 1.0000 * x2 |                            |
| Values of Nonlinear Constraints            |          |                                      |                            |
| Constraint                                 | Value    | Residual                             | Lagrange Multiplier        |
| [ 2 ] c1_G                                 | 8.244E-9 | 8.244E-9                             | 1.5246 Active NLIC         |

Not all of the optimization methods support nonlinear constraints. In particular the Levenberg-Marquardt method, the default for LSQ, does not support nonlinear constraints. (For more information about the particular algorithms, see the section “[Optimization Algorithms](#)” on page 627.) The Quasi-Newton method is the prime choice for solving nonlinear programs with nonlinear constraints. The option `TECH=QUANEW` in the `PROC NLP` statement causes the Quasi-Newton method to be used.

### A Simple Maximum Likelihood Example

The following is a very simple example of a maximum likelihood estimation problem with the log likelihood function:

$$l(\mu, \sigma) = -\log(\sigma) - \frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2$$

The maximum likelihood estimates of the parameters  $\mu$  and  $\sigma$  form the solution to

$$\max_{\mu, \sigma > 0} \sum_i l_i(\mu, \sigma)$$

where

$$l_i(\mu, \sigma) = -\log(\sigma) - \frac{1}{2} \left( \frac{x_i - \mu}{\sigma} \right)^2$$

In the following DATA step, values for  $x$  are input into SAS data set X; this data set provides the values of  $x_i$ .

```
data x;
input x @@;
datalines;
1 3 4 5 7
;
```

In the following statements, the **DATA=X** specification drives the building of the objective function. When each observation in the **DATA=X** data set is read, a new term  $l_i(\mu, \sigma)$  using the value of  $x_i$  is added to the objective function **LOGLIK** specified in the **MAX** statement.

```
proc nlp data=x vardef=n covariance=h pcov phes;
  profile mean sigma / alpha=.5 .1 .05 .01;
  max loglik;
  parms mean=0, sigma=1;
  bounds sigma > 1e-12;
  loglik=-0.5*((x-mean)/sigma)**2-log(sigma);
run;
```



After a few iterations of the default Newton-Raphson optimization algorithm, **PROC NLP** produces the results shown in [Figure 8.7](#).

**Figure 8.7** Maximum Likelihood Estimates

| PROC NLP: Nonlinear Maximization           |                                   |                   |          |                   |
|--|-----------------------------------|-------------------|----------|-------------------|
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Estimate                          | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                                     | 4.000000                          | 0.894427          | 4.472136 | 0.006566          |
| 2 sigma                                    | 2.000000                          | 0.632456          | 3.162278 | 0.025031          |
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Gradient<br>Objective<br>Function |                   |          |                   |
| 1 mean                                     | -1.33149E-10                      |                   |          |                   |
| 2 sigma                                    | 5.6064146E-9                      |                   |          |                   |
| Value of Objective Function = -5.965735903 |                                   |                   |          |                   |

In unconstrained maximization, the gradient (that is, the vector of first derivatives) at the solution must be very close to zero and the Hessian matrix at the solution (that is, the matrix of second derivatives) must have nonpositive eigenvalues. The Hessian matrix is displayed in [Figure 8.8](#).

**Figure 8.8** Hessian Matrix

| PROC NLP: Nonlinear Maximization     |              |              |
|--------------------------------------|--------------|--------------|
| Hessian Matrix                       |              |              |
|                                      | mean         | sigma        |
| mean                                 | -1.250000003 | 1.33149E-10  |
| sigma                                | 1.33149E-10  | -2.500000014 |
| Determinant = 3.1250000245           |              |              |
| Matrix has Only Negative Eigenvalues |              |              |

Under reasonable assumptions, the approximate standard errors of the estimates are the square roots of the diagonal elements of the covariance matrix of the parameter estimates, which (because of the **COV=H** specification) is the same as the inverse of the Hessian matrix. The covariance matrix is shown in [Figure 8.9](#).

**Figure 8.9** Covariance Matrix

| PROC NLP: Nonlinear Maximization         |              |              |
|--|--------------|--------------|
| Covariance Matrix 2: H = (NOBS/d) inv(G) |              |              |
|  | mean         | sigma        |
| mean                                     | 0.7999999982 | 4.260769E-11 |
| sigma                                    | 4.260769E-11 | 0.3999999978 |
| Factor sigm = 1                          |              |              |
| Determinant = 0.3199999975               |              |              |
| Matrix has 2 Positive Eigenvalue(s)      |              |              |

The **PROFILE** statement computes the values of the profile likelihood confidence limits on SIGMA and MEAN, as shown in Figure 8.10.

**Figure 8.10** Confidence Limits

| PROC NLP: Nonlinear Maximization |           |          |          |   |          |
|----------------------------------|-----------|----------|----------|---|----------|
| Wald and PL Confidence Limits    |           |          |          |   |          |
| N                                | Parameter | Estimate | Alpha    | Profile Likelihood<br>Confidence Limits |          |
| 1                                | mean      | 4.000000 | 0.500000 | 3.384431                                | 4.615569 |
| 1                                | mean      | .        | 0.100000 | 2.305716                                | 5.694284 |
| 1                                | mean      | .        | 0.050000 | 1.849538                                | 6.150462 |
| 1                                | mean      | .        | 0.010000 | 0.670351                                | 7.329649 |
| 2                                | sigma     | 2.000000 | 0.500000 | 1.638972                                | 2.516078 |
| 2                                | sigma     | .        | 0.100000 | 1.283506                                | 3.748633 |
| 2                                | sigma     | .        | 0.050000 | 1.195936                                | 4.358321 |
| 2                                | sigma     | .        | 0.010000 | 1.052584                                | 6.064107 |
| Wald and PL Confidence Limits    |           |          |          |   |          |
| Wald Confidence Limits           |           |          |          |   |          |
|                                  |           | 3.396718 | 4.603282 |   |          |
|                                  |           | 2.528798 | 5.471202 |   |          |
|                                  |           | 2.246955 | 5.753045 |   |          |
|                                  |           | 1.696108 | 6.303892 |   |          |
|                                  |           | 1.573415 | 2.426585 |   |          |
|                                  |           | 0.959703 | 3.040297 |   |          |
|                                  |           | 0.760410 | 3.239590 |   |          |
|                                  |           | 0.370903 | 3.629097 |   |          |

# Syntax: NLP Procedure

Below are statements used in **PROC NLP**, listed in alphabetical order as they appear in the text that follows.

```

PROC NLP options ;
  ARRAY function names ;
  BOUNDS boundary constraints ;
  BY variables ;
  CRPJAC variables ;
  DECVAR function names ;
  GRADIENT variables ;
  HESSIAN variables ;
  INCLUDE model files ;
  JACNLC variables ;
  JACOBIAN function names ;
  LABEL decision variable labels ;
  LINCON linear constraints ;
  MATRIX matrix specification ;
  MIN, MAX, or LSQ function names ;
  MINQUAD or MAXQUAD matrix, vector, or number ;
  NLINCON nonlinear constraints ;
  PROFILE profile specification ;
  Program Statements ; ;

```

## Functional Summary

The following table outlines the options in PROC NLP classified by function.

**Table 8.1** Functional Summary

| Description                          | Statement | Option    |
|--------------------------------------|-----------|-----------|
| <b>Input Data Set Options:</b>       |           |           |
| Input data set                       | PROC NLP  | DATA=     |
| Initial values and constraints       | PROC NLP  | INEST=    |
| Quadratic objective function         | PROC NLP  | INQUAD=   |
| Program statements                   | PROC NLP  | MODEL=    |
| Skip missing value observations      | PROC NLP  | NOMISS    |
| <b>Output Data Set Options:</b>      |           |           |
| Variables and derivatives            | PROC NLP  | OUT=      |
| Result parameter values              | PROC NLP  | OUTEST=   |
| Program statements                   | PROC NLP  | OUTMODEL= |
| Combine various OUT... statements    | PROC NLP  | OUTALL    |
| CRP Jacobian in the OUTEST= data set | PROC NLP  | OUTCRPJAC |
| Derivatives in the OUT= data set     | PROC NLP  | OUTDER=   |
| Grid in the OUTEST= data set         | PROC NLP  | OUTGRID   |

| Description  | Statement | Option       |
|--|-----------|--------------|
| Hessian in the OUTEST= data set                    | PROC NLP  | OUTHESSIAN   |
| Iterative output in the OUTEST= data set           | PROC NLP  | OUTITER      |
| Jacobian in the OUTEST= data set                   | PROC NLP  | OUTJAC       |
| NLC Jacobian in the OUTEST= data set               | PROC NLP  | OUTNLCJAC    |
| Time in the OUTEST= data set                       | PROC NLP  | OUTTIME      |
| <b>Optimization Options:</b>                       |           |              |
| Minimization method                                | PROC NLP  | TECH=        |
| Update technique                                   | PROC NLP  | UPDATE=      |
| Version of optimization technique                  | PROC NLP  | VERSION=     |
| Line-search method                                 | PROC NLP  | LINESEARCH=  |
| Line-search precision                              | PROC NLP  | LSPRECISION= |
| Type of Hessian scaling                            | PROC NLP  | HESCAL=      |
| Start for approximated Hessian                     | PROC NLP  | INHESIAN=    |
| Iteration number for update restart                | PROC NLP  | RESTART=     |
| <b>Initial Value Options:</b>                      |           |              |
| Produce best grid points                           | PROC NLP  | BEST=        |
| Infeasible points in grid search                   | PROC NLP  | INFEASIBLE   |
| Pseudorandom initial values                        | PROC NLP  | RANDOM=      |
| Constant initial values                            | PROC NLP  | INITIAL=     |
| <b>Derivative Options:</b>                         |           |              |
| Finite-difference derivatives                      | PROC NLP  | FD=          |
| Finite-difference derivatives                      | PROC NLP  | FDHESSIAN=   |
| Compute finite-difference interval                 | PROC NLP  | FDINT=       |
| Use only diagonal of Hessian                       | PROC NLP  | DIAHES       |
| Test gradient specification                        | PROC NLP  | GRADCHECK=   |
| <b>Constraint Options:</b>                         |           |              |
| Range for active constraints                       | PROC NLP  | LCEPSILON=   |
| LM tolerance for deactivating                      | PROC NLP  | LCDEACT=     |
| Tolerance for dependent constraints                | PROC NLP  | LCSINGULAR=  |
| Sum all observations for continuous functions      | NLINCON   | / SUMOBS     |
| Evaluate each observation for continuous functions | NLINCON   | / EVERYOBS   |
| <b>Termination Criteria Options:</b>               |           |              |
| Maximum number of function calls                   | PROC NLP  | MAXFUNC=     |
| Maximum number of iterations                       | PROC NLP  | MAXITER=     |
| Minimum number of iterations                       | PROC NLP  | MINITER=     |
| Upper limit on real time                           | PROC NLP  | MAXTIME=     |
| Absolute function convergence criterion            | PROC NLP  | ABSCONV=     |
| Absolute function convergence criterion            | PROC NLP  | ABSFCONV=    |
| Absolute gradient convergence criterion            | PROC NLP  | ABSGCONV=    |
| Absolute parameter convergence criterion           | PROC NLP  | ABSXCONV=    |

| Description                                  | Statement | Option     |
|--|-----------|------------|
| Relative function convergence criterion      | PROC NLP  | FCONV=     |
| Relative function convergence criterion      | PROC NLP  | FCONV2=    |
| Relative gradient convergence criterion      | PROC NLP  | GCONV=     |
| Relative gradient convergence criterion      | PROC NLP  | GCONV2=    |
| Relative parameter convergence criterion     | PROC NLP  | XCONV=     |
| Used in FCONV, GCONV criterion               | PROC NLP  | FSIZE=     |
| Used in XCONV criterion                      | PROC NLP  | XSIZE=     |
| <b>Covariance Matrix Options:</b>            |           |            |
| Type of covariance matrix                    | PROC NLP  | COV=       |
| $\sigma^2$ factor of COV matrix              | PROC NLP  | SIGSQ=     |
| Determine factor of COV matrix               | PROC NLP  | VARDEF=    |
| Absolute singularity for inertia             | PROC NLP  | ASINGULAR= |
| Relative M singularity for inertia           | PROC NLP  | MSINGULAR= |
| Relative V singularity for inertia           | PROC NLP  | VSINGULAR= |
| Threshold for Moore-Penrose inverse          | PROC NLP  | G4=        |
| Tolerance for singular COV matrix            | PROC NLP  | COVSING=   |
| Profile confidence limits                    | PROC NLP  | CLPARM=    |
| <b>Printed Output Options:</b>               |           |            |
| Display (almost) all printed output          | PROC NLP  | PALL       |
| Suppress all printed output                  | PROC NLP  | NOPRINT    |
| Reduce some default output                   | PROC NLP  | PSHORT     |
| Reduce most default output                   | PROC NLP  | PSUMMARY   |
| Display initial values and gradients         | PROC NLP  | PINIT      |
| Display optimization history                 | PROC NLP  | PHISTORY   |
| Display Jacobian matrix                      | PROC NLP  | PJACOBI    |
| Display crossproduct Jacobian matrix         | PROC NLP  | PCRPJAC    |
| Display Hessian matrix                       | PROC NLP  | PHESSIAN   |
| Display Jacobian of nonlinear constraints    | PROC NLP  | PNLCJAC    |
| Display values of grid points                | PROC NLP  | PGRID      |
| Display values of functions in LSQ, MIN, MAX | PROC NLP  | PFUNCTION  |
| Display approximate standard errors          | PROC NLP  | PSTDERR    |
| Display covariance matrix                    | PROC NLP  | PCOV       |
| Display eigenvalues for covariance matrix    | PROC NLP  | PEIGVAL    |
| Print code evaluation problems               | PROC NLP  | PERROR     |
| Print measures of real time                  | PROC NLP  | PTIME      |
| Display model program, variables             | PROC NLP  | LIST       |
| Display compiled model program               | PROC NLP  | LISTCODE   |
| <b>Step Length Options:</b>                  |           |            |
| Damped steps in line search                  | PROC NLP  | DAMPSTEP=  |
| Maximum trust region radius                  | PROC NLP  | MAXSTEP=   |
| Initial trust region radius                  | PROC NLP  | INSTEP=    |

| Description  | Statement | Option     |
|--|-----------|------------|
| <b>Profile Point and Confidence Interval Options:</b>              |           |            |
| Factor relating discrepancy function to $\chi^2$ quantile          | PROFILE   | FFACTOR=   |
| Scale for y values written to OUTEST= data set                     | PROFILE   | FORCHI=    |
| Upper bound for confidence limit search                            | PROFILE   | FEASRATIO= |
| Write all confidence limit parameter estimates to OUTEST= data set | PROFILE   | OUTTABLE   |
| <b>Miscellaneous Options:</b>                                      |           |            |
| Number of accurate digits in objective function                    | PROC NLP  | FDIGITS=   |
| Number of accurate digits in nonlinear constraints                 | PROC NLP  | CDIGITS=   |
| General singularity criterion                                      | PROC NLP  | SINGULAR=  |
| Do not compute inertia of matrices                                 | PROC NLP  | NOEIGNUM   |
| Check optimality in neighborhood                                   | PROC NLP  | OPTCHECK=  |

## PROC NLP Statement

**PROC NLP** *options* ;

This statement invokes the NLP procedure. The following options are used with the PROC NLP statement.

**ABSCONV**=*r*

**ABSTOL**=*r*

specifies an absolute function convergence criterion. For minimization (maximization), termination requires  $f(x^{(k)}) \leq (\geq) r$ . The default value of ABSCONV is the negative (positive) square root of the largest double precision value.

**ABSFCONV**=*r*[*n*]

**ABSFTOL**=*r*[*n*]

specifies an absolute function convergence criterion. For all techniques except NMSIMP, termination requires a small change of the function value in successive iterations:

$$|f(x^{(k-1)}) - f(x^{(k)})| \leq r$$

For the NMSIMP technique the same formula is used, but  $x^{(k)}$  is defined as the vertex with the lowest function value, and  $x^{(k-1)}$  is defined as the vertex with the highest function value in the simplex. The default value is  $r = 0$ . The optional integer value *n* specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**ABSGCONV**=*r*[*n*]

**ABSGTOL**=*r*[*n*]

specifies the absolute gradient convergence criterion. Termination requires the maximum absolute gradient element to be small:

$$\max_j |g_j(x^{(k)})| \leq r$$

This criterion is not used by the NMSIMP technique. The default value is  $r = 1\text{E}-5$ . The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**ABSXCONV**= $r[n]$

**ABSXTOL**= $r[n]$

specifies the absolute parameter convergence criterion. For all techniques except NMSIMP, termination requires a small Euclidean distance between successive parameter vectors:

$$\|x^{(k)} - x^{(k-1)}\|_2 \leq r$$

For the NMSIMP technique, termination requires either a small length  $\alpha^{(k)}$  of the vertices of a restart simplex

$$\alpha^{(k)} \leq r$$

or a small simplex size

$$\delta^{(k)} \leq r$$

where the simplex size  $\delta^{(k)}$  is defined as the  $L_1$  distance of the simplex vertex  $y^{(k)}$  with the smallest function value to the other  $n$  simplex points  $x_l^{(k)} \neq y^{(k)}$ :

$$\delta^{(k)} = \sum_{x_l \neq y} \|x_l^{(k)} - y^{(k)}\|_1$$

The default value is  $r = 1\text{E}-4$  for the COBYLA NMSIMP technique,  $r = 1\text{E}-8$  for the standard NMSIMP technique, and  $r = 0$  otherwise. The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**ASINGULAR**= $r$

**ASING**= $r$

specifies an absolute singularity criterion for measuring singularity of Hessian and crossproduct Jacobian and their projected forms, which may have to be converted to compute the covariance matrix. The default is the square root of the smallest positive double precision value. For more information, see the section “[Covariance Matrix](#)” on page 649.

**BEST**= $i$

produces the  $i$  best grid points only. This option not only restricts the output, it also can significantly reduce the computation time needed for sorting the grid point information.

**CDIGITS**= $r$

specifies the number of accurate digits in nonlinear constraint evaluations. Fractional values such as  $\text{CDIGITS}=4.7$  are allowed. The default value is  $r = -\log_{10}(\epsilon)$ , where  $\epsilon$  is the machine precision. The value of  $r$  is used to compute the interval length  $h$  for the computation of finite-difference approximations of the Jacobian matrix of nonlinear constraints.

**CLPARM**= **PL** | **WALD** | **BOTH**

is similar to but not the same as that used by other SAS procedures. Using **CLPARM=BOTH** is equivalent to specifying

```
PROFILE / ALPHA=0.5 0.1 0.05 0.01 OUTTABLE;
```



The CLPARM=BOTH option specifies that profile confidence limits (PL CLs) for all parameters and for  $\alpha = .5, .1, .05, .01$  are computed and displayed or written to the OUTEST= data set. Computing the profile confidence limits for all parameters can be very expensive and should be avoided when a difficult optimization problem or one with many parameters is solved. The OUTTABLE option is valid only when an OUTEST= data set is specified in the PROC NLP statement. For CLPARM=BOTH, the table of displayed output contains the Wald confidence limits computed from the standard errors as well as the PL CLs. The Wald confidence limits are not computed (displayed or written to the OUTEST= data set) unless the approximate covariance matrix of parameters is computed.

**COV= 1 | 2 | 3 | 4 | 5 | 6 | M | H | J | B | E | U**

**COVARIANCE= 1 | 2 | 3 | 4 | 5 | 6 | M | H | J | B | E | U**

specifies one of six formulas for computing the covariance matrix. For more information, see the section “Covariance Matrix” on page 649.

**COVSING=*r***

specifies a threshold  $r > 0$  that determines whether the eigenvalues of a singular Hessian matrix or crossproduct Jacobian matrix are considered to be zero. For more information, see the section “Covariance Matrix” on page 649.

**DAMPSTEP[=*r*]**

**DS[=*r*]**

specifies that the initial step length value  $\alpha^{(0)}$  for each line search (used by the QUANEW, HYQUAN, CONGRA, or NEWRAP technique) cannot be larger than  $r$  times the step length value used in the former iteration. If the DAMPSTEP option is specified but  $r$  is not specified, the default is  $r = 2$ . The DAMPSTEP= $r$  option can prevent the line-search algorithm from repeatedly stepping into regions where some objective functions are difficult to compute or where they could lead to floating point overflows during the computation of objective functions and their derivatives. The DAMPSTEP= $r$  option can save time-costly function calls during the line searches of objective functions that result in very small steps. For more information, see the section “Restricting the Step Length” on page 645.

**DATA=SAS-data-set**

allows variables from the specified data set to be used in the specification of the objective function  $f$ . For more information, see the section “DATA= Input Data Set” on page 652.

**DIAHES**

specifies that only the diagonal of the Hessian or crossproduct Jacobian is used. This saves function evaluations but may slow the convergence process considerably. Note that the DIAHES option refers to both the Hessian and the crossproduct Jacobian when using the LSQ statement. When derivatives are specified using the HESSIAN or CRPJAC statement, these statements must refer only to the  $n$  diagonal derivative elements (otherwise, the  $n(n + 1)/2$  derivatives of the lower triangle must be specified). The DIAHES option is ignored if a quadratic programming with a constant Hessian is specified by TECH=QUADAS or TECH=LICOMP.

**FCONV= $r$ [ $n$ ]**

**FTOL= $r$ [ $n$ ]**

specifies the relative function convergence criterion. For all techniques except NMSIMP, termination requires a small relative change of the function value in successive iterations:

$$\frac{|f(x^{(k)}) - f(x^{(k-1)})|}{\max(|f(x^{(k-1)})|, FSIZE)} \leq r$$

where  $FSIZE$  is defined by the **FSIZE=** option. For the NMSIMP technique, the same formula is used, but  $x^{(k)}$  is defined as the vertex with the lowest function value, and  $x^{(k-1)}$  is defined as the vertex with the highest function value in the simplex. The default value is  $r = 10^{-FDIGITS}$  where  $FDIGITS$  is the value of the **FDIGITS=** option. The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**FCNV2=r[n]**

**FTOL2=r[n]**

FCNV2= option specifies another function convergence criterion. For least squares problems and all techniques except NMSIMP, termination requires a small predicted reduction

$$df^{(k)} \approx f(x^{(k)}) - f(x^{(k)} + s^{(k)})$$

of the objective function. The predicted reduction

$$\begin{aligned} df^{(k)} &= -g^{(k)T} s^{(k)} - \frac{1}{2} s^{(k)T} G^{(k)} s^{(k)} \\ &= -\frac{1}{2} s^{(k)T} g^{(k)} \\ &\leq r \end{aligned}$$

is based on approximating the objective function  $f$  by the first two terms of the Taylor series and substituting the Newton step

$$s^{(k)} = -G^{(k)-1} g^{(k)}$$

For the NMSIMP technique, termination requires a small standard deviation of the function values of the  $n + 1$  simplex vertices  $x_l^{(k)}$ ,  $l = 0, \dots, n$ ,

$$\sqrt{\frac{1}{n+1} \sum_l (f(x_l^{(k)}) - \bar{f}(x^{(k)}))^2} \leq r$$

where  $\bar{f}(x^{(k)}) = \frac{1}{n+1} \sum_l f(x_l^{(k)})$ . If there are  $n_{act}$  boundary constraints active at  $x^{(k)}$ , the mean and standard deviation are computed only for the  $n + 1 - n_{act}$  unconstrained vertices. The default value is  $r = 1E-6$  for the NMSIMP technique and the QUANEW technique with nonlinear constraints, and  $r = 0$  otherwise. The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**FD[=FORWARD | CENTRAL | number]**

specifies that all derivatives be computed using finite-difference approximations. The following specifications are permitted:

FD=FORWARD uses forward differences.

FD=CENTRAL uses central differences.

FD=number uses central differences for the initial and final evaluations of the gradient, Jacobian, and Hessian. During iteration, start with forward differences and switch to a corresponding central-difference formula during the iteration process when one of the following two criteria is satisfied:

- The absolute maximum gradient element is less than or equal to *number* times the **ABSGCONV** threshold.

- The term left of the **GCONV** criterion is less than or equal to  $\max(1.0\text{E} - 6, \text{number} \times \text{GCONV threshold})$ . The  $1.0\text{E} - 6$  ensures that the switch is done, even if you set the **GCONV** threshold to zero.

**FD** is equivalent to **FD=100**.

Note that the **FD** and **FDHESSIAN** options cannot apply at the same time. The **FDHESSIAN** option is ignored when only first-order derivatives are used, for example, when the **LSQ** statement is used and the **HESSIAN** is not explicitly needed (displayed or written to a data set). For more information, see the section “[Finite-Difference Approximations of Derivatives](#)” on page 637.

**FDHESSIAN[=FORWARD | CENTRAL]**

**FDHES[=FORWARD | CENTRAL]**

**FDH[=FORWARD | CENTRAL]**

specifies that second-order derivatives be computed using finite-difference approximations based on evaluations of the gradients.

|                          |   |
|--------------------------|---|
| <b>FDHESSIAN=FORWARD</b> | uses forward differences.   |
| <b>FDHESSIAN=CENTRAL</b> | uses central differences.   |
| <b>FDHESSIAN</b>         | uses forward differences for the Hessian except for the initial and final output. |

Note that the **FD** and **FDHESSIAN** options cannot apply at the same time. For more information, see the section “[Finite-Difference Approximations of Derivatives](#)” on page 637

**FDIGITS=***r*

specifies the number of accurate digits in evaluations of the objective function. Fractional values such as **FDIGITS=4.7** are allowed. The default value is  $r = -\log_{10}(\epsilon)$ , where  $\epsilon$  is the machine precision. The value of *r* is used to compute the interval length *h* for the computation of finite-difference approximations of the derivatives of the objective function and for the default value of the **FCONV=** option.

**FDINT= OBJ | CON | ALL**

specifies how the finite-difference intervals *h* should be computed. For **FDINT=OBJ**, the interval *h* is based on the behavior of the objective function; for **FDINT=CON**, the interval *h* is based on the behavior of the nonlinear constraints functions; and for **FDINT=ALL**, the interval *h* is based on the behavior of the objective function and the nonlinear constraints functions. For more information, see the section “[Finite-Difference Approximations of Derivatives](#)” on page 637.

**FSIZE=***r*

specifies the **FSIZE** parameter of the relative function and relative gradient termination criteria. The default value is  $r = 0$ . For more details, refer to the **FCONV=** and **GCONV=** options.

**G4=***n*

is used when the covariance matrix is singular. The value  $n > 0$  determines which generalized inverse is computed. The default value of *n* is 60. For more information, see the section “[Covariance Matrix](#)” on page 649.

**GCONV**= $r[n]$ **GTOL**= $r[n]$ 

specifies the relative gradient convergence criterion. For all techniques except the CONGRA and NMSIMP techniques, termination requires that the normalized predicted function reduction is small:

$$\frac{g(x^{(k)})^T [G^{(k)}]^{-1} g(x^{(k)})}{\max(|f(x^{(k)})|, FSIZE)} \leq r$$

where  $FSIZE$  is defined by the **FSIZE**= option. For the CONGRA technique (where a reliable Hessian estimate  $G$  is not available),

$$\frac{\|g(x^{(k)})\|_2^2 \|s(x^{(k)})\|_2}{\|g(x^{(k)}) - g(x^{(k-1)})\|_2 \max(|f(x^{(k)})|, FSIZE)} \leq r$$

is used. This criterion is not used by the NMSIMP technique. The default value is  $r = 1\text{E}-8$ . The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**GCONV2**= $r[n]$ **GTOL2**= $r[n]$ 

**GCONV2**= option specifies another relative gradient convergence criterion,

$$\max_j \frac{|g_j(x^{(k)})|}{\sqrt{f(x^{(k)}) G_{j,j}^{(k)}}} \leq r$$

This option is valid only when using the TRUREG, LEVMAR, NRRIDG, and NEWRAP techniques on least squares problems. The default value is  $r = 0$ . The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.

**GRADCHECK**[= NONE | FAST | DETAIL]**GC**[= NONE | FAST | DETAIL]

Specifying **GRADCHECK**=DETAIL computes a test vector and test matrix to check whether the gradient  $g$  specified by a **GRADIENT** statement (or indirectly by a **JACOBIAN** statement) is appropriate for the function  $f$  computed by the program statements. If the specification of the first derivatives is correct, the elements of the test vector and test matrix should be relatively small. For very large optimization problems, the algorithm can be too expensive in terms of computer time and memory. If the **GRADCHECK** option is not specified, a fast derivative test identical to the **GRADCHECK**=FAST specification is performed by default. It is possible to suppress the default derivative test by specifying **GRADCHECK**=NONE. For more information, see the section “Testing the Gradient Specification” on page 640.

**HESCAL**= 0 | 1 | 2 | 3**HS**= 0 | 1 | 2 | 3

specifies the scaling version of the Hessian or crossproduct Jacobian matrix used in NRRIDG, TRUREG, LEVMAR, NEWRAP, or DBLDOG optimization. If the value of the **HESCAL**= option is not equal to zero, the first iteration and each restart iteration sets the diagonal scaling matrix  $D^{(0)} = \text{diag}(d_i^{(0)})$ :

$$d_i^{(0)} = \sqrt{\max(|G_{i,i}^{(0)}|, \epsilon)}$$

where  $G_{i,i}^{(0)}$  are the diagonal elements of the Hessian or crossproduct Jacobian matrix. In all other iterations, the diagonal scaling matrix  $D^{(0)} = \text{diag}(d_i^{(0)})$  is updated depending on the HESCAL= option:

HESCAL=0 specifies that no scaling is done

HESCAL=1 specifies the Moré (1978) scaling update:

$$d_i^{(k+1)} = \max \left( d_i^{(k)}, \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)} \right)$$

HESCAL=2 specifies the Dennis, Gay, and Welsch (1981) scaling update:

$$d_i^{(k+1)} = \max \left( 0.6d_i^{(k)}, \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)} \right)$$

HESCAL=3 specifies that  $d_i$  is reset in each iteration:

$$d_i^{(k+1)} = \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)}$$

where  $\epsilon$  is the relative machine precision. The default value is HESCAL=1 for LEVMAR minimization and HESCAL=0 otherwise. Scaling of the Hessian or crossproduct Jacobian matrix can be time-consuming in the case where general linear constraints are active.

**INEST=SAS-data-set**

**INVAR=SAS-data-set**

**ESTDATA=SAS-data-set**

can be used to specify the initial values of the parameters defined in a **DECVAR** statement as well as simple boundary constraints and general linear constraints. The INEST= data set can contain additional variables with names corresponding to constants used in the program statements. At the beginning of each run of **PROC NLP**, the values of the constants are read from the PARMS observation, initializing the constants in the program statements. For more information, see the section “**INEST= Input Data Set**” on page 652.

**INFEASIBLE**

**IFP**

specifies that the function values of both feasible and infeasible grid points are to be computed, displayed, and written to the **OUTEST=** data set, although only the feasible grid points are candidates for the starting point  $x^{(0)}$ . This option enables you to explore the shape of the objective function of points surrounding the feasible region. For the output, the grid points are sorted first with decreasing values of the maximum constraint violation. Points with the same value of the maximum constraint violation are then sorted with increasing (minimization) or decreasing (maximization) value of the objective function. Using the **BEST=** option restricts only the number of best grid points in the displayed output, not those in the data set. The INFEASIBLE option affects both the displayed output and the output saved to the **OUTEST=** data set. The **OUTGRID** option can be used to write the grid points and their function values to an **OUTEST=** data set. After small modifications (deleting unneeded information), this data set can be used with the G3D procedure of SAS/GRAPH to generate a three-dimensional surface plot of the objective function depending on two selected parameters. For more information on grids, see the section “**DECVAR Statement**” on page 610.

**INHESSIAN[=*r*]****INHESS[=*r*]**

specifies how the initial estimate of the approximate Hessian is defined for the quasi-Newton techniques QUANEW, DBLDOG, and HYQUAN. There are two alternatives:

- The = *r* specification is not used: the initial estimate of the approximate Hessian is set to the true Hessian or crossproduct Jacobian at  $x^{(0)}$ .
- The = *r* specification is used: the initial estimate of the approximate Hessian is set to the multiple of the identity matrix  $rI$ .

By default, if INHESSIAN=*r* is not specified, the initial estimate of the approximate Hessian is set to the multiple of the identity matrix  $rI$ , where the scalar *r* is computed from the magnitude of the initial gradient. For most applications, this is a sufficiently good first approximation.

**INITIAL=*r***

specifies a value *r* as the common initial value for all parameters for which no other initial value assignments by the **DECVAR** statement or an **INEST=** data set are made.

**INQUAD=SAS-data-set**

can be used to specify (the nonzero elements of) the matrix  $H$ , the vector  $g$ , and the scalar  $c$  of a quadratic programming problem,  $f(x) = \frac{1}{2}x^T Hx + g^T x + c$ . This option cannot be used together with the **NLINCON** statement. Two forms (*dense* and *sparse*) of the **INQUAD=** data set can be used. For more information, see the section “**INQUAD= Input Data Set**” on page 653.

**INSTEP=*r***

For highly nonlinear objective functions, such as the EXP function, the default initial radius of the trust region algorithms TRUREG, DBLDOG, or LEVMAR or the default step length of the line-search algorithms can result in arithmetic overflows. If this occurs, decreasing values of  $0 < r < 1$  should be specified, such as INSTEP=1E–1, INSTEP=1E–2, INSTEP=1E–4, and so on, until the iteration starts successfully.

- For trust region algorithms (TRUREG, DBLDOG, LEVMAR), the INSTEP= option specifies a factor  $r > 0$  for the initial radius  $\Delta^{(0)}$  of the trust region. The default initial trust region radius is the length of the scaled gradient. This step corresponds to the default radius factor of  $r = 1$ .
- For line-search algorithms (NEWRAP, CONGRA, QUANEW, HYQUAN), the INSTEP= option specifies an upper bound for the initial step length for the line search during the first five iterations. The default initial step length is  $r = 1$ .
- For the Nelder-Mead simplex algorithm (NMSIMP), the INSTEP=*r* option defines the size of the initial simplex.

For more details, see the section “**Computational Problems**” on page 646.

**LCDEACT=*r*****LCD=*r***

specifies a threshold *r* for the Lagrange multiplier that decides whether an active inequality constraint remains active or can be deactivated. For a maximization (minimization), an active inequality constraint can be deactivated only if its Lagrange multiplier is greater (less) than the threshold value *r*. For

maximization,  $r$  must be greater than zero; for minimization,  $r$  must be smaller than zero. The default value is

$$r = \pm \min(0.01, \max(0.1 \times \text{ABSGCONV}, 0.001 \times gmax^{(k)}))$$

where the  $+$  stands for maximization, the  $-$  for minimization, **ABSGCONV** is the value of the absolute gradient criterion, and  $gmax^{(k)}$  is the maximum absolute element of the (projected) gradient  $g^{(k)}$  or  $Z^T g^{(k)}$ .

**LCEPSILON**= $r$

**LCEPS**= $r$

**LCE**= $r$

specifies the range  $r > 0$  for active and violated boundary and linear constraints. During the optimization process, the introduction of rounding errors can force **PROC NLP** to increase the value of  $r$  by a factor of 10, 100, . . . . If this happens it is indicated by a message written to the log. For more information, see the section “**Linear Complementarity (LICOMP)**” on page 631.

**LCSINGULAR**= $r$

**LCSING**= $r$

**LCS**= $r$

specifies a criterion  $r > 0$  used in the update of the QR decomposition that decides whether an active constraint is linearly dependent on a set of other active constraints. The default value is  $r = 1\text{E}-8$ . The larger  $r$  becomes, the more the active constraints are recognized as being linearly dependent. If the value of  $r$  is larger than 0.1, it is reset to 0.1.

**LINESEARCH**= $i$

**LIS**= $i$

specifies the line-search method for the CONGRA, QUANEW, HYQUAN, and NEWRAP optimization techniques. Refer to Fletcher (1987) for an introduction to line-search techniques. The value of  $i$  can be 1, . . . , 8. For CONGRA, QUANEW, and NEWRAP, the default value is  $i = 2$ . A special line-search method is the default for the least squares technique HYQUAN that is based on an algorithm developed by Lindström and Wedin (1984). Although it needs more memory, this default line-search method sometimes works better with large least squares problems. However, by specifying **LIS**= $i$ ,  $i = 1, \dots, 8$ , it is possible to use one of the standard techniques with HYQUAN.

**LIS**=1 specifies a line-search method that needs the same number of function and gradient calls for cubic interpolation and cubic extrapolation.

**LIS**=2 specifies a line-search method that needs more function than gradient calls for quadratic and cubic interpolation and cubic extrapolation; this method is implemented as shown in Fletcher (1987) and can be modified to an exact line search by using the **LSPRECISION**= option.

**LIS**=3 specifies a line-search method that needs the same number of function and gradient calls for cubic interpolation and cubic extrapolation; this method is implemented as shown in Fletcher (1987) and can be modified to an exact line search by using the **LSPRECISION**= option.

**LIS**=4 specifies a line-search method that needs the same number of function and gradient calls for stepwise extrapolation and cubic interpolation.

**LIS**=5 specifies a line-search method that is a modified version of **LIS**=4.



|       |  |
|-------|--|
| LIS=6 | specifies golden section line search (Polak 1971), which uses only function values for linear approximation.       |
| LIS=7 | specifies bisection line search (Polak 1971), which uses only function values for linear approximation.            |
| LIS=8 | specifies the Armijo line-search technique (Polak 1971), which uses only function values for linear approximation. |

**LIST**

displays the model program and variable lists. The LIST option is a debugging feature and is not normally needed. This output is not included in either the default output or the output specified by the [PALL](#) option.

**LISTCODE**

displays the derivative tables and the compiled program code. The LISTCODE option is a debugging feature and is not normally needed. This output is not included in either the default output or the output specified by the [PALL](#) option. The option is similar to that used in MODEL procedure in SAS/ETS software.

**LSPRECISION=*r*****LSP=*r***

specifies the degree of accuracy that should be obtained by the line-search algorithms [LIS=2](#) and [LIS=3](#). Usually an imprecise line search is inexpensive and sufficient for convergence to the optimum. For difficult optimization problems, a more precise and expensive line search may be necessary (Fletcher 1987). The second (default for NEWRAP, QUANEW, and CONGRA) and third line-search methods approach exact line search for small LSPRECISION= values. In the presence of numerical problems, it is advised to decrease the LSPRECISION= value to obtain a more precise line search. The default values are as follows:

| TECH=  | UPDATE=     | LSP default |
|--------|-------------|-------------|
| QUANEW | DBFGS, BFGS | $r = 0.4$   |
| QUANEW | DDFP, DFP   | $r = 0.06$  |
| HYQUAN | DBFGS       | $r = 0.1$   |
| HYQUAN | DDFP        | $r = 0.06$  |
| CONGRA | all         | $r = 0.1$   |
| NEWRAP | no update   | $r = 0.9$   |

For more details, refer to Fletcher (1987).

**MAXFUNC=*i*****MAXFU=*i***

specifies the maximum number *i* of function calls in the optimization process. The default values are

- TRUREG, LEVMAR, NRRIDG, NEWRAP: 125
- QUANEW, HYQUAN, DBLDOG: 500
- CONGRA, QUADAS: 1000
- NMSIMP: 3000



Note that the optimization can be terminated only after completing a full iteration. Therefore, the number of function calls that are actually performed can exceed the number that is specified by the MAXFUNC= option.

**MAXITER**=*i* [*n*]

**MAXIT**=*i* [*n*]

specifies the maximum number *i* of iterations in the optimization process. The default values are:

- TRUREG, LEVMAR, NRRIDG, NEWRAP: 50
- QUANEW, HYQUAN, DBLDOG: 200
- CONGRA, QUADAS: 400
- NMSIMP: 1000

This default value is valid also when *i* is specified as a missing value. The optional second value *n* is valid only for **TECH**=QUANEW with nonlinear constraints. It specifies an upper bound *n* for the number of iterations of an algorithm used to reduce the violation of nonlinear constraints at a starting point. The default value is *n* = 20.

**MAXSTEP**=*r* [*n*]

specifies an upper bound for the step length of the line-search algorithms during the first *n* iterations. By default, *r* is the largest double precision value and *n* is the largest integer available. Setting this option can increase the speed of convergence for **TECH**=CONGRA, **TECH**=QUANEW, **TECH**=HYQUAN, and **TECH**=NEWRAP.

**MAXTIME**=*r*

specifies an upper limit of *r* seconds of real time for the optimization process. The default value is the largest floating point double representation of the computer. Note that the time specified by the MAXTIME= option is checked only once at the end of each iteration. Therefore, the actual running time of the PROC NLP job may be longer than that specified by the MAXTIME= option. The actual running time includes the rest of the time needed to finish the iteration, time for the output of the (temporary) results, and (if required) the time for saving the results in an **OUTEST**= data set. Using the MAXTIME= option with a permanent **OUTEST**= data set enables you to separate large optimization problems into a series of smaller problems that need smaller amounts of real time.

**MINITER**=*i*

**MINIT**=*i*

specifies the minimum number of iterations. The default value is zero. If more iterations than are actually needed are requested for convergence to a stationary point, the optimization algorithms can behave strangely. For example, the effect of rounding errors can prevent the algorithm from continuing for the required number of iterations.

**MODEL**=*model-name, model-list*

**MOD**=*model-name, model-list*

**MODFILE**=*model-name, model-list*

reads the program statements from one or more input model files created by previous **PROC NLP** steps using the **OUTMODEL**= option. If it is necessary to include the program code at a special location in newly written code, the **INCLUDE** statement can be used instead of using the **MODEL**= option. Using both the **MODEL**= option and the **INCLUDE** statement with the same model file will include the same model twice, which can produce different results than including it once. The **MODEL**= option is similar to the option used in PROC MODEL in SAS/ETS software.

**MSINGULAR=*r*****MSING=*r***

specifies a relative singularity criterion  $r > 0$  for measuring singularity of Hessian and crossproduct Jacobian and their projected forms. The default value is  $1\text{E}-12$  if the **SINGULAR=** option is not specified and  $\max(10 \times \epsilon, 1\text{E} - 4 \times \text{SINGULAR})$  otherwise. For more information, see the section “Covariance Matrix” on page 649.

**NOEIGNUM**

suppresses the computation and output of the determinant and the inertia of the Hessian, crossproduct Jacobian, and covariance matrices. The inertia of a symmetric matrix are the numbers of negative, positive, and zero eigenvalues. For large applications, the NOEIGNUM option can save computer time.

**NOMISS**

is valid only for those variables of the **DATA=** data set that are referred to in program statements. If the NOMISS option is specified, observations with any missing value for those variables are skipped. If the NOMISS option is not specified, the missing value may result in a missing value of the objective function, implying that the corresponding BY group of data is not processed.

**NOPRINT****NOP**

suppresses the output.

**OPTCHECK[=*r*]**

computes the function values  $f(x_l)$  of a grid of points  $x_l$  in a small neighborhood of  $x^*$ . The  $x_l$  are located in a ball of radius  $r$  about  $x^*$ . If the OPTCHECK option is specified without  $r$ , the default value is  $r = 0.1$  at the starting point and  $r = 0.01$  at the terminating point. If a point  $x_l^*$  is found with a better function value than  $f(x^*)$ , then optimization is restarted at  $x_l^*$ . For more information on grids, see the section “DECVAR Statement” on page 610.

**OUT=SAS-data-set**

creates an output data set that contains those variables of a **DATA=** input data set referred to in the program statements plus additional variables computed by performing the program statements of the objective function, derivatives, and nonlinear constraints. The **OUT=** data set can also contain first- and second-order derivatives of these variables if the **OUTDER=** option is specified. The variables and derivatives are evaluated at  $x^*$ ; for **TECH=NONE**, they are evaluated at  $x^0$ .

**OUTALL**

If an **OUTEST=** data set is specified, this option sets the **OUTHESSIAN** option if the **MIN** or **MAX** statement is used. If the **LSQ** statement is used, the OUTALL option sets the **OUTCRPJAC** option. If nonlinear constraints are specified using the **NLINCON** statement, the OUTALL option sets the **OUTNLCJAC** option.

**OUTCRPJAC**

If an **OUTEST=** data set is specified, the crossproduct Jacobian matrix of the  $m$  functions composing the least squares function is written to the **OUTEST=** data set.

**OUTDER= 0 | 1 | 2**

specifies whether or not derivatives are written to the **OUT=** data set. For **OUTDER=2**, first- and second-order derivatives are written to the data set; for **OUTDER=1**, only first-order derivatives are written; for **OUTDER=0**, no derivatives are written to the data set. The default value is **OUTDER=0**. Derivatives are evaluated at  $x^*$ .

**OUTEST**=*SAS-data-set*

**OUTVAR**=*SAS-data-set*

creates an output data set that contains the results of the optimization. This is useful for reporting and for restarting the optimization in a subsequent execution of the procedure. Information in the data set can include parameter estimates, gradient values, constraint information, Lagrangian values, Hessian values, Jacobian values, covariance, standard errors, and confidence intervals.

**OUTGRID**

writes the grid points and their function values to the **OUTEST**= data set. By default, only the feasible grid points are saved; however, if the **INFEASIBLE** option is specified, all feasible and infeasible grid points are saved. Note that the **BEST**= option does not affect the output of grid points to the **OUTEST**= data set. For more information on grids, see the section “**DECVAR Statement**” on page 610.

**OUTHESSIAN**

**OUTHES**

writes the Hessian matrix of the objective function to the **OUTEST**= data set. If the Hessian matrix is computed for some other reason (if, for example, the **PHESSIAN** option is specified), the **OUTHESSIAN** option is set by default.

**OUTITER**

writes during each iteration the parameter estimates, the value of the objective function, the gradient (if available), and (if **OUTTIME** is specified) the time in seconds from the start of the optimization to the **OUTEST**= data set.

**OUTJAC**

writes the Jacobian matrix of the  $m$  functions composing the least squares function to the **OUTEST**= data set. If the **PJACOBI** option is specified, the **OUTJAC** option is set by default.

**OUTMODEL**=*model-name*

**OUTMOD**=*model-name*

**OUTM**=*model-name*

specifies the name of an output model file to which the program statements are to be written. The program statements of this file can be included into the program statements of a succeeding **PROC NLP** run using the **MODEL**= option or the **INCLUDE** program statement. The **OUTMODEL**= option is similar to the option used in **PROC MODEL** in SAS/ETS software. Note that the following statements are not part of the program code that is written to an **OUTMODEL**= data set: **MIN**, **MAX**, **LSQ**, **MINQUAD**, **MAXQUAD**, **DECVAR**, **BOUNDS**, **BY**, **CRPJAC**, **GRADIENT**, **HESSIAN**, **JACNLC**, **JACOBIAN**, **LABEL**, **LINCON**, **MATRIX**, and **NLINCON**.

**OUTNLCJAC**

If an **OUTEST**= data set is specified, the Jacobian matrix of the nonlinear constraint functions specified by the **NLINCON** statement is written to the **OUTEST**= data set. If the Jacobian matrix of the nonlinear constraint functions is computed for some other reason (if, for example, the **PNLCJAC** option is specified), the **OUTNLCJAC** option is set by default.

**OUTTIME**

is used if an **OUTEST**= data set is specified and if the **OUTITER** option is specified. If **OUTTIME** is specified, the time in seconds from the start of the optimization to the start of each iteration is written to the **OUTEST**= data set.

**PALL****ALL**

displays all optional output except the output generated by the **PSTDERR**, **PCOV**, **LIST**, or **LISTCODE** option.

**PCOV**

displays the covariance matrix specified by the **COV=** option. The **PCOV** option is set automatically if the **PALL** and **COV=** options are set.

**PCRPJAC****PJTJ**

displays the  $n \times n$  crossproduct Jacobian matrix  $J^T J$ . If the **PALL** option is specified and the **LSQ** statement is used, this option is set automatically. If general linear constraints are active at the solution, the projected crossproduct Jacobian matrix is also displayed.

**PEIGVAL**

displays the distribution of eigenvalues if a G4 inverse is computed for the covariance matrix. The **PEIGVAL** option is useful for observing which eigenvalues of the matrix are recognized as zero eigenvalues when the generalized inverse is computed, and it is the basis for setting the **COVSING=** option in a subsequent execution of **PROC NLP**. For more information, see the section “**Covariance Matrix**” on page 649.

**PERROR**

specifies additional output for such applications where the program code for objective function or nonlinear constraints cannot be evaluated during the iteration process. The **PERROR** option is set by default during the evaluations at the starting point but not during the optimization process.

**PFUNCTION**

displays the values of all functions specified in a **LSQ**, **MIN**, or **MAX** statement for each observation read from the **DATA=** input data set. The **PALL** option sets the **PFUNCTION** option automatically.

**PGRID**

displays the function values from the grid search. For more information on grids, see the section “**DECVAR Statement**” on page 610.

**PHESSIAN****PHESS**

displays the  $n \times n$  Hessian matrix  $G$ . If the **PALL** option is specified and the **MIN** or **MAX** statement is used, this option is set automatically. If general linear constraints are active at the solution, the projected Hessian matrix is also displayed.

**PHISTORY****PHIS**

displays the optimization history. No optimization history is displayed for **TECH=LICOMP**. This output is included in both the default output and the output specified by the **PALL** option.

**PINIT**

**PIN**

displays the initial values and derivatives (if available). This output is included in both the default output and the output specified by the [PALL](#) option.

**PJACOBI****PJAC**

displays the  $m \times n$  Jacobian matrix  $J$ . Because of the memory requirement for large least squares problems, this option is not invoked when using the [PALL](#) option.

**PNLCJAC**

displays the Jacobian matrix of nonlinear constraints specified by the [NLINCON](#) statement. The [PNLCJAC](#) option is set automatically if the [PALL](#) option is specified.

**PSHORT****SHORT****PSH**

restricts the amount of default output. If [PSHORT](#) is specified, then

- The initial values are not displayed.
- The listing of constraints is not displayed.
- If there is more than one function in the [MIN](#), [MAX](#), or [LSQ](#) statement, their values are not displayed.
- If the [GRADCHECK](#) option is used, only the test vector is displayed.

**PSTDERR****STDERR****SE**

computes standard errors that are defined as square roots of the diagonal elements of the covariance matrix. The  $t$  values and probabilities  $> |t|$  are displayed together with the approximate standard errors. The type of covariance matrix must be specified using the [COV=](#) option. The [SIGSQ=](#) option, the [VARDEF=](#) option, and the special variables `_NOBS_` and `_DF_` defined in the program statements can be used to define a scalar factor  $\sigma^2$  of the covariance matrix and the approximate standard errors. For more information, see the section “[Covariance Matrix](#)” on page 649.

**PSUMMARY****SUMMARY****SUM**

restricts the amount of default displayed output to a short form of iteration history and notes, warnings, and errors.

**PTIME**

specifies the output of four different but partially overlapping differences of real time:

- total running time
- total time for the evaluation of objective function, nonlinear constraints, and derivatives: shows the total time spent executing the programming statements specifying the objective function, derivatives, and nonlinear constraints, and (if necessary) their first- and second-order derivatives. This is the total time needed for code evaluation before, during, and after iterating.

- total time for optimization: shows the total time spent iterating.
- time for some CMP parsing: shows the time needed for parsing the program statements and its derivatives. In most applications this is a negligible number, but for applications that contain ARRAY statements or DO loops or use an optimization technique with analytic second-order derivatives, it can be considerable.

**RANDOM=*i***

specifies a positive integer as a seed value for the pseudorandom number generator. Pseudorandom numbers are used as the initial value  $x^{(0)}$ .

**RESTART=*i*****REST=*i***

specifies that the QUANEW, HYQUAN, or CONGRA algorithm is restarted with a steepest descent/ascent search direction after at most  $i > 0$  iterations. Default values are as follows:

- CONGRA with **UPDATE=PB**: restart is done automatically so specification of  $i$  is not used
- CONGRA with **UPDATE**≠PB:  $i = \min(10n, 80)$ , where  $n$  is the number of parameters
- QUANEW, HYQUAN:  $i$  is the largest integer available

**SIGSQ=*sq***

specifies a scalar factor  $sq > 0$  for computing the covariance matrix. If the SIGSQ= option is specified, **VARDEF=N** is the default. For more information, see the section “Covariance Matrix” on page 649.

**SINGULAR=*r*****SING=*r***

specifies the singularity criterion  $r > 0$  for the inversion of the Hessian matrix and crossproduct Jacobian. The default value is  $1E-8$ . For more information, refer to the **MSINGULAR=** and **VSINGULAR=** options.

**TECH=*name*****TECHNIQUE=*name***

specifies the optimization technique. Valid values for it are as follows:

- CONGRA  
chooses one of four different conjugate gradient optimization algorithms, which can be more precisely specified with the **UPDATE=** option and modified with the **LINESEARCH=** option. When this option is selected, **UPDATE=PB** by default. For  $n \geq 400$ , CONGRA is the default optimization technique.
- DBLDOG  
performs a version of double dogleg optimization, which can be more precisely specified with the **UPDATE=** option. When this option is selected, **UPDATE=DBFGS** by default.
- HYQUAN  
chooses one of three different hybrid quasi-Newton optimization algorithms which can be more precisely defined with the **VERSION=** option and modified with the **LINESEARCH=** option. By default, **VERSION=2** and **UPDATE=DBFGS**.

- **LEVVAR**  
performs the Levenberg-Marquardt minimization. For  $n < 40$ , this is the default minimization technique for least squares problems.
- **LICOMP**  
solves a quadratic program as a linear complementarity problem.
- **NMSIMP**  
performs the Nelder-Mead simplex optimization method.
- **NONE**  
does not perform any optimization. This option can be used
  - to do grid search without optimization
  - to compute and display derivatives and covariance matrices which cannot be obtained efficiently with any of the optimization techniques
- **NEWRAP**  
performs the Newton-Raphson optimization technique. The algorithm combines a line-search algorithm with ridging. The line-search algorithm **LINESEARCH=2** is the default.
- **NRRIDG**  
performs the Newton-Raphson optimization technique. For  $n \leq 40$  and non-linear least squares, this is the default.
- **QUADAS**  
performs a special quadratic version of the active set strategy.
- **QUANEW**  
chooses one of four quasi-Newton optimization algorithms which can be defined more precisely with the **UPDATE=** option and modified with the **LINESEARCH=** option. This is the default for  $40 < n < 400$  or if there are nonlinear constraints.
- **TRUREG**  
performs the trust region optimization technique.

**UPDATE=method**

**UPD=method**

specifies the update method for the (dual) quasi-Newton, double dogleg, hybrid quasi-Newton, or conjugate gradient optimization technique. Not every update method can be used with each optimizer. For more information, see the section “[Optimization Algorithms](#)” on page 627. Valid values for *method* are as follows:

|              |   |
|--------------|---|
| <b>BFGS</b>  | performs the original BFGS (Broyden, Fletcher, Goldfarb, & Shanno) update of the inverse Hessian matrix.            |
| <b>DBFGS</b> | performs the dual BFGS (Broyden, Fletcher, Goldfarb, & Shanno) update of the Cholesky factor of the Hessian matrix. |
| <b>DDFP</b>  | performs the dual DFP (Davidon, Fletcher, & Powell) update of the Cholesky factor of the Hessian matrix.            |
| <b>DFP</b>   | performs the original DFP (Davidon, Fletcher, & Powell) update of the inverse Hessian matrix.                       |
| <b>PB</b>    | performs the automatic restart update method of Powell (1977) and Beale (1972).                                     |

|    |   |
|----|---|
| FR | performs the Fletcher-Reeves update (Fletcher 1987).    |
| PR | performs the Polak-Ribiere update (Fletcher 1987).      |
| CD | performs a conjugate-descent update of Fletcher (1987). |

**VARDEF= DF | N**

specifies the divisor  $d$  used in the calculation of the covariance matrix and approximate standard errors. If the **SIGSQ=** option is not specified, the default value is VARDEF=DF; otherwise, VARDEF=N is the default. For more information, see the section “[Covariance Matrix](#)” on page 649.

**VERSION= 1 | 2 | 3****VS= 1 | 2 | 3**

specifies the version of the hybrid quasi-Newton optimization technique or the version of the quasi-Newton optimization technique with nonlinear constraints.

For the hybrid quasi-Newton optimization technique,

**VS=1** specifies version HY1 of Fletcher and Xu (1987).

**VS=2** specifies version HY2 of Fletcher and Xu (1987).

**VS=3** specifies version HY3 of Fletcher and Xu (1987).

For the quasi-Newton optimization technique with nonlinear constraints,

**VS=1** specifies update of the  $\mu$  vector like Powell (1978a, b) (update like VF02AD).

**VS=2** specifies update of the  $\mu$  vector like Powell (1982b) (update like VMCWD).

In both cases, the default value is VS=2.

**VSINGULAR= $r$** **VSING= $r$** 

specifies a relative singularity criterion  $r > 0$  for measuring singularity of Hessian and crossproduct Jacobian and their projected forms, which may have to be converted to compute the covariance matrix. The default value is 1E–8 if the **SINGULAR=** option is not specified and the value of **SINGULAR** otherwise. For more information, see the section “[Covariance Matrix](#)” on page 649.

**XCONV= $r[n]$** **XTOL= $r[n]$** 

specifies the relative parameter convergence criterion. For all techniques except NMSIMP, termination requires a small relative parameter change in subsequent iterations:

$$\frac{\max_j |x_j^{(k)} - x_j^{(k-1)}|}{\max(|x_j^{(k)}|, |x_j^{(k-1)}|, \text{XSIZE})} \leq r$$

For the NMSIMP technique, the same formula is used, but  $x_j^{(k)}$  is defined as the vertex with the lowest function value and  $x_j^{(k-1)}$  is defined as the vertex with the highest function value in the simplex. The default value is  $r = 1\text{E}–8$  for the NMSIMP technique and  $r = 0$  otherwise. The optional integer value  $n$  specifies the number of successive iterations for which the criterion must be satisfied before the process can be terminated.



**XSIZE=*r***

specifies the parameter  $r > 0$  of the relative parameter termination criterion. The default value is  $r = 0$ . For more details, see the **XCONV=** option.

---

## ARRAY Statement

**ARRAY** *arrayname* [ *dimensions* ] [\$] [*variables and constants*] ; ;

The ARRAY statement is similar to, but not the same as, the ARRAY statement in the SAS DATA step. The ARRAY statement is used to associate a name (of no more than eight characters) with a list of variables and constants. The array name is used with subscripts in the program to refer to the array elements. The following code illustrates this:

```
array r[8] r1-r8;

do i = 1 to 8;
  r[i] = 0;
end;
```

The ARRAY statement does not support all the features of the DATA step ARRAY statement. It cannot be used to give initial values to array elements. Implicit indexing of variables cannot be used; all array references must have explicit subscript expressions. Only exact array dimensions are allowed; lower-bound specifications are not supported and a maximum of six dimensions is allowed.

On the other hand, the ARRAY statement does allow both variables and constants to be used as array elements. (Constant array elements cannot have values assigned to them.) Both dimension specification and the list of elements are optional, but at least one must be given. When the list of elements is not given or fewer elements than the size of the array are listed, array variables are created by suffixing element numbers to the array name to complete the element list.

---

## BOUNDS Statement

**BOUNDS** *b\_con* [ , *b\_con* . . . ] ;

where *b\_con* is given in one of the following formats:

- number *operator* parameter\_list *operator* number
- number *operator* parameter\_list
- parameter\_list *operator* number

and *operator* is  $\leq$ ,  $<$ ,  $\geq$ ,  $>$ , or  $=$ .

Boundary constraints are specified with a BOUNDS statement. One- or two-sided boundary constraints are allowed. The list of boundary constraints are separated by commas. For example,

```

bounds 0 <= a1-a9 x <= 1, -1 <= c2-c5;
bounds b1-b10 y >= 0;

```

More than one BOUNDS statement can be used. If more than one lower (upper) bound for the same parameter is specified, the maximum (minimum) of these is taken. If the maximum  $l_j$  of all lower bounds is larger than the minimum of all upper bounds  $u_j$  for the same variable  $x_j$ , the boundary constraint is replaced by  $x_j = l_j = \min(u_j)$  defined by the minimum of all upper bounds specified for  $x_j$ .

---

## BY Statement

**BY variables ;**

A BY statement can be used with **PROC NLP** to obtain separate analyses on **DATA=** data set observations in groups defined by the BY variables. That means, for values of the **TECH=** option other than NONE, an optimization problem is solved for each BY group separately. When a BY statement appears, the procedure expects the input **DATA=** data set to be sorted in order of the BY variables. If the input data set is not sorted in ascending order, it is necessary to use one of the following alternatives:

- Use the SORT procedure with a similar BY statement to sort the data.
- Use the BY statement option NOTSORTED or DESCENDING in the BY statement for the NLP procedure. As a cautionary note, the NOTSORTED option does not mean that the data are unsorted but rather that the data are arranged in groups (according to values of the BY variables) and that these groups are not necessarily in alphabetical or increasing numeric order.
- Use the DATASETS procedure (in Base SAS software) to create an index on the BY variables.

For more information on the BY statement, refer to the discussion in *SAS Language Reference: Concepts*. For more information on the DATASETS procedure, refer to the *SAS Procedures Guide*.

---

## CRPJAC Statement

**CRPJAC variables ;**

The CRPJAC statement defines the crossproduct Jacobian matrix  $J^T J$  used in solving least squares problems. For more information, see the section “Derivatives” on page 626. If the DIAHES option is not specified, the CRPJAC statement lists  $n(n + 1)/2$  variable names, which correspond to the elements  $(J^T J)_{j,k}$ ,  $j \geq k$  of the lower triangle of the symmetric crossproduct Jacobian matrix listed by rows. For example, the statements

```
lsq f1-f3;
decvar x1-x3;
crpjac jj1-jj6;
```

correspond to the crossproduct Jacobian matrix

$$J^T J = \begin{bmatrix} JJ1 & JJ2 & JJ4 \\ JJ2 & JJ3 & JJ5 \\ JJ4 & JJ5 & JJ6 \end{bmatrix}$$

If the **DIAHES** option is specified, only the  $n$  diagonal elements must be listed in the CRPJAC statement. The  $n$  rows and  $n$  columns of the crossproduct Jacobian matrix must be in the same order as the  $n$  corresponding parameter names listed in the **DECVAR** statement. To specify the values of nonzero derivatives, the variables specified in the CRPJAC statement have to be defined at the left-hand side of algebraic expressions in programming statements. For example, consider the Rosenbrock function:

```
proc nlp tech=levmar;
  lsq f1 f2;
  decvar x1 x2;
  gradient g1 g2;
  crpjac cpj1-cpj3;

  f1   = 10 * (x2 - x1 * x1);
  f2   = 1 - x1;
  g1   = -200 * x1 * (x2 - x1 * x1) - (1 - x1);
  g2   = 100 * (x2 - x1 * x1);

  cpj1 = 400 * x1 * x1 + 1 ;
  cpj2 = -200 * x1;
  cpj3 = 100;
run;
```

---

## DECVAR Statement

```

DECVAR name_list [=numbers] [, name_list [=numbers] ...] ;
VAR name_list [=numbers] [, name_list [=numbers] ...] ;
PARMS name_list [=numbers] [, name_list [=numbers] ...] ;
PARAMETERS name_list [=numbers] [, name_list [=numbers] ...] ;

```

The DECVAR statement lists the names of the  $n > 0$  decision variables and specifies grid search and initial values for an iterative optimization process. The decision variables listed in the DECVAR statement cannot also be used in the [MIN](#), [MAX](#), [MINQUAD](#), [MAXQUAD](#), [LSQ](#), [GRADIENT](#), [HESSIAN](#), [JACOBIAN](#), [CRPJAC](#), or [NLINCON](#) statement.

The DECVAR statement contains a list of decision variable names (not separated by commas) optionally followed by an equals sign and a list of numbers. If the number list consists of only one number, this number defines the initial value for all the decision variables listed to the left of the equals sign.

If the number list consists of more than one number, these numbers specify the grid locations for each of the decision variables listed left of the equals sign. The TO and BY keywords can be used to specify a number list for a grid search. When a grid of points is specified with a DECVAR statement, [PROC NLP](#) computes the objective function value at each grid point and chooses the best (feasible) grid point as a starting point for the optimization process. The use of the [BEST=](#) option is recommended to save computing time and memory for the storing and sorting of all grid point information. Usually only feasible grid points are included in the grid search. If the specified grid contains points located outside the feasible region and you are interested in the function values at those points, it is possible to use the [INFEASIBLE](#) option to compute (and display) their function values as well.

---

## GRADIENT Statement

```

GRADIENT variables ;

```

The GRADIENT statement defines the gradient vector which contains the first-order derivatives of the objective function  $f$  with respect to  $x_1, \dots, x_n$ . For more information, see the section “[Derivatives](#)” on page 626. To specify the values of nonzero derivatives, the variables specified in the GRADIENT statement must be defined on the left-hand side of algebraic expressions in programming statements. For example, consider the Rosenbrock function:

```

proc nlp tech=congra;
  min y;
  decvar x1 x2;
  gradient g1 g2;

  y1 = 10 * (x2 - x1 * x1);
  y2 = 1 - x1;

  y = .5 * (y1 * y1 + y2 * y2);

  g1 = -200 * x1 * (x2 - x1 * x1) - (1 - x1);
  g2 = 100 * (x2 - x1 * x1);
run;

```

## HESSIAN Statement

**HESSIAN** *variables* ;

The HESSIAN statement defines the Hessian matrix  $G$  containing the second-order derivatives of the objective function  $f$  with respect to  $x_1, \dots, x_n$ . For more information, see the section “[Derivatives](#)” on page 626.

If the [DIAHES](#) option is not specified, the HESSIAN statement lists  $n(n + 1)/2$  variable names which correspond to the elements  $G_{j,k}$ ,  $j \geq k$ , of the lower triangle of the symmetric Hessian matrix listed by rows. For example, the statements

```
min f;
decvar x1 - x3;
hessian g1-g6;
```

correspond to the Hessian matrix

$$G = \begin{bmatrix} G1 & G2 & G4 \\ G2 & G3 & G5 \\ G4 & G5 & G6 \end{bmatrix} = \begin{bmatrix} \partial^2 f / \partial x_1^2 & \partial^2 f / \partial x_1 \partial x_2 & \partial^2 f / \partial x_1 \partial x_3 \\ \partial^2 f / \partial x_2 \partial x_1 & \partial^2 f / \partial x_2^2 & \partial^2 f / \partial x_2 \partial x_3 \\ \partial^2 f / \partial x_3 \partial x_1 & \partial^2 f / \partial x_3 \partial x_2 & \partial^2 f / \partial x_3^2 \end{bmatrix}$$

If the [DIAHES](#) option is specified, only the  $n$  diagonal elements must be listed in the HESSIAN statement. The  $n$  rows and  $n$  columns of the Hessian matrix  $G$  must correspond to the order of the  $n$  parameter names listed in the [DECVAR](#) statement. To specify the values of nonzero derivatives, the variables specified in the HESSIAN statement must be defined on the left-hand side of algebraic expressions in the programming statements. For example, consider the Rosenbrock function:

```
proc nlp tech=nrridg;
  min f;
  decvar x1 x2;
  gradient g1 g2;
  hessian h1-h3;

  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;

  f = .5 * (f1 * f1 + f2 * f2);

  g1 = -200 * x1 * (x2 - x1 * x1) - (1 - x1);
  g2 = 100 * (x2 - x1 * x1);

  h1 = -200 * (x2 - 3 * x1 * x1) + 1;
  h2 = -200 * x1;
  h3 = 100;
run;
```

## INCLUDE Statement

**INCLUDE** *model files* ;

The INCLUDE statement can be used to append model code to the current model code. The contents of included model files, created using the **OUTMODEL=** option, are inserted into the model program at the position in which the INCLUDE statement appears.

## JACNLC Statement

**JACNLC** *variables* ;

The JACNLC statement defines the Jacobian matrix for the system of constraint functions  $c_1(x), \dots, c_{mc}(x)$ . The statements list the  $mc \times n$  variable names which correspond to the elements  $CJ_{i,j}$ ,  $i = 1, \dots, mc$ ;  $j = 1, \dots, n$ , of the Jacobian matrix by rows.

For example, the statements

```
nlincon c1-c3;
decvar x1-x2;
jacnlc cj1-cj6;
```

correspond to the Jacobian matrix

$$CJ = \begin{bmatrix} CJ1 & CJ2 \\ CJ3 & CJ4 \\ CJ5 & CJ6 \end{bmatrix} = \begin{bmatrix} \partial c_1 / \partial x_1 & \partial c_1 / \partial x_2 \\ \partial c_2 / \partial x_1 & \partial c_2 / \partial x_2 \\ \partial c_3 / \partial x_1 & \partial c_3 / \partial x_2 \end{bmatrix}$$

The  $mc$  rows of the Jacobian matrix must be in the same order as the  $mc$  corresponding names of nonlinear constraints listed in the **NLINCON** statement. The  $n$  columns of the Jacobian matrix must be in the same order as the  $n$  corresponding parameter names listed in the **DECVAR** statement. To specify the values of nonzero derivatives, the variables specified in the JACNLC statement must be defined on the left-hand side of algebraic expressions in programming statements.

For example,

```
array cd[3,4] cd1-cd12;
nlincon c1-c3 >= 0;
jacnlc cd1-cd12;

c1 = 8 - x1 * x1 - x2 * x2 - x3 * x3 - x4 * x4 -
      x1 + x2 - x3 + x4;
c2 = 10 - x1 * x1 - 2 * x2 * x2 - x3 * x3 - 2 * x4 * x4 +
      x1 + x4;
c3 = 5 - 2 * x1 * x2 - x2 * x2 - x3 * x3 - 2 * x1 + x2 + x4;

cd[1,1]= -1 - 2 * x1;   cd[1,2]= 1 - 2 * x2;
cd[1,3]= -1 - 2 * x3;   cd[1,4]= 1 - 2 * x4;
cd[2,1]= 1 - 2 * x1;    cd[2,2]= -4 * x2;
cd[2,3]= -2 * x3;       cd[2,4]= 1 - 4 * x4;
cd[3,1]= -2 - 4 * x1;   cd[3,2]= 1 - 2 * x2;
cd[3,3]= -2 * x3;       cd[3,4]= 1;
```

## JACOBIAN Statement

**JACOBIAN** *variables* ;

The JACOBIAN statement defines the JACOBIAN matrix  $J$  for a system of objective functions. For more information, see the section “Derivatives” on page 626.

The JACOBIAN statement lists  $m \times n$  variable names that correspond to the elements  $J_{i,j}$ ,  $i = 1, \dots, m$ ;  $j = 1, \dots, n$ , of the Jacobian matrix listed by rows.

For example, the statements

```
lsq f1-f3;
decvar x1 x2;
jacobian j1-j6;
```

correspond to the Jacobian matrix

$$J = \begin{bmatrix} J1 & J2 \\ J3 & J4 \\ J5 & J6 \end{bmatrix} = \begin{bmatrix} \partial f_1 / \partial x_1 & \partial f_1 / \partial x_2 \\ \partial f_2 / \partial x_1 & \partial f_2 / \partial x_2 \\ \partial f_3 / \partial x_1 & \partial f_3 / \partial x_2 \end{bmatrix}$$

The  $m$  rows of the Jacobian matrix must correspond to the order of the  $m$  function names listed in the **MIN**, **MAX**, or **LSQ** statement. The  $n$  columns of the Jacobian matrix must correspond to the order of the  $n$  decision variables listed in the **DECVAR** statement. To specify the values of nonzero derivatives, the variables specified in the JACOBIAN statement must be defined on the left-hand side of algebraic expressions in programming statements.

For example, consider the Rosenbrock function:

```
proc nlp tech=levmar;
  array j[2,2] j1-j4;
  lsq f1 f2;
  decvar x1 x2;
  jacobian j1-j4;

  f1 = 10 * (x2 - x1 * x1);
  f2 = 1 - x1;

  j[1,1] = -20 * x1;
  j[1,2] = 10;
  j[2,1] = -1;
  j[2,2] = 0;    /* is not needed */
run;
```

The JACOBIAN statement is useful only if more than one objective function is given in the **MIN**, **MAX**, or **LSQ** statement, or if a **DATA=** input data set specifies more than one function. If the **MIN**, **MAX**, or **LSQ** statement contains only one objective function and no **DATA=** input data set is used, the JACOBIAN and **GRADIENT** statements are equivalent. In the case of least squares minimization, the crossproduct Jacobian is used as an approximate Hessian matrix.

## LABEL Statement

**LABEL** *variable*='label' [ , *variable*='label'... ] ;

The LABEL statement can be used to assign labels (up to 40 characters) to the decision variables listed in the **DECVAR** statement. The **INEST=** data set can also be used to assign labels. The labels are attached to the output and are used in an **OUTEST=** data set.

## LINCON Statement

**LINCON** *l\_con* [ , *l\_con*... ] ;

where *l\_con* is given in one of the following formats:

- linear\_term *operator* number
- number *operator* linear\_term

and linear\_term is of the following form:

< +|- > < number\* > variable < +|- < number\* > variable... >

The value of *operator* can be one of the following:  $\leq$ ,  $<$ ,  $\geq$ ,  $>$ , or  $=$ .

The LINCON statement specifies equality or inequality constraints

$$\sum_{j=1}^n a_{ij} x_j \{ \leq \mid = \mid \geq \} b_i \quad \text{for } i = 1, \dots, m$$

separated by commas. For example, the constraint  $4x_1 - 3x_2 = 0$  is expressed as

```
decvar x1 x2;
lincon 4 * x1 - 3 * x2 = 0;
```

and the constraints

$$10x_1 - x_2 \geq 10$$

$$x_1 + 5x_2 \geq 15$$

are expressed as

```
decvar x1 x2;
lincon 10 <= 10 * x1 - x2,
      x1 + 5 * x2 >= 15;
```



## MATRIX Statement

**MATRIX** *M\_name pattern\_definitions* ;

The MATRIX statement defines a matrix  $H$  and the vector  $g$ , which can be given in the MINQUAD or MAXQUAD statement. The matrix  $H$  and vector  $g$  are initialized to zero, so that only the nonzero elements are given. The five different forms of the MATRIX statement are illustrated with the following example:

$$H = \begin{bmatrix} 100 & 10 & 1 & 0 \\ 10 & 100 & 10 & 1 \\ 1 & 10 & 100 & 10 \\ 0 & 1 & 10 & 100 \end{bmatrix} \quad g = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix} \quad c = 0$$

Each MATRIX statement first names the matrix or vector and then lists its elements. If more than one MATRIX statement is given for the same matrix, the later definitions override the earlier ones.

The rows and columns in matrix  $H$  and vector  $g$  correspond to the order of decision variables in the DECVAR statement.

- **Full Matrix Definition:** The MATRIX statement consists of  $H\_name$  or  $g\_name$  followed by an equals sign and all (nonredundant) numerical values of the matrix  $H$  or vector  $g$ . Assuming symmetry, only the elements of the lower triangular part of the matrix  $H$  must be listed. This specification should be used mainly for small problems with almost dense  $H$  matrices.

```
MATRIX H= 100
          10 100
           1 10 100
           0 1 10 100;
MATRIX G= 1 2 3 4;
```

- **Band-diagonal Matrix Definition:** This form of *pattern definition* is useful if the  $H$  matrix has (almost) constant band-diagonal structure. The MATRIX statement consists of  $H\_name$  followed by empty brackets  $[,]$ , an equals sign, and a list of numbers to be assigned to the diagonal and successive subdiagonals.

```
MATRIX H[,]= 100 10 1;
MATRIX G= 1 2 3 4;
```

- **Sparse Matrix Definitions:** In each of the following three specification types, the  $H\_name$  or  $g\_name$  is followed by a list of *pattern definitions* separated by commas. Each *pattern definition* consists of a location specification in brackets on the left side of an equals sign that is followed by a list of numbers.
  - **(Sub)Diagonalwise:** This form of *pattern definition* is useful if the  $H$  matrix contains nonzero elements along diagonals or subdiagonals. The starting location is specified by an index pair in brackets  $[i, j]$ . The expression  $k * num$  on the right-hand side specifies that  $num$  is assigned to the elements  $[i, j], \dots, [i + k - 1, j + k - 1]$  in a diagonal direction of the  $H$  matrix. The special case  $k = 1$  can be used to assign values to single nonzero element locations in  $H$ .

```
MATRIX H [1,1]= 4 * 100,
          [2,1]= 3 * 10,
          [3,1]= 2 * 1;
MATRIX G [1,1]= 1 2 3 4;
```

- **Columnwise Starting in Diagonal:** This form of *pattern definition* is useful if the  $H$  matrix contains nonzero elements columnwise starting in the diagonal. The starting location is specified by only one index  $j$  in brackets  $[, j]$ . The  $k$  numbers at the right-hand side are assigned to the elements  $[j, j], \dots, [\min(j + k - 1, n), j]$ .

```
MATRIX H [,1]= 100  10   1,
           [,2]= 100  10   1,
           [,3]= 100  10,
           [,4]= 100;
MATRIX G [,1]= 1  2  3  4;
```

- **Rowwise Starting in First Column:** This form of *pattern definition* is useful if the  $H$  matrix contains nonzero elements rowwise ending in the diagonal. The starting location is specified by only one index  $i$  in brackets  $[i, ]$ . The  $k$  numbers at the right-hand side are assigned to the elements  $[i, 1], \dots, [i, \min(k, i)]$ .

```
MATRIX H [1,]= 100,
           [2,]=  10 100,
           [3,]=   1  10 100,
           [4,]=   0   1  10 100;
MATRIX G [1,]= 1  2  3  4;
```

---

## MIN, MAX, and LSQ Statements

**MIN** *variables* ;

**MAX** *variables* ;

**LSQ** *variables* ;

The MIN, MAX, or LSQ statement specifies the objective functions. Only one of the three statements can be used at a time and at least one must be given. The MIN and LSQ statements are for minimizing the objective function, and the MAX statement is for maximizing the objective function. The MIN, MAX, or LSQ statement lists one or more variables naming the objective functions  $f_i, i = 1, \dots, m$  (later defined by SAS program code).

- If the MIN or MAX statement lists  $m$  function names  $f_1, \dots, f_m$ , the objective function  $f$  is

$$f(x) = \sum_{i=1}^m f_i$$

- If the LSQ statement lists  $m$  function names  $f_1, \dots, f_m$ , the objective function  $f$  is

$$f(x) = \frac{1}{2} \sum_{i=1}^m f_i^2(x)$$

Note that the LSQ statement can be used only if **TECH=LEVMAR** or **TECH=HYQUAN**.

## MINQUAD and MAXQUAD Statements

**MINQUAD** *H\_name* [, *g\_name* [, *c\_number* ] ] ;

**MAXQUAD** *H\_name* [, *g\_name* [, *c\_number* ] ] ;

The MINQUAD and MAXQUAD statements specify the matrix  $H$ , vector  $g$ , and scalar  $c$  that define a quadratic objective function. The MINQUAD statement is for minimizing the objective function and the MAXQUAD statement is for maximizing the objective function.

The rows and columns in  $H$  and  $g$  correspond to the order of decision variables given in the **DECVAR** statement. Specifying the objective function with a MINQUAD or MAXQUAD statement indirectly defines the analytic derivatives for the objective function. Therefore, statements specifying derivatives are not valid in these cases. Also, only use these statements when **TECH=LICOMP** or **TECH=QUADAS** and no nonlinear constraints are imposed.

There are three ways of using the MINQUAD or MAXQUAD statement:

- **Using ARRAY Statements:**

The names *H\_name* and *g\_name* specified in the MINQUAD or MAXQUAD statement can be used in **ARRAY** statements. This specification is mainly for small problems with almost dense  $H$  matrices.

```
proc nlp p11;
  array h[2,2] .4 0
        0 4;
  minquad h, -100;
  decvar x1 x2 = -1;
  bounds 2 <= x1 <= 50,
        -50 <= x2 <= 50;
  lincon 10 <= 10 * x1 - x2;
run;
```

- **Using Elementwise Setting:**

The names *H\_name* and *g\_name* specified in the MINQUAD or MAXQUAD statement can be followed directly by one-dimensional indices specifying the corresponding elements of the matrix  $H$  and vector  $g$ . These element names can be used on the left side of numerical assignments. The one-dimensional index value  $l$  following *H\_name*, which corresponds to the element  $H_{ij}$ , is computed by  $l = (i - 1)n + j, i \geq j$ . The matrix  $H$  and vector  $g$  are initialized to zero, so that only the nonzero elements must be given. This specification is efficient for small problems with sparse  $H$  matrices.

```
proc nlp p11;
  minquad h, -100;
  decvar x1 x2;
  bounds 2 <= x1 <= 50,
        -50 <= x2 <= 50;
  lincon 10 <= 10 * x1 - x2;
  h1 = .4; h4 = 4;
run;
```

- **Using MATRIX Statements:**

The names  $H\_name$  and  $g\_name$  specified in the MINQUAD or MAXQUAD statement can be used in **MATRIX** statements. There are different ways to specify the nonzero elements of the matrix  $H$  and vector  $g$  by **MATRIX** statements. The following example illustrates one way to use the **MATRIX** statement.

```
proc nlp all;
  matrix h[1,1] = .4 4;
  minquad h, -100;
  decvar x1 x2 = -1;
  bounds 2 <= x1 <= 50,
        -50 <= x2 <= 50;
  lincon 10 <= 10 * x1 - x2;
run;
```

---

## NLINCON Statement

**NLINCON** *nlcon* [ , *nlcon* ... ] [ / *option* ] ;

**NLC** *nlcon* [ , *nlcon* ... ] [ / *option* ] ;

where *nlcon* is given in one of the following formats:

- number *operator* variable\_list *operator* number
- number *operator* variable\_list
- variable\_list *operator* number

and *operator* is  $\leq$ ,  $<$ ,  $\geq$ ,  $>$ , or  $=$ . The value of *option* can be SUMOBS or EVERYOBS.

General nonlinear equality and inequality constraints are specified with the NLINCON statement. The syntax of the NLINCON statement is similar to that of the **BOUNDS** statement with two small additions:

- The **BOUNDS** statement can contain only the names of decision variables. The NLINCON statement can also contain the names of continuous functions of the decision variables. These functions must be computed in the program statements, and since they can depend on the values of some of the variables in the **DATA=** data set, there are two possibilities:
  - If the continuous functions should be summed across all observations read from the **DATA=** data set, the NLINCON statement must be terminated by the / SUMOBS option.
  - If the continuous functions should be evaluated separately for each observation in the data set, the NLINCON statement must be terminated by the / EVERYOBS option. One constraint is generated for each observation in the data set.
- If the continuous function should be evaluated only once for the entire data set, the NLINCON statement has the same form as the **BOUNDS** statement. If this constraint does depend on the values of variables in the **DATA=** data set, it is evaluated using the data of the first observation.

One- or two-sided constraints can be specified in the NLINCON statement. However, equality constraints must be one-sided. The pairs of operators (<,<=) and (>,>=) are treated in the same way.

These three statements require the values of the three functions  $v_1, v_2, v_3$  to be between zero and ten, and they are equivalent:

```
nlincon 0 <= v1-v3,
        v1-v3 <= 10;

nlincon 0 <= v1-v3 <= 10;

nlincon 10 >= v1-v3 >= 0;
```

Also, consider the Rosen-Suzuki problem. It has three nonlinear inequality constraints:

$$\begin{aligned} 8 - x_1^2 - x_2^2 - x_3^2 - x_4^2 - x_1 + x_2 - x_3 + x_4 &\geq 0 \\ 10 - x_1^2 - 2x_2^2 - x_3^2 - 2x_4^2 + x_1 + x_4 &\geq 0 \\ 5 - 2x_1^2 - x_2^2 - x_3^2 - 2x_1 + x_2 + x_4 &\geq 0 \end{aligned}$$

These are specified as

```
nlincon c1-c3 >= 0;

c1 = 8 - x1 * x1 - x2 * x2 - x3 * x3 - x4 * x4 -
      x1 + x2 - x3 + x4;
c2 = 10 - x1 * x1 - 2 * x2 * x2 - x3 * x3 - 2 * x4 * x4 +
      x1 + x4;
c3 = 5 - 2 * x1 * x1 - x2 * x2 - x3 * x3 - 2 * x1 + x2 + x4;
```

**NOTE:** QUANEW and NMSIMP are the only optimization subroutines that support the NLINCON statement.

---

## PROFILE Statement

**PROFILE** *parms* [/[ *ALPHA= values* ] [ *options* ]];

where *parms* is given in the format *pnam\_1 pnam\_2 ... pnam\_n*, and *values* is the list of  $\alpha$  values in (0,1).

The PROFILE statement

- writes the ( $x, y$ ) coordinates of profile points for each of the listed parameters to the **OUTEST=** data set
- displays, or writes to the **OUTEST=** data set, the profile likelihood confidence limits (PL CLs) for the listed parameters for the specified  $\alpha$  values. If the approximate standard errors are available, the corresponding Wald confidence limits can be computed.

When computing the profile points or likelihood profile confidence intervals, **PROC NLP** assumes that a maximization of the log likelihood function is desired. Each point of the profile and each endpoint of the confidence interval is computed by solving corresponding nonlinear optimization problems.

The keyword **PROFILE** must be followed by the names of parameters for which the profile or the PL CLs should be computed. If the parameter name list is empty, the profiles and PL CLs for all parameters are computed. Then, optionally, the  $\alpha$  values follow. The list of  $\alpha$  values may contain **TO** and **BY** keywords. Each element must satisfy  $0 < \alpha < 1$ . The following is an example:

```
profile l11-l15 u1-u5 c /
      alpha= .9 to .1 by -.1 .09 to .01 by -.01;
```

Duplicate  $\alpha$  values or values outside (0, 1) are automatically eliminated from the list.

A number of additional options can be specified.

|                        |  |
|------------------------|--|
| <b>FFACTOR=</b> $r$    | specifies the factor relating the discrepancy function $f(\theta)$ to the $\chi^2$ quantile. The default value is $r = 2$ .  |
| <b>FORCHI=</b> F   CHI | defines the scale for the $y$ values written to the <b>OUTEST=</b> data set. For <b>FORCHI=F</b> , the $y$ values are scaled to the values of the log likelihood function $f = f(\theta)$ ; for <b>FORCHI=CHI</b> , the $y$ values are scaled so that $\hat{y} = \chi^2$ . The default value is <b>FORCHI=F</b> .  |
| <b>FEASRATIO=</b> $r$  | specifies a factor of the Wald confidence limit (or an approximation of it if standard errors are not computed) defining an upper bound for the search for confidence limits. In general, the range of $x$ values in the profile graph is between $r = 1$ and $r = 2$ times the length of the corresponding Wald interval. For many examples, the $\chi^2$ quantiles corresponding to small $\alpha$ values define a $y$ level $\hat{y} - \frac{1}{2}q_1(1 - \alpha)$ , which is too far away from $\hat{y}$ to be reached by $y(x)$ for $x$ within the range of twice the Wald confidence limit. The search for an intersection with such a $y$ level at a practically infinite value of $x$ can be computationally expensive. A smaller value for $r$ can speed up computation time by restricting the search for confidence limits to a region closer to $\hat{x}$ . The default value of $r = 1000$ practically disables the <b>FEASRATIO=</b> option. |
| <b>OUTTABLE</b>        | specifies that the complete set $\theta$ of parameter estimates rather than only $x = \theta_j$ for each confidence limit is written to the <b>OUTEST=</b> data set. This output can be helpful for further analyses on how small changes in $x = \theta_j$ affect the changes in the $\theta_i, i \neq j$ .   |

For some applications, it may be computationally less expensive to compute the PL confidence limits for a few parameters than to compute the approximate covariance matrix of many parameters, which is the basis for the Wald confidence limits. However, the computation of the profile of the discrepancy function and the corresponding CLs in general will be much more time-consuming than that of the Wald CLs.

---

## Program Statements

This section lists the program statements used to code the objective function and nonlinear constraints and their derivatives, and it documents the differences between program statements in the NLP procedure and

program statements in the DATA step. The syntax of program statements used in **PROC NLP** is identical to that used in the CALIS, GENMOD, and MODEL procedures (refer to the *SAS/ETS User's Guide*).

Most of the program statements which can be used in the SAS DATA step can also be used in the NLP procedure. See the *SAS Language Guide* or base SAS documentation for a description of the SAS program statements.

```

ABORT;
CALL name [ ( expression [, expression ... ] ) ];
DELETE;
DO [ variable = expression
    [ TO expression ] [ BY expression ]
    [, expression [ TO expression ] [ BY expression ] ... ]
]
[ WHILE expression ] [ UNTIL expression ];
END;
GOTO statement_label;
IF expression;
IF expression THEN program_statement;
    ELSE program_statement;
variable = expression;
variable + expression;
LINK statement_label;
PUT [ variable] [=] [...];
RETURN;
SELECT [ ( expression ) ];
STOP;
SUBSTR( variable, index, length ) = expression;
WHEN ( expression) program_statement;
    OTHERWISE program_statement;

```

For the most part, the SAS program statements work as they do in the SAS DATA step as documented in the *SAS Language Guide*. However, there are several differences that should be noted.

- The ABORT statement does not allow any arguments.
- The DO statement does not allow a character index variable. Thus

```
do i = 1,2,3;
```

is supported; however,

```
do i = 'A','B','C';
```

is not.

- The PUT statement, used mostly for program debugging in **PROC NLP**, supports only some of the features of the DATA step PUT statement, and has some new features that the DATA step PUT statement does not:
  - The PROC NLP PUT statement does not support line pointers, factored lists, iteration factors, overprinting, \_INFILE\_, the colon (:) format modifier, or “\$”.

- The PROC NLP PUT statement does support expressions, but the expression must be enclosed inside of parentheses. For example, the following statement displays the square root of  $x$ :  

```
put (sqrt(x));
```
- The PROC NLP PUT statement supports the print item `_PDV_` to print a formatted listing of all variables in the program. For example, the following statement displays a more readable listing of the variables than the `_all_` print item:  

```
put _pdv_;
```
- The WHEN and OTHERWISE statements allow more than one target statement. That is, DO/END groups are not necessary for multiple statement WHENs. For example, the following syntax is valid:

```
SELECT;
WHEN ( exp1 )  stmt1;
                stmt2;
WHEN ( exp2 )  stmt3;
                stmt4;
END;
```

It is recommended to keep some kind of order in the input of NLP, that is, between the statements that define decision variables and constraints and the program code used to specify objective functions and derivatives.

### Use of Special Variables in Program Code

Except for the quadratic programming techniques (QUADAS and LICOMP) that do not execute program statements during the iteration process, several special variables in the program code can be used to communicate with PROC NLP in special situations:

- **\_OBS\_** If a `DATA=` input data set is used, it is possible to access a variable `_OBS_` which contains the number of the observation processed from the data set. You should not change the content of the `_OBS_` variable. This variable enables you to modify the programming statements depending on the observation number processed in the `DATA=` input data set. For example, to set variable A to 1 when observation 10 is processed, and otherwise to 2, it is possible to specify

```
IF _OBS_ = 10 THEN A=1; ELSE A=2;
```

- **\_ITER\_** This variable is set by PROC NLP, and it contains the number of the current iteration of the optimization technique as it is displayed in the optimization history. You should not change the content of the `_ITER_` variable. It is possible to read the value of this variable in order to modify the programming statements depending on the iteration number processed. For example, to display the content of the variables A, B, and C when there are more than 100 iterations processed, it is possible to use

```
IF _ITER_ > 100 THEN PUT A B C;
```

- **\_DPROC\_** This variable is set by PROC NLP to indicate whether the code is called only to obtain the values of the  $m$  objective functions  $f_i$  (`_DPROC_=0`) or whether specified derivatives (defined by the `GRADIENT`, `JACOBIAN`, `CRPJAC`, or `HESSIAN` statement) also have to be computed (`_DPROC_=1`). You should not change the content of the `_DPROC_` variable. Checking the `_DPROC_` variable makes it possible to save computer time by not performing derivative code that is not needed by the current call. In particular, when a `DATA=` input data set is used, the code is processed many times to compute



only the function values. If the programming statements in the program contain the specification of computationally expensive first- and second-order derivatives, you can put the derivative code in an IF statement that is processed only if `_DPROC_` is not zero.

- **`_INDF_`** The `_INDF_` variable is set by `PROC NLP` to inform you of the source of calls to the function or derivative programming.

**`_INDF_=0`** indicates the first function call in a grid search. This is also the first call evaluating the programming statements if there is a grid search defined by grid values in the `DECVAR` statement.

**`_INDF_=1`** indicates further function calls in a grid search.

**`_INDF_=2`** indicates the call for the feasible starting point. This is also the first call evaluating the programming statements if there is no grid search defined.

**`_INDF_=3`** indicates calls from a gradient-checking algorithm.

**`_INDF_=4`** indicates calls from the minimization algorithm. The `_ITER_` variable contains the iteration number.

**`_INDF_=5`** If the active set algorithm leaves the feasible region (due to rounding errors), an algorithm tries to return it into the feasible region; `_INDF_=5` indicates a call that is done when such a step is successful.

**`_INDF_=6`** indicates calls from a factorial test subroutine that tests the neighborhood of a point  $x$  for optimality.

**`_INDF_=7, 8`** indicates calls from subroutines needed to compute finite-difference derivatives using only values of the objective function. No nonlinear constraints are evaluated.

**`_INDF_=9`** indicates calls from subroutines needed to compute second-order finite-difference derivatives using analytic (specified) first-order derivatives. No nonlinear constraints are evaluated.

**`_INDF_=10`** indicates calls where only the nonlinear constraints but no objective function are needed. The analytic derivatives of the nonlinear constraints are computed.

**`_INDF_=11`** indicates calls where only the nonlinear constraints but no objective function are needed. The analytic derivatives of the nonlinear constraints are not computed.

**`_INDF_=-1`** indicates the last call at the final solution.

You should not change the content of the `_INDF_` variable.

- **`_LIST_`** You can set the `_LIST_` variable to control the output during the iteration process:

**`_LIST_=0`** is equivalent to the `NOPRINT` option. It suppresses all output.

**`_LIST_=1`** is equivalent to the `PSUMMARY` but not the `PHISTORY` option. The optimization start and termination messages are displayed. However, the `PSUMMARY` option suppresses the output of the iteration history.

**`_LIST_=2`** is equivalent to the `PSHORT` option or to a combination of the `PSUMMARY` and `PHISTORY` options. The optimization start information, the iteration history, and termination message are displayed.

**`_LIST_=3`** is equivalent to not `PSUMMARY`, not `PSHORT`, and not `PALL`. The optimization start information, the iteration history, and the termination message are displayed.

**`_LIST_=4`** is equivalent to the `PALL` option. The extended optimization start information (also containing settings of termination criteria and other control parameters) is displayed.

**\_LIST\_=5** In addition to the iteration history, the vector  $x^{(k)}$  of parameter estimates is displayed for each iteration  $k$ .

**\_LIST\_=6** In addition to the iteration history, the vector  $x^{(k)}$  of parameter estimates and the gradient  $g^{(k)}$  (if available) of the objective function are displayed for each iteration  $k$ .

It is possible to set the **\_LIST\_** variable in the program code to obtain more or less output in each iteration of the optimization process. For example,

```
IF _ITER_ = 11      THEN _LIST_=5;
ELSE IF _ITER_ > 11 THEN _LIST_=1;
                  ELSE _LIST_=3;
```

- **\_TOOBIG\_** The value of **\_TOOBIG\_** is initialized to 0 by **PROC NLP**, but you can set it to 1 during the iteration, indicating problems evaluating the program statements. The objective function and derivatives must be computable at the starting point. However, during the iteration it is possible to set the **\_TOOBIG\_** variable to 1, indicating that the programming statements (computing the value of the objective function or the specified derivatives) cannot be performed for the current value of  $x_k$ . Some of the optimization techniques check the value of **\_TOOBIG\_** and try to modify the parameter estimates so that the objective function (or derivatives) can be computed in a following trial.
- **\_NOBS\_** The value of the **\_NOBS\_** variable is initialized by **PROC NLP** to the product of the number of functions *mfun* specified in the **MIN**, **MAX** or **LSQ** statement and the number of valid observations *nobs* in the current BY group of the **DATA=** input data set. The value of the **\_NOBS\_** variable is used for computing the scalar factor of the covariance matrix (see the **COV=**, **VARDEF=**, and **SIGSQ=** options). If you reset the value of the **\_NOBS\_** variable, the value that is available at the end of the iteration is used by **PROC NLP** to compute the scalar factor of the covariance matrix.
- **\_DF\_** The value of the **\_DF\_** variable is initialized by **PROC NLP** to the number  $n$  of parameters specified in the **DECVAR** statement. The value of the **\_DF\_** variable is used for computing the scalar factor  $d$  of the covariance matrix (see the **COV=**, **VARDEF=**, and **SIGSQ=** options). If you reset the value of the **\_DF\_** variable, the value that is available at the end of the iteration is used by **PROC NLP** to compute the scalar factor of the covariance matrix.
- **\_LASTF\_** In each iteration (except the first one), the value of the **\_LASTF\_** variable is set by **PROC NLP** to the final value of the objective function that was achieved during the last iteration. This value should agree with the value that is displayed in the iteration history and that is written in the **OUTEST=** data set when the **OUTITER** option is specified.

## Details: NLP Procedure

### Criteria for Optimality

PROC NLP solves

$$\begin{array}{ll} \min_{x \in \mathcal{R}^n} & f(x) \\ \text{subject to} & c_i(x) = 0, \quad i = 1, \dots, m_e \\ & c_i(x) \geq 0, \quad i = m_e + 1, \dots, m \end{array}$$

where  $f$  is the objective function and the  $c_i$ 's are the constraint functions.

A point  $x$  is feasible if it satisfies all the constraints. The feasible region  $\mathcal{G}$  is the set of all the feasible points. A feasible point  $x^*$  is a global solution of the preceding problem if no point in  $\mathcal{G}$  has a smaller function value than  $f(x^*)$ . A feasible point  $x^*$  is a local solution of the problem if there exists some open neighborhood surrounding  $x^*$  in that no point has a smaller function value than  $f(x^*)$ . Nonlinear programming algorithms cannot consistently find global minima. All the algorithms in PROC NLP find a local minimum for this problem. If you need to check whether the obtained solution is a global minimum, you may have to run PROC NLP with different starting points obtained either at random or by selecting a point on a grid that contains  $\mathcal{G}$ .

Every local minimizer  $x^*$  of this problem satisfies the following local optimality conditions:

- The gradient (vector of first derivatives)  $g(x^*) = \nabla f(x^*)$  of the objective function  $f$  (projected toward the feasible region if the problem is constrained) at the point  $x^*$  is zero.
- The Hessian (matrix of second derivatives)  $G(x^*) = \nabla^2 f(x^*)$  of the objective function  $f$  (projected toward the feasible region  $\mathcal{G}$  in the constrained case) at the point  $x^*$  is positive definite.

Most of the optimization algorithms in PROC NLP use iterative techniques that result in a sequence of points  $x^0, \dots, x^n, \dots$ , that converges to a local solution  $x^*$ . At the solution, PROC NLP performs tests to confirm that the (projected) gradient is close to zero and that the (projected) Hessian matrix is positive definite.

#### **Karush-Kuhn-Tucker Conditions**

An important tool in the analysis and design of algorithms in constrained optimization is the *Lagrangian function*, a linear combination of the objective function and the constraints:

$$L(x, \lambda) = f(x) - \sum_{i=1}^m \lambda_i c_i(x)$$

The coefficients  $\lambda_i$  are called *Lagrange multipliers*. This tool makes it possible to state necessary and sufficient conditions for a local minimum. The various algorithms in PROC NLP create sequences of points, each of which is closer than the previous one to satisfying these conditions.

Assuming that the functions  $f$  and  $c_i$  are twice continuously differentiable, the point  $x^*$  is a *local minimum* of the nonlinear programming problem, if there exists a vector  $\lambda^* = (\lambda_1^*, \dots, \lambda_m^*)$  that meets the following conditions.

**1. First-order Karush-Kuhn-Tucker conditions:**

$$\begin{aligned} c_i(x^*) &= 0, & i &= 1, \dots, m_e \\ c_i(x^*) &\geq 0, & \lambda_i^* &\geq 0, \quad \lambda_i^* c_i(x^*) = 0, & i &= m_e + 1, \dots, m \\ \nabla_x L(x^*, \lambda^*) &= 0 \end{aligned}$$

**2. Second-order conditions:** Each nonzero vector  $y \in \mathcal{R}^n$  that satisfies

$$y^T \nabla_x c_i(x^*) = 0 \begin{cases} i = 1, \dots, m_e \\ \forall i \in \{m_e + 1, \dots, m : \lambda_i^* > 0\} \end{cases}$$

also satisfies

$$y^T \nabla_x^2 L(x^*, \lambda^*) y > 0$$

Most of the algorithms to solve this problem attempt to find a combination of vectors  $x$  and  $\lambda$  for which the gradient of the Lagrangian function with respect to  $x$  is zero.

## Derivatives

The first- and second-order conditions of optimality are based on first and second derivatives of the objective function  $f$  and the constraints  $c_i$ .

The gradient vector contains the first derivatives of the objective function  $f$  with respect to the parameters  $x_1, \dots, x_n$ , as follows:

$$g(x) = \nabla f(x) = \left( \frac{\partial f}{\partial x_j} \right)$$

The  $n \times n$  symmetric Hessian matrix contains the second derivatives of the objective function  $f$  with respect to the parameters  $x_1, \dots, x_n$ , as follows:

$$G(x) = \nabla^2 f(x) = \left( \frac{\partial^2 f}{\partial x_j \partial x_k} \right)$$

For least squares problems, the  $m \times n$  Jacobian matrix contains the first-order derivatives of the  $m$  objective functions  $f_i(x)$  with respect to the parameters  $x_1, \dots, x_n$ , as follows:

$$J(x) = (\nabla f_1, \dots, \nabla f_m) = \left( \frac{\partial f_i}{\partial x_j} \right)$$

In the case of least squares problems, the crossproduct Jacobian

$$J^T J = \left( \sum_{i=1}^m \frac{\partial f_i}{\partial x_j} \frac{\partial f_i}{\partial x_k} \right)$$

is used as an approximate Hessian matrix. It is a very good approximation of the Hessian if the residuals at the solution are “small.” (If the residuals are not sufficiently small at the solution, this approach may result in

slow convergence.) The fact that it is possible to obtain Hessian approximations for this problem that do not require any computation of second derivatives means that least squares algorithms are more efficient than unconstrained optimization algorithms. Using the vector  $f(x) = (f_1(x), \dots, f_m(x))^T$  of function values, PROC NLP computes the gradient  $g(x)$  by

$$g(x) = J^T(x)f(x)$$

The  $mc \times n$  Jacobian matrix contains the first-order derivatives of the  $mc$  nonlinear constraint functions  $c_i(x)$ ,  $i = 1, \dots, mc$ , with respect to the parameters  $x_1, \dots, x_n$ , as follows:

$$CJ(x) = (\nabla c_1, \dots, \nabla c_{mc}) = \left( \frac{\partial c_i}{\partial x_j} \right)$$

PROC NLP provides three ways to compute derivatives:

- It computes analytical first- and second-order derivatives of the objective function  $f$  with respect to the  $n$  variables  $x_j$ .
- It computes first- and second-order finite-difference approximations to the derivatives. For more information, see the section “[Finite-Difference Approximations of Derivatives](#)” on page 637.
- The user supplies formulas for analytical or numerical first- and second-order derivatives of the objective function in the [GRADIENT](#), [JACOBIAN](#), [CRPJAC](#), and [HESSIAN](#) statements. The [JACNLC](#) statement can be used to specify the derivatives for the nonlinear constraints.

## Optimization Algorithms

There are three groups of optimization techniques available in PROC NLP. A particular optimizer can be selected with the [TECH=](#) option in the [PROC NLP](#) statement.

**Table 8.2** Karush-Kuhn-Tucker Conditions

| Algorithm                                     | TECH=  |
|---|--------|
| Linear Complementarity Problem                | LICOMP |
| Quadratic Active Set Technique                | QUADAS |
| Trust-Region Method                           | TRUREG |
| Newton-Raphson Method with Line Search        | NEWRAP |
| Newton-Raphson Method with Ridging            | NRRIDG |
| Quasi-Newton Methods (DBFGS, DDFP, BFGS, DFP) | QUANEW |
| Double Dogleg Method (DBFGS, DDFP)            | DBLDOG |
| Conjugate Gradient Methods (PB, FR, PR, CD)   | CONGRA |
| Nelder-Mead Simplex Method                    | NMSIMP |
| Levenberg-Marquardt Method                    | LEVMAR |
| Hybrid Quasi-Newton Methods (DBFGS, DDFP)     | HYQUAN |

Since no single optimization technique is invariably superior to others, PROC NLP provides a variety of optimization techniques that work well in various circumstances. However, it is possible to devise problems for which none of the techniques in PROC NLP can find the correct solution. Moreover, nonlinear optimization can be computationally expensive in terms of time and memory, so care must be taken when matching an algorithm to a problem.

All optimization techniques in PROC NLP use  $O(n^2)$  memory except the conjugate gradient methods, which use only  $O(n)$  memory and are designed to optimize problems with many variables. Since the techniques are iterative, they require the repeated computation of

- the function value (optimization criterion)
- the gradient vector (first-order partial derivatives)
- for some techniques, the (approximate) Hessian matrix (second-order partial derivatives)
- values of linear and nonlinear constraints
- the first-order partial derivatives (Jacobian) of nonlinear constraints

However, since each of the optimizers requires different derivatives and supports different types of constraints, some computational efficiencies can be gained. The following table shows, for each optimization technique, which derivatives are needed (FOD: first-order derivatives; SOD: second-order derivatives) and what kinds of constraints (BC: boundary constraints; LIC: linear constraints; NLC: nonlinear constraints) are supported.

| Algorithm | FOD | SOD | BC | LIC | NLC |
|-----------|-----|-----|----|-----|-----|
| LICOMP    | -   | -   | X  | X   | -   |
| QUADAS    | -   | -   | X  | X   | -   |
| TRUREG    | X   | X   | X  | X   | -   |
| NEWRAP    | X   | X   | X  | X   | -   |
| NRRIDG    | X   | X   | X  | X   | -   |
| QUANEW    | X   | -   | X  | X   | X   |
| DBLDOG    | X   | -   | X  | X   | -   |
| CONGRA    | X   | -   | X  | X   | -   |
| NMSIMP    | -   | -   | X  | X   | X   |
| LEVMAR    | X   | -   | X  | X   | -   |
| HYQUAN    | X   | -   | X  | X   | -   |

### Preparation for Using Optimization Algorithms

It is rare that a problem is submitted to an optimization algorithm “as is.” By making a few changes in your problem, you can reduce its complexity, which would increase the chance of convergence and save execution time.

- Whenever possible, use linear functions instead of nonlinear functions. PROC NLP will reward you with faster and more accurate solutions.

- Most optimization algorithms are based on quadratic approximations to nonlinear functions. You should try to avoid the use of functions that cannot be properly approximated by quadratic functions. Try to avoid the use of rational functions.

For example, the constraint

$$\frac{\sin(x)}{x+1} > 0$$

should be replaced by the equivalent constraint

$$\sin(x)(x+1) > 0$$

and the constraint

$$\frac{\sin(x)}{x+1} = 1$$

should be replaced by the equivalent constraint

$$\sin(x) - (x+1) = 0$$

- Try to avoid the use of exponential functions, if possible.
- If you can reduce the complexity of your function by the addition of a small number of variables, it may help the algorithm avoid stationary points.
- Provide the best starting point you can. A good starting point leads to better quadratic approximations and faster convergence.

## Choosing an Optimization Algorithm

The factors that go into choosing a particular optimizer for a particular problem are complex and may involve trial and error. Several things must be taken into account. First, the structure of the problem has to be considered: Is it quadratic? least squares? Does it have linear or nonlinear constraints? Next, it is important to consider the type of derivatives of the objective function and the constraints that are needed and whether these are analytically tractable or not. This section provides some guidelines for making the right choices.

For many optimization problems, computing the gradient takes more computer time than computing the function value, and computing the Hessian sometimes takes *much* more computer time and memory than computing the gradient, especially when there are many decision variables. Optimization techniques that do not use the Hessian usually require more iterations than techniques that do use Hessian approximations (such as finite differences or BFGS update) and so are often slower. Techniques that do not use Hessians at all tend to be slow and less reliable.

The derivative compiler is not efficient in the computation of second-order derivatives. For large problems, memory and computer time can be saved by programming your own derivatives using the **GRADIENT**, **JACOBIAN**, **CRPJAC**, **HESSIAN**, and **JACNLC** statements. If you are not able to specify first- and second-order derivatives of the objective function, you can rely on finite-difference gradients and Hessian update formulas. This combination is frequently used and works very well for small and medium problems. For

large problems, you are advised not to use an optimization technique that requires the computation of second derivatives.

The following provides some guidance for matching an algorithm to a particular problem.

- Quadratic Programming
  - **QUADAS**
  - **LICOMP**
- General Nonlinear Optimization
  - Nonlinear Constraints
    - \* **Small Problems: NMSIMP**  
Not suitable for highly nonlinear problems or for problems with  $n > 20$ .
    - \* **Medium Problems: QUANEW**
  - Only Linear Constraints
    - \* **Small Problems: TRUREG (NEWRAP, NRRIDG)**  
( $n \leq 40$ ) where the Hessian matrix is not expensive to compute. Sometimes NRRIDG can be faster than TRUREG, but TRUREG can be more stable. NRRIDG needs only one matrix with  $n(n + 1)/2$  double words; TRUREG and NEWRAP need two such matrices.
    - \* **Medium Problems: QUANEW (DBLDOG)**  
( $n \leq 200$ ) where the objective function and the gradient are much faster to evaluate than the Hessian. QUANEW and DBLDOG in general need more iterations than TRUREG, NRRIDG, and NEWRAP, but each iteration can be much faster. QUANEW and DBLDOG need only the gradient to update an approximate Hessian. QUANEW and DBLDOG need slightly less memory than TRUREG or NEWRAP (essentially one matrix with  $n(n + 1)/2$  double words).
    - \* **Large Problems: CONGRA**  
( $n > 200$ ) where the objective function and the gradient can be computed much faster than the Hessian and where too much memory is needed to store the (approximate) Hessian. CONGRA in general needs more iterations than QUANEW or DBLDOG, but each iteration can be much faster. Since CONGRA needs only a factor of  $n$  double-word memory, many large applications of PROC NLP can be solved only by CONGRA.
    - \* **No Derivatives: NMSIMP**  
( $n \leq 20$ ) where derivatives are not continuous or are very difficult to compute.
- Least Squares Minimization
  - **Small Problems: LEVMAR (HYQUAN)**  
( $n \leq 60$ ) where the crossproduct Jacobian matrix is inexpensive to compute. In general, LEVMAR is more reliable, but there are problems with high residuals where HYQUAN can be faster than LEVMAR.
  - **Medium Problems: QUANEW (DBLDOG)**  
( $n \leq 200$ ) where the objective function and the gradient are much faster to evaluate than the crossproduct Jacobian. QUANEW and DBLDOG in general need more iterations than LEVMAR or HYQUAN, but each iteration can be much faster.



- **Large Problems:** CONGRA
- **No Derivatives:** NMSIMP

### Quadratic Programming Method

The QUADAS and LICOMP algorithms can be used to minimize or maximize a quadratic objective function,

$$f(x) = \frac{1}{2}x^T Gx + g^T x + c, \quad \text{with } G^T = G$$

subject to linear or boundary constraints

$$Ax \geq b \quad \text{or} \quad l_j \leq x_j \leq u_j$$

where  $x = (x_1, \dots, x_n)^T$ ,  $g = (g_1, \dots, g_n)^T$ ,  $G$  is an  $n \times n$  symmetric matrix,  $A$  is an  $m \times n$  matrix of general linear constraints, and  $b = (b_1, \dots, b_m)^T$ . The value of  $c$  modifies only the value of the objective function, not its derivatives, and the location of the optimizer  $x^*$  does not depend on the value of the constant term  $c$ . For QUADAS or LICOMP, the objective function must be specified using the **MINQUAD** or **MAXQUAD** statement or using an **INQUAD=** data set.

In this case, derivatives do not need to be specified because the gradient vector

$$\nabla f(x) = Gx + g$$

and the  $n \times n$  Hessian matrix

$$\nabla^2 f(x) = G$$

are easily obtained from the data input.

Simple boundary and general linear constraints can be specified using the **BOUNDS** or **LINCON** statement or an **INQUAD=** or **INEST=** data set.

#### General Quadratic Programming (QUADAS)

The QUADAS algorithm is an active set method that iteratively updates the  $QT$  decomposition of the matrix  $A_k$  of active linear constraints and the Cholesky factor of the projected Hessian  $Z_k^T G Z_k$  simultaneously. The update of active boundary and linear constraints is done separately; refer to Gill et al. (1984). Here  $Q$  is an  $n_{free} \times n_{free}$  orthogonal matrix composed of vectors spanning the null space  $Z$  of  $A_k$  in its first  $n_{free} - n_{alc}$  columns and range space  $Y$  in its last  $n_{alc}$  columns;  $T$  is an  $n_{alc} \times n_{alc}$  triangular matrix of special form,  $t_{ij} = 0$  for  $i < n - j$ , where  $n_{free}$  is the number of free parameters ( $n$  minus the number of active boundary constraints), and  $n_{alc}$  is the number of active linear constraints. The Cholesky factor of the projected Hessian matrix  $Z_k^T G Z_k$  and the  $QT$  decomposition are updated simultaneously when the active set changes.

#### Linear Complementarity (LICOMP)

The LICOMP technique solves a quadratic problem as a linear complementarity problem. It can be used only if  $G$  is positive (negative) semidefinite for minimization (maximization) and if the parameters are restricted to be positive.

This technique finds a point that meets the Karush-Kuhn-Tucker conditions by solving the linear complementarity problem

$$w = Mz + q$$

with constraints

$$w^T z \geq 0, \quad w \geq 0, \quad z \geq 0,$$

where

$$z = \begin{bmatrix} x \\ \lambda \end{bmatrix} \quad M = \begin{bmatrix} G & -A^T \\ A & 0 \end{bmatrix} \quad q = \begin{bmatrix} g \\ -b \end{bmatrix}$$

Only the `LCEPSILON=` option can be used to specify a tolerance used in computations.

## General Nonlinear Optimization

### **Trust-Region Optimization (TRUREG)**

The trust region method uses the gradient  $g(x^{(k)})$  and Hessian matrix  $G(x^{(k)})$  and thus requires that the objective function  $f(x)$  have continuous first- and second-order derivatives inside the feasible region.

The trust region method iteratively optimizes a quadratic approximation to the nonlinear objective function within a hyperelliptic trust region with radius  $\Delta$  that constrains the step length corresponding to the quality of the quadratic approximation. The trust region method is implemented using Dennis, Gay, and Welsch (1981), Gay (1983).

The trust region method performs well for small to medium problems and does not require many function, gradient, and Hessian calls. If the computation of the Hessian matrix is computationally expensive, use the `UPDATE=` option for update formulas (that gradually build the second-order information in the Hessian). For larger problems, the conjugate gradient algorithm may be more appropriate.

### **Newton-Raphson Optimization With Line-Search (NEWRAP)**

The NEWRAP technique uses the gradient  $g(x^{(k)})$  and Hessian matrix  $G(x^{(k)})$  and thus requires that the objective function have continuous first- and second-order derivatives inside the feasible region. If second-order derivatives are computed efficiently and precisely, the NEWRAP method may perform well for medium to large problems, and it does not need many function, gradient, and Hessian calls.

This algorithm uses a pure Newton step when the Hessian is positive definite and when the Newton step reduces the value of the objective function successfully. Otherwise, a combination of ridging and line search is done to compute successful steps. If the Hessian is not positive definite, a multiple of the identity matrix is added to the Hessian matrix to make it positive definite (Eskow and Schnabel 1991).

In each iteration, a line search is done along the search direction to find an approximate optimum of the objective function. The default line-search method uses quadratic interpolation and cubic extrapolation (`LIS=2`).

### **Newton-Raphson Ridge Optimization (NRRIDG)**

The NRRIDG technique uses the gradient  $g(x^{(k)})$  and Hessian matrix  $G(x^{(k)})$  and thus requires that the objective function have continuous first- and second-order derivatives inside the feasible region.

This algorithm uses a pure Newton step when the Hessian is positive definite and when the Newton step reduces the value of the objective function successfully. If at least one of these two conditions is not satisfied, a multiple of the identity matrix is added to the Hessian matrix. If this algorithm is used for least squares problems, it performs a ridged Gauss-Newton minimization.

The NRRIDG method performs well for small to medium problems and does not need many function, gradient, and Hessian calls. However, if the computation of the Hessian matrix is computationally expensive, one of the (dual) quasi-Newton or conjugate gradient algorithms may be more efficient.

Since NRRIDG uses an orthogonal decomposition of the approximate Hessian, each iteration of NRRIDG can be slower than that of NEWRAP, which works with Cholesky decomposition. However, usually NRRIDG needs fewer iterations than NEWRAP.

### **Quasi-Newton Optimization (QUANEW)**

The (dual) quasi-Newton method uses the gradient  $g(x^{(k)})$  and does not need to compute second-order derivatives since they are approximated. It works well for medium to moderately large optimization problems where the objective function and the gradient are much faster to compute than the Hessian, but in general it requires more iterations than the techniques TRUREG, NEWRAP, and NRRIDG, which compute second-order derivatives.

The QUANEW algorithm depends on whether or not there are nonlinear constraints.

**Unconstrained or Linearly Constrained Problems** If there are no nonlinear constraints, QUANEW is either

- the original quasi-Newton algorithm that updates an approximation of the inverse Hessian, or
- the dual quasi-Newton algorithm that updates the Cholesky factor of an approximate Hessian (default),

depending on the value of the `UPDATE=` option. For problems with general linear inequality constraints, the dual quasi-Newton methods can be more efficient than the original ones.

Four update formulas can be specified with the `UPDATE=` option:

|       |  |
|-------|--|
| DBFGS | performs the dual BFGS (Broyden, Fletcher, Goldfarb, & Shanno) update of the Cholesky factor of the Hessian matrix. This is the default. |
| DDFP  | performs the dual DFP (Davidon, Fletcher, & Powell) update of the Cholesky factor of the Hessian matrix.                                 |
| BFGS  | performs the original BFGS (Broyden, Fletcher, Goldfarb, & Shanno) update of the inverse Hessian matrix.                                 |
| DFP   | performs the original DFP (Davidon, Fletcher, & Powell) update of the inverse Hessian matrix.  |

In each iteration, a line search is done along the search direction to find an approximate optimum. The default line-search method uses quadratic interpolation and cubic extrapolation to obtain a step length  $\alpha$  satisfying the Goldstein conditions. One of the Goldstein conditions can be violated if the feasible region defines an upper limit of the step length. Violating the left-side Goldstein condition can affect the positive definiteness of the quasi-Newton update. In those cases, either the update is skipped or the iterations are restarted with an identity matrix resulting in the steepest descent or ascent search direction. Line-search algorithms other than the default one can be specified with the `LINESEARCH=` option.

**Nonlinearly Constrained Problems** The algorithm used for nonlinearly constrained quasi-Newton optimization is an efficient modification of Powell's (1978a, 1982b) *Variable Metric Constrained WatchDog* (VMCWD) algorithm. A similar but older algorithm (VF02AD) is part of the Harwell library. Both VMCWD and VF02AD use Fletcher's VE02AD algorithm (part of the Harwell library) for positive-definite quadratic programming. The PROC NLP QUANEW implementation uses a quadratic programming subroutine that updates and downdates the approximation of the Cholesky factor when the active set changes. The nonlinear QUANEW algorithm is not a feasible-point algorithm, and the value of the objective function need not decrease (minimization) or increase (maximization) monotonically. Instead, the algorithm tries to reduce a linear combination of the objective function and constraint violations, called the *merit function*.

The following are similarities and differences between this algorithm and the VMCWD algorithm:

- A modification of this algorithm can be performed by specifying **VERSION=1**, which replaces the update of the Lagrange vector  $\mu$  with the original update of Powell (1978a, b) that is used in VF02AD. This can be helpful for some applications with linearly dependent active constraints.
- If the **VERSION** option is not specified or if **VERSION=2** is specified, the evaluation of the Lagrange vector  $\mu$  is performed in the same way as Powell (1982b) describes.
- Instead of updating an approximate Hessian matrix, this algorithm uses the dual BFGS (or DFP) update that updates the Cholesky factor of an approximate Hessian. If the condition of the updated matrix gets too bad, a restart is done with a positive diagonal matrix. At the end of the first iteration after each restart, the Cholesky factor is scaled.
- The Cholesky factor is loaded into the quadratic programming subroutine, automatically ensuring positive definiteness of the problem. During the quadratic programming step, the Cholesky factor of the projected Hessian matrix  $Z_k^T G Z_k$  and the  $QT$  decomposition are updated simultaneously when the active set changes. Refer to Gill et al. (1984) for more information.
- The line-search strategy is very similar to that of Powell (1982b). However, this algorithm does not call for derivatives during the line search, so the algorithm generally needs fewer derivative calls than function calls. VMCWD always requires the same number of derivative and function calls. Sometimes Powell's line-search method uses steps that are too long. In these cases, use the **INSTEP=** option to restrict the step length  $\alpha$ .
- The watchdog strategy is similar to that of Powell (1982b); however, it does not return automatically after a fixed number of iterations to a former better point. A return here is further delayed if the observed function reduction is close to the expected function reduction of the quadratic model.
- The Powell termination criterion still is used (as **FCONV2**) but the QUANEW implementation uses two additional termination criteria (**GCONV** and **ABSGCONV**).

The nonlinear QUANEW algorithm needs the Jacobian matrix of the first-order derivatives (constraints normals) of the constraints  $CJ(x)$ .

You can specify two update formulas with the **UPDATE=** option:

|       |  |
|-------|--|
| DBFGS | performs the dual BFGS update of the Cholesky factor of the Hessian matrix. This is the default. |
| DDFP  | performs the dual DFP update of the Cholesky factor of the Hessian matrix.                       |

This algorithm uses its own line-search technique. No options or parameters (except the **INSTEP=** option) controlling the line search in the other algorithms apply here. In several applications, large steps in the first iterations were troublesome. You can use the **INSTEP=** option to impose an upper bound for the step length  $\alpha$  during the first five iterations. You may also use the **INHESIAN=** option to specify a different starting approximation for the Hessian. Choosing simply the **INHESIAN** option will use the Cholesky factor of a (possibly ridged) finite-difference approximation of the Hessian to initialize the quasi-Newton update process. The values of the **LCSINGULAR=**, **LCEPSILON=**, and **LCDEACT=** options, which control the processing of linear and boundary constraints, are valid only for the quadratic programming subroutine used in each iteration of the nonlinear constraints QUANEW algorithm.

### **Double Dogleg Optimization (DBLDOG)**

The double dogleg optimization method combines the ideas of the quasi-Newton and trust region methods. The double dogleg algorithm computes in each iteration the step  $s^{(k)}$  as a linear combination of the steepest descent or ascent search direction  $s_1^{(k)}$  and a quasi-Newton search direction  $s_2^{(k)}$ :

$$s^{(k)} = \alpha_1 s_1^{(k)} + \alpha_2 s_2^{(k)}$$

The step is requested to remain within a prespecified trust region radius; refer to Fletcher (1987, p. 107). Thus, the DBLDOG subroutine uses the dual quasi-Newton update but does not perform a line search. Two update formulas can be specified with the **UPDATE=** option:

|       |  |
|-------|--|
| DBFGS | performs the dual BFGS (Broyden, Fletcher, Goldfarb, & Shanno) update of the Cholesky factor of the Hessian matrix. This is the default. |
| DDFP  | performs the dual DFP (Davidon, Fletcher, & Powell) update of the Cholesky factor of the Hessian matrix.                                 |

The double dogleg optimization technique works well for medium to moderately large optimization problems where the objective function and the gradient are much faster to compute than the Hessian. The implementation is based on Dennis and Mei (1979) and Gay (1983) but is extended for dealing with boundary and linear constraints. DBLDOG generally needs more iterations than the techniques TRUREG, NEWRAP, or NRRIDG that need second-order derivatives, but each of the DBLDOG iterations is computationally cheap. Furthermore, DBLDOG needs only gradient calls for the update of the Cholesky factor of an approximate Hessian.

### **Conjugate Gradient Optimization (CONGRA)**

Second-order derivatives are not used by CONGRA. The CONGRA algorithm can be expensive in function and gradient calls but needs only  $O(n)$  memory for unconstrained optimization. In general, many iterations are needed to obtain a precise solution, but each of the CONGRA iterations is computationally cheap. Four different update formulas for generating the conjugate directions can be specified using the **UPDATE=** option:

|    |  |
|----|--|
| PB | performs the automatic restart update method of Powell (1977) and Beale (1972). This is the default. |
| FR | performs the Fletcher-Reeves update (Fletcher 1987).   |
| PR | performs the Polak-Ribiere update (Fletcher 1987).   |
| CD | performs a conjugate-descent update of Fletcher (1987).  |

The default value is `UPDATE=PB`, since it behaved best in most test examples. You are advised to avoid the option `UPDATE=CD`, as it behaved worst in most test examples.

The CONGRA subroutine should be used for optimization problems with large  $n$ . For the unconstrained or boundary constrained case, CONGRA needs only  $O(n)$  bytes of working memory, whereas all other optimization methods require order  $O(n^2)$  bytes of working memory. During  $n$  successive iterations, uninterrupted by restarts or changes in the working set, the conjugate gradient algorithm computes a cycle of  $n$  conjugate search directions. In each iteration, a line search is done along the search direction to find an approximate optimum of the objective function. The default line-search method uses quadratic interpolation and cubic extrapolation to obtain a step length  $\alpha$  satisfying the Goldstein conditions. One of the Goldstein conditions can be violated if the feasible region defines an upper limit for the step length. Other line-search algorithms can be specified with the `LINESEARCH=` option.

### ***Nelder-Mead Simplex Optimization (NMSIMP)***

The Nelder-Mead simplex method does not use any derivatives and does not assume that the objective function has continuous derivatives. The objective function itself needs to be continuous. This technique requires a large number of function evaluations. It is unlikely to give accurate results for  $n \gg 40$ .

Depending on the kind of constraints, one of the following Nelder-Mead simplex algorithms is used:

- unconstrained or only boundary constrained problems

The original Nelder-Mead simplex algorithm is implemented and extended to boundary constraints. This algorithm does not compute the objective for infeasible points. This algorithm is automatically invoked if the `LINCON` or `NLINCON` statement is not specified.

- general linearly constrained or nonlinearly constrained problems

A slightly modified version of Powell's (1992) COBYLA (Constrained Optimization BY Linear Approximations) implementation is used. This algorithm is automatically invoked if either the `LINCON` or the `NLINCON` statement is specified.

The original Nelder-Mead algorithm cannot be used for general linear or nonlinear constraints but can be faster for the unconstrained or boundary constrained case. The original Nelder-Mead algorithm changes the shape of the simplex adapting the nonlinearities of the objective function which contributes to an increased speed of convergence. The two NMSIMP subroutines use special sets of termination criteria. For more details, refer to the section "[Termination Criteria](#)" on page 641.

### ***Powell's COBYLA Algorithm (COBYLA)***

Powell's COBYLA algorithm is a sequential trust region algorithm (originally with a monotonically decreasing radius  $\rho$  of a spherical trust region) that tries to maintain a regular-shaped simplex over the iterations. A small modification was made to the original algorithm that permits an increase of the trust region radius  $\rho$  in special situations. A sequence of iterations is performed with a constant trust region radius  $\rho$  until the computed objective function reduction is much less than the predicted reduction. Then, the trust region radius  $\rho$  is reduced. The trust region radius is increased only if the computed function reduction is relatively close to the predicted reduction and the simplex is well-shaped. The start radius  $\rho_{beg}$  and the final radius  $\rho_{end}$  can be specified using  $\rho_{beg}=\text{INSTEP}$  and  $\rho_{end}=\text{ABSXTOL}$ . The convergence to small values of  $\rho_{end}$  (high precision) may take many calls of the function and constraint modules and may result in numerical problems. There are two main reasons for the slow convergence of the COBYLA algorithm:



- Only linear approximations of the objective and constraint functions are used locally.
- Maintaining the regular-shaped simplex and not adapting its shape to nonlinearities yields very small simplices for highly nonlinear functions (for example, fourth-order polynomials).

## Nonlinear Least Squares Optimization

### **Levenberg-Marquardt Least Squares Method (LEVMAR)**

The Levenberg-Marquardt method is a modification of the trust region method for nonlinear least squares problems and is implemented as in Moré (1978).

This is the recommended algorithm for small to medium least squares problems. Large least squares problems can be transformed into minimization problems, which can be processed with conjugate gradient or (dual) quasi-Newton techniques. In each iteration, LEVMAR solves a quadratically constrained quadratic minimization problem that restricts the step to stay at the surface of or inside an  $n$ -dimensional elliptical (or spherical) trust region. In each iteration, LEVMAR uses the crossproduct Jacobian matrix  $J^T J$  as an approximate Hessian matrix.

### **Hybrid Quasi-Newton Least Squares Methods (HYQUAN)**

In each iteration of one of the Fletcher and Xu (1987) (refer also to Al-Baali and Fletcher (1985,1986)) hybrid quasi-Newton methods, a criterion is used to decide whether a Gauss-Newton or a dual quasi-Newton search direction is appropriate. The **VERSION=** option can be used to choose one of three criteria (HY1, HY2, HY3) proposed by Fletcher and Xu (1987). The default is **VERSION=2**; that is, HY2. In each iteration, HYQUAN computes the crossproduct Jacobian (used for the Gauss-Newton step), updates the Cholesky factor of an approximate Hessian (used for the quasi-Newton step), and does a line search to compute an approximate minimum along the search direction. The default line-search technique used by HYQUAN is especially designed for least squares problems (refer to Lindström and Wedin (1984) and Al-Baali and Fletcher (1986)). Using the **LINESEARCH=** option you can choose a different line-search algorithm than the default one.

Two update formulas can be specified with the **UPDATE=** option:

|       |  |
|-------|--|
| DBFGS | performs the dual BFGS (Broyden, Fletcher, Goldfarb, and Shanno) update of the Cholesky factor of the Hessian matrix. This is the default. |
| DDFP  | performs the dual DFP (Davidon, Fletcher, and Powell) update of the Cholesky factor of the Hessian matrix.                                 |

The HYQUAN subroutine needs about the same amount of working memory as the LEVMAR algorithm. In most applications, LEVMAR seems to be superior to HYQUAN, and using HYQUAN is recommended only when problems are experienced with the performance of LEVMAR.

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## Finite-Difference Approximations of Derivatives

The **FD=** and **FDHESSIAN=** options specify the use of finite-difference approximations of the derivatives. The **FD=** option specifies that all derivatives are approximated using function evaluations, and the **FDHESSIAN=** option specifies that second-order derivatives are approximated using gradient evaluations.

Computing derivatives by finite-difference approximations can be very time-consuming, especially for second-order derivatives based only on values of the objective function ( **FD=** option). If analytical derivatives are difficult to obtain (for example, if a function is computed by an iterative process), you might consider one of the optimization techniques that uses first-order derivatives only (**TECH=QUANEW**, **TECH=DBLDOG**, or **TECH=CONGRA**).

### Forward-Difference Approximations

The forward-difference derivative approximations consume less computer time but are usually not as precise as those using central-difference formulas.

- First-order derivatives:  $n$  additional function calls are needed:

$$g_i = \frac{\partial f}{\partial x_i} = \frac{f(x + h_i e_i) - f(x)}{h_i}$$

- Second-order derivatives based on function calls only (Dennis and Schnabel 1983, p. 80, 104): for dense Hessian,  $n(n + 3)/2$  additional function calls are needed:

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{f(x + h_i e_i + h_j e_j) - f(x + h_i e_i) - f(x + h_j e_j) + f(x)}{h_j}$$

- Second-order derivatives based on gradient calls (Dennis and Schnabel 1983, p. 103):  $n$  additional gradient calls are needed:

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{g_i(x + h_j e_j) - g_i(x)}{2h_j} + \frac{g_j(x + h_i e_i) - g_j(x)}{2h_i}$$

### Central-Difference Approximations

- First-order derivatives:  $2n$  additional function calls are needed:

$$g_i = \frac{\partial f}{\partial x_i} = \frac{f(x + h_i e_i) - f(x - h_i e_i)}{2h_i}$$

- Second-order derivatives based on function calls only (Abramowitz and Stegun 1972, p. 884): for dense Hessian,  $2n(n + 1)$  additional function calls are needed:

$$\frac{\partial^2 f}{\partial x_i^2} = \frac{-f(x + 2h_i e_i) + 16f(x + h_i e_i) - 30f(x) + 16f(x - h_i e_i) - f(x - 2h_i e_i)}{12h_i^2}$$

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{f(x + h_i e_i + h_j e_j) - f(x + h_i e_i - h_j e_j) - f(x - h_i e_i + h_j e_j) + f(x - h_i e_i - h_j e_j)}{4h_i h_j}$$

- Second-order derivatives based on gradient:  $2n$  additional gradient calls are needed:

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{g_i(x + h_j e_j) - g_i(x - h_j e_j)}{4h_j} + \frac{g_j(x + h_i e_i) - g_j(x - h_i e_i)}{4h_i}$$



The **FDIGITS=** and **CDIGITS=** options can be used for specifying the number of accurate digits in the evaluation of objective function and nonlinear constraints. These specifications are helpful in determining an appropriate interval length  $h$  to be used in the finite-difference formulas.

The **FDINT=** option specifies whether the finite-difference intervals  $h$  should be computed using an algorithm of Gill, Murray, Saunders, and Wright (1983) or based only on the information of the **FDIGITS=** and **CDIGITS=** options. For **FDINT=OBJ**, the interval  $h$  is based on the behavior of the objective function; for **FDINT=CON**, the interval  $h$  is based on the behavior of the nonlinear constraints functions; and for **FDINT=ALL**, the interval  $h$  is based on the behaviors of both the objective function and the nonlinear constraints functions. Note that the algorithm of Gill, Murray, Saunders, and Wright (1983) to compute the finite-difference intervals  $h_j$  can be very expensive in the number of function calls. If the **FDINT=** option is specified, it is currently performed twice, the first time before the optimization process starts and the second time after the optimization terminates.

If **FDINT=** is not specified, the step lengths  $h_j$ ,  $j = 1, \dots, n$ , are defined as follows:

- for the forward-difference approximation of first-order derivatives using function calls and second-order derivatives using gradient calls:  $h_j = \sqrt[2]{\eta_j}(1 + |x_j|)$ ,
- for the forward-difference approximation of second-order derivatives that use only function calls and all central-difference formulas:  $h_j = \sqrt[3]{\eta_j}(1 + |x_j|)$ ,

where  $\eta$  is defined using the **FDIGITS=** option:

- If the number of accurate digits is specified with **FDIGITS=r**,  $\eta$  is set to  $10^{-r}$ .
- If **FDIGITS=** is not specified,  $\eta$  is set to the machine precision  $\epsilon$ .

For **FDINT=OBJ** and **FDINT=ALL**, the **FDIGITS=** specification is used in computing the forward and central finite-difference intervals.

If the problem has nonlinear constraints and the **FD=** option is specified, the first-order formulas are used to compute finite-difference approximations of the Jacobian matrix  $J C(x)$ . You can use the **CDIGITS=** option to specify the number of accurate digits in the constraint evaluations to define the step lengths  $h_j$ ,  $j = 1, \dots, n$ . For **FDINT=CON** and **FDINT=ALL**, the **CDIGITS=** specification is used in computing the forward and central finite-difference intervals.

**NOTE:** If you are unable to specify analytic derivatives and the finite-difference approximations provided by PROC NLP are not good enough to solve your problem, you may program better finite-difference approximations using the **GRADIENT**, **JACOBIAN**, **CRPJAC**, or **HESSIAN** statement and the program statements.

---

## Hessian and CRP Jacobian Scaling

The rows and columns of the Hessian and crossproduct Jacobian matrix can be scaled when using the trust region, Newton-Raphson, double dogleg, and Levenberg-Marquardt optimization techniques. Each element  $G_{i,j}$ ,  $i, j = 1, \dots, n$ , is divided by the scaling factor  $d_i \times d_j$ , where the scaling vector  $d = (d_1, \dots, d_n)$  is iteratively updated in a way specified by the **HESCAL=i** option, as follows:

$i = 0$  No scaling is done (equivalent to  $d_i = 1$ ).

$i \neq 0$  First iteration and each restart iteration:

$$d_i^{(0)} = \sqrt{\max(|G_{i,i}^{(0)}|, \epsilon)}$$

$i = 1$  refer to Moré (1978):

$$d_i^{(k+1)} = \max \left( d_i^{(k)}, \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)} \right)$$

$i = 2$  refer to Dennis, Gay, and Welsch (1981):

$$d_i^{(k+1)} = \max \left( 0.6d_i^{(k)}, \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)} \right)$$

$i = 3$   $d_i$  is reset in each iteration:

$$d_i^{(k+1)} = \sqrt{\max(|G_{i,i}^{(k)}|, \epsilon)}$$

where  $\epsilon$  is the relative machine precision or, equivalently, the largest double precision value that when added to 1 results in 1.

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## Testing the Gradient Specification

There are three main ways to check the correctness of derivative specifications:

- Specify the **FD=** or **FDHESSIAN=** option in the **PROC NLP** statement to compute finite-difference approximations of first- and second-order derivatives. In many applications, the finite-difference approximations are computed with high precision and do not differ too much from the derivatives that are computed by specified formulas.
- Specify the **GRADCHECK** option in the **PROC NLP** statement to compute and display a test vector and a test matrix of the gradient values at the starting point  $x^{(0)}$  by the method of Wolfe (1982). If you do not specify the **GRADCHECK** option, a fast derivative test identical to the **GRADCHECK=FAST** specification is done by default.
- If the default analytical derivative compiler is used or if derivatives are specified using the **GRADIENT** or **JACOBIAN** statement, the gradient or Jacobian computed at the initial point  $x^{(0)}$  is tested by default using finite-difference approximations. In some examples, the relative test can show significant differences between the two forms of derivatives, resulting in a warning message indicating that the specified derivatives could be wrong, even if they are correct. This happens especially in cases where the magnitude of the gradient at the starting point  $x^{(0)}$  is small.

The algorithm of Wolfe (1982) is used to check whether the gradient  $g(x)$  specified by a **GRADIENT** statement (or indirectly by a **JACOBIAN** statement) is appropriate for the objective function  $f(x)$  specified by the program statements.

Using function and gradient evaluations in the neighborhood of the starting point  $x^{(0)}$ , second derivatives are approximated by finite-difference formulas. Forward differences of gradient values are used to approximate the Hessian element  $G_{jk}$ ,

$$G_{jk} \approx H_{jk} = \frac{g_j(x + \delta e_k) - g_j(x)}{\delta}$$

where  $\delta$  is a small step length and  $e_k = (0, \dots, 0, 1, 0, \dots, 0)^T$  is the unit vector along the  $k$ th coordinate axis. The test vector  $s$ , with

$$s_j = H_{jj} - \frac{2}{\delta} \left\{ \frac{f(x + \delta e_j) - f(x)}{\delta} - g_j(x) \right\}$$

contains the differences between two sets of finite-difference approximations for the diagonal elements of the Hessian matrix

$$G_{jj} = \partial^2 f(x^{(0)}) / \partial x_j^2, \quad j = 1, \dots, n$$

The test matrix  $\Delta H$  contains the absolute differences of symmetric elements in the approximate Hessian  $|H_{jk} - H_{kj}|$ ,  $j, k = 1, \dots, n$ , generated by forward differences of the gradient elements.

If the specification of the first derivatives is correct, the elements of the test vector and test matrix should be relatively small. The location of large elements in the test matrix points to erroneous coordinates in the gradient specification. For very large optimization problems, this algorithm can be too expensive in terms of computer time and memory.

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## Termination Criteria

All optimization techniques stop iterating at  $x^{(k)}$  if at least one of a set of termination criteria is satisfied. PROC NLP also terminates if the point  $x^{(k)}$  is fully constrained by  $n$  linearly independent active linear or boundary constraints, and all Lagrange multiplier estimates of active inequality constraints are greater than a small negative tolerance.

Since the Nelder-Mead simplex algorithm does not use derivatives, no termination criterion is available based on the gradient of the objective function. Powell's COBYLA algorithm uses only one more termination criterion. COBYLA is a trust region algorithm that sequentially reduces the radius  $\rho$  of a spherical trust region from a start radius  $\rho_{beg} = \text{INSTEP}$  to the final radius  $\rho_{end} = \text{ABSXTOL}$ . The default value is  $\rho_{end} = 1\text{e-}4$ . The convergence to small values of  $\rho_{end}$  (high precision) may take many calls of the function and constraint modules and may result in numerical problems.

In some applications, the small default value of the **ABSGCONV=** criterion is too difficult to satisfy for some of the optimization techniques. This occurs most often when finite-difference approximations of derivatives are used.

The default setting for the **GCONV=** option sometimes leads to early termination far from the location of the optimum. This is especially true for the special form of this criterion used in the CONGRA optimization.

The QUANEW algorithm for nonlinearly constrained optimization does not monotonically reduce the value of either the objective function or some kind of merit function which combines objective and constraint functions. Furthermore, the algorithm uses the watchdog technique with backtracking (Chamberlain et al. 1982). Therefore, no termination criteria were implemented that are based on the values ( $x$  or  $f$ ) of successive

iterations. In addition to the criteria used by all optimization techniques, three more termination criteria are currently available. They are based on satisfying the Karush-Kuhn-Tucker conditions, which require that the gradient of the Lagrange function is zero at the optimal point  $(x^*, \lambda^*)$ :

$$\nabla_x L(x^*, \lambda^*) = 0$$

For more information, refer to the section “Criteria for Optimality” on page 625.

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## Active Set Methods

The parameter vector  $x \in \mathcal{R}^n$  may be subject to a set of  $m$  linear equality and inequality constraints:

$$\begin{aligned} \sum_{j=1}^n a_{ij} x_j &= b_i, \quad i = 1, \dots, m_e \\ \sum_{j=1}^n a_{ij} x_j &\geq b_i, \quad i = m_e + 1, \dots, m \end{aligned}$$

The coefficients  $a_{ij}$  and right-hand sides  $b_i$  of the equality and inequality constraints are collected in the  $m \times n$  matrix  $A$  and the  $m$ -vector  $b$ .

The  $m$  linear constraints define a feasible region  $\mathcal{G}$  in  $\mathcal{R}^n$  that must contain the point  $x^*$  that minimizes the problem. If the feasible region  $\mathcal{G}$  is empty, no solution to the optimization problem exists.

All optimization techniques in PROC NLP (except those processing nonlinear constraints) are *active set methods*. The iteration starts with a feasible point  $x^{(0)}$ , which either is provided by the user or can be computed by the Schittkowski and Stoer (1979) algorithm implemented in PROC NLP. The algorithm then moves from one feasible point  $x^{(k-1)}$  to a better feasible point  $x^{(k)}$  along a feasible search direction  $s^{(k)}$ :

$$x^{(k)} = x^{(k-1)} + \alpha^{(k)} s^{(k)}, \quad \alpha^{(k)} > 0$$

Theoretically, the path of points  $x^{(k)}$  never leaves the feasible region  $\mathcal{G}$  of the optimization problem, but it can hit its boundaries. The active set  $\mathcal{A}^{(k)}$  of point  $x^{(k)}$  is defined as the index set of all linear equality constraints and those inequality constraints that are satisfied at  $x^{(k)}$ . If no constraint is active for  $x^{(k)}$ , the point is located in the interior of  $\mathcal{G}$ , and the active set  $\mathcal{A}^{(k)}$  is empty. If the point  $x^{(k)}$  in iteration  $k$  hits the boundary of inequality constraint  $i$ , this constraint  $i$  becomes active and is added to  $\mathcal{A}^{(k)}$ . Each equality or active inequality constraint reduces the dimension (degrees of freedom) of the optimization problem.

In practice, the active constraints can be satisfied only with finite precision. The `LCEPSILON= $r$`  option specifies the range for active and violated linear constraints. If the point  $x^{(k)}$  satisfies the condition

$$\left| \sum_{j=1}^n a_{ij} x_j^{(k)} - b_i \right| \leq t$$

where  $t = r \times (|b_i| + 1)$ , the constraint  $i$  is recognized as an active constraint. Otherwise, the constraint  $i$  is either an inactive inequality or a violated inequality or equality constraint. Due to rounding errors in computing the projected search direction, error can be accumulated so that an iterate  $x^{(k)}$  steps out of the feasible region. In those cases, PROC NLP may try to pull the iterate  $x^{(k)}$  into the feasible region. However, in some cases the algorithm needs to increase the feasible region by increasing the `LCEPSILON= $r$`  value. If this happens it is indicated by a message displayed in the log output.

If you cannot expect an improvement in the value of the objective function by moving from an active constraint back into the interior of the feasible region, you use this inequality constraint as an equality constraint in the next iteration. That means the active set  $\mathcal{A}^{(k+1)}$  still contains the constraint  $i$ . Otherwise you release the active inequality constraint and increase the dimension of the optimization problem in the next iteration.

A serious numerical problem can arise when some of the active constraints become (nearly) linearly dependent. Linearly dependent equality constraints are removed before entering the optimization. You can use the `LCSINGULAR=` option to specify a criterion  $r$  used in the update of the QR decomposition that decides whether an active constraint is linearly dependent relative to a set of other active constraints.

If the final parameter set  $x^*$  is subjected to  $n_{act}$  linear equality or active inequality constraints, the QR decomposition of the  $n \times n_{act}$  matrix  $\hat{A}^T$  of the linear constraints is computed by  $\hat{A}^T = QR$ , where  $Q$  is an  $n \times n$  orthogonal matrix and  $R$  is an  $n \times n_{act}$  upper triangular matrix. The  $n$  columns of matrix  $Q$  can be separated into two matrices,  $Q = [Y, Z]$ , where  $Y$  contains the first  $n_{act}$  orthogonal columns of  $Q$  and  $Z$  contains the last  $n - n_{act}$  orthogonal columns of  $Q$ . The  $n \times (n - n_{act})$  column-orthogonal matrix  $Z$  is also called the nullspace matrix of the active linear constraints  $\hat{A}^T$ . The  $n - n_{act}$  columns of the  $n \times (n - n_{act})$  matrix  $Z$  form a basis orthogonal to the rows of the  $n_{act} \times n$  matrix  $\hat{A}$ .

At the end of the iteration process, the PROC NLP can display the *projected gradient*

$$g_Z = Z^T g$$

In the case of boundary constrained optimization, the elements of the projected gradient correspond to the gradient elements of the free parameters. A necessary condition for  $x^*$  to be a local minimum of the optimization problem is

$$g_Z(x^*) = Z^T g(x^*) = 0$$

The symmetric  $n_{act} \times n_{act}$  matrix

$$G_Z = Z^T G Z$$

is called a *projected Hessian matrix*. A second-order necessary condition for  $x^*$  to be a local minimizer requires that the projected Hessian matrix is positive semidefinite. If available, the projected gradient and projected Hessian matrix can be displayed and written in an `OUTEST=` data set.

Those elements of the  $n_{act}$  vector of first-order estimates of *Lagrange multipliers*

$$\lambda = (\hat{A}\hat{A}^T)^{-1} \hat{A} Z Z^T g$$

which correspond to active inequality constraints indicate whether an improvement of the objective function can be obtained by releasing this active constraint. For minimization (maximization), a significant negative (positive) Lagrange multiplier indicates that a possible reduction (increase) of the objective function can be obtained by releasing this active linear constraint. The `LCDEACT=r` option can be used to specify a threshold  $r$  for the Lagrange multiplier that decides whether an active inequality constraint remains active or can be deactivated. The Lagrange multipliers are displayed (and written in an `OUTEST=` data set) only if linear constraints are active at the solution  $x^*$ . (In the case of boundary-constrained optimization, the Lagrange multipliers for active lower (upper) constraints are the negative (positive) gradient elements corresponding to the active parameters.)

## Feasible Starting Point

Two algorithms are used to obtain a feasible starting point.

- When only boundary constraints are specified:
  - If the parameter  $x_j$ ,  $1 \leq j \leq n$ , violates a two-sided boundary constraint (or an equality constraint)  $l_j \leq x_j \leq u_j$ , the parameter is given a new value inside the feasible interval, as follows:

$$x_j = \begin{cases} l_j, & \text{if } u_j \leq l_j \\ l_j + \frac{1}{2}(u_j - l_j), & \text{if } u_j - l_j < 4 \\ l_j + \frac{1}{10}(u_j - l_j), & \text{if } u_j - l_j \geq 4 \end{cases}$$

- If the parameter  $x_j$ ,  $1 \leq j \leq n$ , violates a one-sided boundary constraint  $l_j \leq x_j$  or  $x_j \leq u_j$ , the parameter is given a new value near the violated boundary, as follows:

$$x_j = \begin{cases} l_j + \max(1, \frac{1}{10}l_j), & \text{if } x_j < l_j \\ u_j - \max(1, \frac{1}{10}u_j), & \text{if } x_j > u_j \end{cases}$$

- When general linear constraints are specified, the algorithm of Schittkowski and Stoer (1979) computes a feasible point, which may be quite far from a user-specified infeasible point.

## Line-Search Methods

In each iteration  $k$ , the (dual) quasi-Newton, hybrid quasi-Newton, conjugate gradient, and Newton-Raphson minimization techniques use iterative line-search algorithms that try to optimize a linear, quadratic, or cubic approximation of  $f$  along a feasible descent search direction  $s^{(k)}$

$$x^{(k+1)} = x^{(k)} + \alpha^{(k)} s^{(k)}, \quad \alpha^{(k)} > 0$$

by computing an approximately optimal scalar  $\alpha^{(k)}$ .

Therefore, a line-search algorithm is an iterative process that optimizes a nonlinear function  $f = f(\alpha)$  of one parameter ( $\alpha$ ) within each iteration  $k$  of the optimization technique, which itself tries to optimize a linear or quadratic approximation of the nonlinear objective function  $f = f(x)$  of  $n$  parameters  $x$ . Since the outside iteration process is based only on the approximation of the objective function, the inside iteration of the line-search algorithm does not have to be perfect. Usually, the choice of  $\alpha$  significantly reduces (in a minimization) the objective function. Criteria often used for termination of line-search algorithms are the Goldstein conditions (refer to Fletcher (1987)).

Various line-search algorithms can be selected using the **LINESEARCH=** option. The line-search method **LINESEARCH=2** seems to be superior when function evaluation consumes significantly less computation time than gradient evaluation. Therefore, **LINESEARCH=2** is the default value for Newton-Raphson, (dual) quasi-Newton, and conjugate gradient optimizations.

A special default line-search algorithm for **TECH=HYQUAN** is useful only for least squares problems and cannot be chosen by the **LINESEARCH=** option. This method uses three columns of the  $m \times n$  Jacobian matrix, which for large  $m$  can require more memory than using the algorithms designated by **LINESEARCH=1** through **LINESEARCH=8**.

The line-search methods **LINESEARCH=2** and **LINESEARCH=3** can be modified to exact line search by using the **LSPRECISION=** option (specifying the  $\sigma$  parameter in Fletcher (1987)). The line-search methods **LINESEARCH=1**, **LINESEARCH=2**, and **LINESEARCH=3** satisfy the left-hand-side and right-hand-side Goldstein conditions (refer to Fletcher (1987)). When derivatives are available, the line-search methods **LINESEARCH=6**, **LINESEARCH=7**, and **LINESEARCH=8** try to satisfy the right-hand-side Goldstein condition; if derivatives are not available, these line-search algorithms use only function calls.

## Restricting the Step Length

Almost all line-search algorithms use iterative extrapolation techniques which can easily lead them to (feasible) points where the objective function  $f$  is no longer defined. (e.g., resulting in indefinite matrices for ML estimation) or difficult to compute (e.g., resulting in floating point overflows). Therefore, PROC NLP provides options restricting the step length  $\alpha$  or trust region radius  $\Delta$ , especially during the first main iterations.

The inner product  $g^T s$  of the gradient  $g$  and the search direction  $s$  is the slope of  $f(\alpha) = f(x + \alpha s)$  along the search direction  $s$ . The default starting value  $\alpha^{(0)} = \alpha^{(k,0)}$  in each line-search algorithm ( $\min_{\alpha > 0} f(x + \alpha s)$ ) during the main iteration  $k$  is computed in three steps:

1. The first step uses either the difference  $df = |f^{(k)} - f^{(k-1)}|$  of the function values during the last two consecutive iterations or the final step length value  $\alpha^-$  of the last iteration  $k - 1$  to compute a first value of  $\alpha_1^{(0)}$ .

- Not using the **DAMPSTEP=r** option:

$$\alpha_1^{(0)} = \begin{cases} \text{step}, & \text{if } 0.1 \leq \text{step} \leq 10 \\ 10, & \text{if } \text{step} > 10 \\ 0.1, & \text{if } \text{step} < 0.1 \end{cases}$$

with

$$\text{step} = \begin{cases} df/|g^T s|, & \text{if } |g^T s| \geq \epsilon \max(100df, 1) \\ 1, & \text{otherwise} \end{cases}$$

This value of  $\alpha_1^{(0)}$  can be too large and lead to a difficult or impossible function evaluation, especially for highly nonlinear functions such as the EXP function.

- Using the **DAMPSTEP=r** option:

$$\alpha_1^{(0)} = \min(1, r\alpha^-)$$

The initial value for the new step length can be no larger than  $r$  times the final step length  $\alpha^-$  of the previous iteration. The default value is  $r = 2$ .



2. During the first five iterations, the second step enables you to reduce  $\alpha_1^{(0)}$  to a smaller starting value  $\alpha_2^{(0)}$  using the **INSTEP=r** option:

$$\alpha_2^{(0)} = \min(\alpha_1^{(0)}, r)$$

After more than five iterations,  $\alpha_2^{(0)}$  is set to  $\alpha_1^{(0)}$ .

3. The third step can further reduce the step length by

$$\alpha_3^{(0)} = \min(\alpha_2^{(0)}, \min(10, u))$$

where  $u$  is the maximum length of a step inside the feasible region.

The **INSTEP=r** option lets you specify a smaller or larger radius  $\Delta$  of the trust region used in the first iteration of the trust region, double dogleg, and Levenberg-Marquardt algorithms. The default initial trust region radius  $\Delta^{(0)}$  is the length of the scaled gradient (Moré 1978). This step corresponds to the default radius factor of  $r = 1$ . In most practical applications of the TRUREG, DBLDOG, and LEVMAR algorithms, this choice is successful. However, for bad initial values and highly nonlinear objective functions (such as the EXP function), the default start radius can result in arithmetic overflows. If this happens, you may try decreasing values of **INSTEP=r**,  $0 < r < 1$ , until the iteration starts successfully. A small factor  $r$  also affects the trust region radius  $\Delta^{(k+1)}$  of the next steps because the radius is changed in each iteration by a factor  $0 < c \leq 4$ , depending on the ratio  $\rho$  expressing the goodness of quadratic function approximation. Reducing the radius  $\Delta$  corresponds to increasing the ridge parameter  $\lambda$ , producing smaller steps directed more closely toward the (negative) gradient direction.

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## Computational Problems

### First Iteration Overflows

If you use bad initial values for the parameters, the computation of the value of the objective function (and its derivatives) can lead to arithmetic overflows in the first iteration. The line-search algorithms that work with cubic extrapolation are especially sensitive to arithmetic overflows. If an overflow occurs with an optimization technique that uses line search, you can use the **INSTEP=** option to reduce the length of the first trial step during the line search of the first five iterations or use the **DAMPSTEP** or **MAXSTEP=** option to restrict the step length of the initial  $\alpha$  in subsequent iterations. If an arithmetic overflow occurs in the first iteration of the trust region, double dogleg, or Levenberg-Marquardt algorithm, you can use the **INSTEP=** option to reduce the default trust region radius of the first iteration. You can also change the minimization technique or the line-search method. If none of these methods helps, consider the following actions:

- scale the parameters
- provide better initial values
- use boundary constraints to avoid the region where overflows may happen
- change the algorithm (specified in program statements) which computes the objective function



## Problems in Evaluating the Objective Function

The starting point  $x^{(0)}$  must be a point that can be evaluated by all the functions involved in your problem. However, during optimization the optimizer may iterate to a point  $x^{(k)}$  where the objective function or nonlinear constraint functions and their derivatives cannot be evaluated. If you can identify the problematic region, you can prevent the algorithm from reaching it by adding another constraint to the problem. Another possibility is a modification of the objective function that will produce a large, undesired function value. As a result, the optimization algorithm reduces the step length and stays closer to the point that has been evaluated successfully in the previous iteration. For more information, refer to the section “[Missing Values in Program Statements](#)” on page 662.

## Problems with Quasi-Newton Methods for Nonlinear Constraints

The sequential quadratic programming algorithm in QUANEW, which is used for solving nonlinearly constrained problems, can have problems updating the Lagrange multiplier vector  $\mu$ . This usually results in very high values of the Lagrangian function and in *watchdog* restarts indicated in the iteration history. If this happens, there are three actions you can try:

- By default, the Lagrange vector  $\mu$  is evaluated in the same way as Powell (1982b) describes. This corresponds to **VERSION=2**. By specifying **VERSION=1**, a modification of this algorithm replaces the update of the Lagrange vector  $\mu$  with the original update of Powell (1978a, b), which is used in VF02AD.
- You can use the **INSTEP=** option to impose an upper bound for the step length  $\alpha$  during the first five iterations.
- You can use the **INHESSIAN=** option to specify a different starting approximation for the Hessian. Choosing only the **INHESSIAN** option will use the Cholesky factor of a (possibly ridged) finite-difference approximation of the Hessian to initialize the quasi-Newton update process.

## Other Convergence Difficulties

There are a number of things to try if the optimizer fails to converge.

- Check the derivative specification:  
If derivatives are specified by using the **GRADIENT**, **HESSIAN**, **JACOBIAN**, **CRPJAC**, or **JACNLC** statement, you can compare the specified derivatives with those computed by finite-difference approximations (specifying the **FD** and **FDHESSIAN** option). Use the **GRADCHECK** option to check if the gradient  $g$  is correct. For more information, refer to the section “[Testing the Gradient Specification](#)” on page 640.
- Forward-difference derivatives specified with the **FD=** or **FDHESSIAN=** option may not be precise enough to satisfy strong gradient termination criteria. You may need to specify the more expensive central-difference formulas or use analytical derivatives. The finite-difference intervals may be too small or too big and the finite-difference derivatives may be erroneous. You can specify the **FDINT=** option to compute better finite-difference intervals.
- Change the optimization technique:  
For example, if you use the default **TECH=LEVMAR**, you can

- change to **TECH=QUANEW** or to **TECH=NRRIDG**
- run some iterations with **TECH=CONGRA**, write the results in an **OUTEST=** data set, and use them as initial values specified by an **INEST=** data set in a second run with a different **TECH=** technique
- Change or modify the update technique and the line-search algorithm:  
This method applies only to **TECH=QUANEW**, **TECH=HYQUAN**, or **TECH=CONGRA**. For example, if you use the default update formula and the default line-search algorithm, you can
  - change the update formula with the **UPDATE=** option
  - change the line-search algorithm with the **LINESEARCH=** option
  - specify a more precise line search with the **LSPRECISION=** option, if you use **LINESEARCH=2** or **LINESEARCH=3**
- Change the initial values by using a grid search specification to obtain a set of good feasible starting values.

### Convergence to Stationary Point

The (projected) gradient at a stationary point is zero and that results in a zero step length. The stopping criteria are satisfied.

There are two ways to avoid this situation:

- Use the **DECVAR** statement to specify a grid of feasible starting points.
- Use the **OPTCHECK=** option to avoid terminating at the stationary point.

The signs of the eigenvalues of the (reduced) Hessian matrix contain information regarding a stationary point:

- If all eigenvalues are positive, the Hessian matrix is positive definite and the point is a minimum point.
- If some of the eigenvalues are positive and all remaining eigenvalues are zero, the Hessian matrix is positive semidefinite and the point is a minimum or saddle point.
- If all eigenvalues are negative, the Hessian matrix is negative definite and the point is a maximum point.
- If some of the eigenvalues are negative and all remaining eigenvalues are zero, the Hessian matrix is negative semidefinite and the point is a maximum or saddle point.
- If all eigenvalues are zero, the point can be a minimum, maximum, or saddle point.

## Precision of Solution

In some applications, PROC NLP may result in parameter estimates that are not precise enough. Usually this means that the procedure terminated too early at a point too far from the optimal point. The termination criteria define the size of the termination region around the optimal point. Any point inside this region can be accepted for terminating the optimization process. The default values of the termination criteria are set to satisfy a reasonable compromise between the computational effort (computer time) and the precision of the computed estimates for the most common applications. However, there are a number of circumstances where the default values of the termination criteria specify a region that is either too large or too small. If the termination region is too large, it can contain points with low precision. In such cases, you should inspect the log or list output to find the message stating which termination criterion terminated the optimization process. In many applications, you can obtain a solution with higher precision by simply using the old parameter estimates as starting values in a subsequent run where you specify a smaller value for the termination criterion that was satisfied at the previous run.

If the termination region is too small, the optimization process may take longer to find a point inside such a region or may not even find such a point due to rounding errors in function values and derivatives. This can easily happen in applications where finite-difference approximations of derivatives are used and the **GCONV** and **ABSGCONV** termination criteria are too small to respect rounding errors in the gradient values.

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## Covariance Matrix

The **COV=** option must be specified to compute an approximate covariance matrix for the parameter estimates under asymptotic theory for least squares, maximum-likelihood, or Bayesian estimation, with or without corrections for degrees of freedom as specified by the **VARDEF=** option.

Two groups of six different forms of covariance matrices (and therefore approximate standard errors) can be computed corresponding to the following two situations:

- The **LSQ** statement is specified, which means that least squares estimates are being computed:

$$\min f(x) = \sum_{i=1}^m f_i^2(x)$$

- The **MIN** or **MAX** statement is specified, which means that maximum-likelihood or Bayesian estimates are being computed:

$$\text{opt } f(x) = \sum_{i=1}^m f_i(x)$$

where opt is either min or max.

In either case, the following matrices are used:

$$G = \nabla^2 f(x)$$

$$J(f) = (\nabla f_1, \dots, \nabla f_m) = \left( \frac{\partial f_i}{\partial x_j} \right)$$

$$JJ(f) = J(f)^T J(f)$$

$$V = J(f)^T \text{diag}(f_i^2) J(f)$$

$$W = J(f)^T \text{diag}(f_i^\dagger) J(f)$$

where

$$f_i^\dagger = \begin{cases} 0, & \text{if } f_i = 0 \\ 1/f_i, & \text{otherwise} \end{cases}$$

For unconstrained minimization, or when none of the final parameter estimates are subjected to linear equality or active inequality constraints, the formulas of the six types of covariance matrices are as follows:

**Table 8.3** Central-Difference Approximations

| COV | MIN or MAX Statement           | LSQ Statement                      |
|-----|--------------------------------|------------------------------------|
| 1 M | $(\_NOBS_/d)G^{-1}JJ(f)G^{-1}$ | $(\_NOBS_/d)G^{-1}VG^{-1}$         |
| 2 H | $(\_NOBS_/d)G^{-1}$            | $\sigma^2 G^{-1}$                  |
| 3 J | $(1/d)W^{-1}$                  | $\sigma^2 JJ(f)^{-1}$              |
| 4 B | $(1/d)G^{-1}WG^{-1}$           | $\sigma^2 G^{-1}JJ(f)G^{-1}$       |
| 5 E | $(\_NOBS_/d)JJ(f)^{-1}$        | $(1/d)V^{-1}$                      |
| 6 U | $(\_NOBS_/d)W^{-1}JJ(f)W^{-1}$ | $(\_NOBS_/d)JJ(f)^{-1}VJJ(f)^{-1}$ |

The value of  $d$  depends on the **VARDEF=** option and on the value of the `_NOBS_` variable:

$$d = \begin{cases} \max(1, \_NOBS_ - \_DF_), & \text{for VARDEF=DF} \\ \_NOBS_, & \text{for VARDEF=N} \end{cases}$$

where `_DF_` is either set in the program statements or set by default to  $n$  (the number of parameters) and `_NOBS_` is either set in the program statements or set by default to  $nobs \times mfun$ , where  $nobs$  is the number of observations in the data set and  $mfun$  is the number of functions listed in the **LSQ**, **MIN**, or **MAX** statement.

The value  $\sigma^2$  depends on the specification of the **SIGSQ=** option and on the value of  $d$ :

$$\sigma^2 = \begin{cases} sq \times \_NOBS_/d, & \text{if SIGSQ=sq is specified} \\ 2f(x^*)/d, & \text{if SIGSQ= is not specified} \end{cases}$$

where  $f(x^*)$  is the value of the objective function at the optimal parameter estimates  $x^*$ .

The two groups of formulas distinguish between two situations:

- For least squares estimates, the error variance can be estimated from the objective function value and is used in three of the six different forms of covariance matrices. If you have an independent estimate of the error variance, you can specify it with the **SIGSQ=** option.
- For maximum-likelihood or Bayesian estimates, the objective function should be the logarithm of the likelihood or of the posterior density when using the **MAX** statement.

For minimization, the inversion of the matrices in these formulas is done so that negative eigenvalues are considered zero, resulting always in a positive semidefinite covariance matrix.

In small samples, estimates of the covariance matrix based on asymptotic theory are often too small and should be used with caution.

If the final parameter estimates are subjected to  $n_{act} > 0$  linear equality or active linear inequality constraints, the formulas of the covariance matrices are modified similar to Gallant (1987) and Cramer (1986, p. 38) and additionally generalized for applications with singular matrices. In the constrained case, the value of  $d$  used in the scalar factor  $\sigma^2$  is defined by

$$d = \begin{cases} \max(1, \_NOBS\_ - \_DF\_ + n_{act}), & \text{for VARDEF=DF} \\ \_NOBS\_ , & \text{for VARDEF=N} \end{cases}$$

where  $n_{act}$  is the number of active constraints and  $\_NOBS\_$  is set as in the unconstrained case.

For minimization, the covariance matrix should be positive definite; for maximization it should be negative definite. There are several options available to check for a rank deficiency of the covariance matrix:

- The **ASINGULAR=**, **MSINGULAR=**, and **VSINGULAR=** options can be used to set three singularity criteria for the inversion of the matrix  $A$  needed to compute the covariance matrix, when  $A$  is either the Hessian or one of the crossproduct Jacobian matrices. The singularity criterion used for the inversion is

$$|d_{j,j}| \leq \max(ASING, VSING \times |A_{j,j}|, MSING \times \max(|A_{1,1}|, \dots, |A_{n,n}|))$$

where  $d_{j,j}$  is the diagonal pivot of the matrix  $A$ , and **ASING**, **VSING** and **MSING** are the specified values of the **ASINGULAR=**, **VSINGULAR=**, and **MSINGULAR=** options. The default values are

- **ASING**: the square root of the smallest positive double precision value
- **MSING**:  $1E-12$  if the **SINGULAR=** option is not specified and  $\max(10 \times \epsilon, 1E-4 \times SINGULAR)$  otherwise, where  $\epsilon$  is the machine precision
- **VSING**:  $1E-8$  if the **SINGULAR=** option is not specified and the value of **SINGULAR** otherwise

**NOTE:** In many cases, a normalized matrix  $D^{-1}AD^{-1}$  is decomposed and the singularity criteria are modified correspondingly.

- If the matrix  $A$  is found singular in the first step, a generalized inverse is computed. Depending on the **G4=** option, a generalized inverse is computed that satisfies either all four or only two Moore-Penrose conditions. If the number of parameters  $n$  of the application is less than or equal to **G4=i**, a G4 inverse is computed; otherwise only a G2 inverse is computed. The G4 inverse is computed by (the computationally very expensive but numerically stable) eigenvalue decomposition; the G2 inverse is computed by Gauss transformation. The G4 inverse is computed using the eigenvalue decomposition  $A = Z\Lambda Z^T$ , where  $Z$  is the orthogonal matrix of eigenvectors and  $\Lambda$  is the diagonal matrix of eigenvalues,  $\Lambda = \text{diag}(\lambda_1, \dots, \lambda_n)$ . If the **PEIGVAL** option is specified, the eigenvalues  $\lambda_i$  are displayed. The G4 inverse of  $A$  is set to

$$A^- = Z\Lambda^-Z^T$$

where the diagonal matrix  $\Lambda^- = \text{diag}(\lambda_1^-, \dots, \lambda_n^-)$  is defined using the **COVSING=** option:

$$\lambda_i^- = \begin{cases} 1/\lambda_i, & \text{if } |\lambda_i| > COVSING \\ 0, & \text{if } |\lambda_i| \leq COVSING \end{cases}$$

If the **COVSING=** option is not specified, the  $nr$  smallest eigenvalues are set to zero, where  $nr$  is the number of rank deficiencies found in the first step.

For optimization techniques that do not use second-order derivatives, the covariance matrix is usually computed using finite-difference approximations of the derivatives. By specifying **TECH=NONE**, any of the covariance matrices can be computed using analytical derivatives. The covariance matrix specified by the **COV=** option can be displayed (using the **PCOV** option) and is written to the **OUTEST=** data set.

## Input and Output Data Sets

### DATA= Input Data Set

The **DATA=** data set is used only to specify an objective function  $f$  that is a combination of  $m$  other functions  $f_i$ . For each function  $f_i$ ,  $i = 1, \dots, m$ , listed in a **MAX**, **MIN**, or **LSQ** statement, each observation  $l$ ,  $l = 1, \dots, nobs$ , in the **DATA=** data set defines a specific function  $f_{il}$  that is evaluated by substituting the values of the variables of this observation into the program statements. If the **MAX** or **MIN** statement is used, the  $m \times nobs$  specific functions  $f_{il}$  are added to a single objective function  $f$ . If the **LSQ** statement is used, the sum-of-squares  $f$  of the  $m \times nobs$  specific functions  $f_{il}$  is minimized. The **NOMISS** option causes observations with missing values to be skipped.

### INEST= Input Data Set

The **INEST=** (or **INVAR=**, or **ESTDATA=**) input data set can be used to specify the initial values of the parameters defined in a **DECVAR** statement as well as boundary constraints and the more general linear constraints which could be imposed on these parameters. This form of input is similar to the dense format input used in PROC LP.

The variables of the **INEST=** data set are

- a character variable **\_TYPE\_** that indicates the type of the observation
- $n$  numeric variables with the parameter names used in the **DECVAR** statement
- the **BY** variables that are used in a **DATA=** input data set
- a numeric variable **\_RHS\_** specifying the right-hand-side constants (needed only if linear constraints are used)
- additional variables with names corresponding to constants used in the program statements

The content of the **\_TYPE\_** variable defines the meaning of the observation of the **INEST=** data set. PROC NLP recognizes the following **\_TYPE\_** values:

- **PARMS**, which specifies initial values for parameters. Additional variables can contain the values of constants that are referred to in program statements. The values of the constants in the **PARMS** observation initialize the constants in the program statements.
- **UPPERBD | UB**, which specifies upper bounds. A missing value indicates that no upper bound is specified for the parameter.
- **LOWERBD | LB**, which specifies lower bounds. A missing value indicates that no lower bound is specified for the parameter.

- LE | <= | <, which specifies linear constraint  $\sum_j a_{ij}x_j \leq b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.
- GE | >= | >, which specifies linear constraint  $\sum_j a_{ij}x_j \geq b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.
- EQ | =, which specifies linear constraint  $\sum_j a_{ij}x_j = b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.

The constraints specified in an **INEST=** data set are added to the constraints specified in the **BOUNDS** and **LINCON** statements. You can use an **OUTEST=** data set as an **INEST=** data set in a subsequent run of PROC NLP. However, be aware that the **OUTEST=** data set also contains the boundary and general linear constraints specified in the previous run of PROC NLP. When you are using this **OUTEST=** data set without changes as an **INEST=** data set, PROC NLP adds the constraints from the data set to the constraints specified by a **BOUNDS** and **LINCON** statement. Although PROC NLP automatically eliminates multiple identical constraints you should avoid specifying the same constraint twice.

## INQUAD= Input Data Set

Two types of **INQUAD=** data sets can be used to specify the objective function of a quadratic programming problem for **TECH=QUADAS** or **TECH=LICOMP**,

$$f(x) = \frac{1}{2}x^T Gx + g^T x + c, \quad \text{with } G^T = G$$

The *dense* **INQUAD=** data set must contain all numerical values of the symmetric matrix  $G$ , the vector  $g$ , and the scalar  $c$ . Using the *sparse* **INQUAD=** data set enables you to specify only the nonzero positions in matrix  $G$  and vector  $g$ . Those locations that are not set by the *sparse* **INQUAD=** data set are assumed to be zero.

### Dense INQUAD= Data Set

A dense **INQUAD=** data set must contain two character variables, `_TYPE_` and `_NAME_`, and at least  $n$  numeric variables whose names are the parameter names. The `_TYPE_` variable takes the following values:

- QUAD lists the  $n$  values of the row of the  $G$  matrix that is defined by the parameter name used in the `_NAME_` variable.
- LINEAR lists the  $n$  values of the  $g$  vector.
- CONST sets the value of the scalar  $c$  and cannot contain different numerical values; however, it could contain up to  $n - 1$  missing values.
- PARMS specifies initial values for parameters.
- UPPERBD | UB specifies upper bounds. A missing value indicates that no upper bound is specified.
- LOWERBD | LB specifies lower bounds. A missing value indicates that no lower bound is specified.
- LE | <= | < specifies linear constraint  $\sum_j a_{ij}x_j \leq b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.
- GE | >= | > specifies linear constraint  $\sum_j a_{ij}x_j \geq b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.



- `EQ` | = specifies linear constraint  $\sum_j a_{ij}x_j = b_i$ . The  $n$  parameter values contain the coefficients  $a_{ij}$ , and the `_RHS_` variable contains the right-hand side  $b_i$ . Missing values indicate zeros.

Constraints specified in a dense `INQUAD=` data set are added to the constraints specified in `BOUNDS` and `LINCON` statements.

### **Sparse INQUAD= Data Set**

A sparse `INQUAD=` data set must contain three character variables `_TYPE_`, `_ROW_`, and `_COL_`, and one numeric variable `_VALUE_`. The `_TYPE_` variable can assume two values:

- `QUAD` specifies that the `_ROW_` and `_COL_` variables define the row and column locations of the values in the  $G$  matrix.
- `LINEAR` specifies that the `_ROW_` variable defines the row locations of the values in the  $g$  vector. The `_COL_` variable is not used.

Using both the `MODEL=` option and the `INCLUDE` statement with the same model file will include the file twice (erroneous in most cases).

### **OUT= Output Data Set**

The `OUT=` data set contains those variables of a `DATA=` input data set that are referred to in the program statements and additional variables computed by the program statements for the objective function. Specifying the `NOMISS` option enables you to skip observations with missing values in variables used in the program statements. The `OUT=` data set can also contain first- and second-order derivatives of these variables if the `OUTDER=` option is specified. The variables and derivatives are the final parameter estimates  $x^*$  or (for `TECH=NONE`) the initial value  $x^0$ .

The variables of the `OUT=` data set are

- the `BY` variables and all other variables that are used in a `DATA=` input data set and referred to in the program code
- a variable `_OBS_` containing the number of observations read from a `DATA=` input data set, where the counting is restarted with the start of each `BY` group. If there is no `DATA=` input data set, then `_OBS_=1`.
- a character variable `_TYPE_` naming the type of the observation
- the parameter variables listed in the `DECVAR` statement
- the function variables listed in the `MIN`, `MAX`, or `LSQ` statement
- all other variables computed in the program statements
- the character variable `_WRT_` (if `OUTDER=1`) containing the *with respect to* variable for which the first-order derivatives are written in the function variables
- the two character variables `_WRT1_` and `_WRT2_` (if `OUTDER=2`) containing the two *with respect to* variables for which the first- and second-order derivatives are written in the function variables



## OUTEST= Output Data Set

The **OUTEST=** or **OUTVAR=** output data set saves the optimization solution of PROC NLP. You can use the **OUTEST=** or **OUTVAR=** data set as follows:

- to save the values of the objective function on grid points to examine, for example, surface plots using PROC G3D (use the **OUTGRID** option)
- to avoid any costly computation of analytical (first- or second-order) derivatives during optimization when they are needed only upon termination. In this case a two-step approach is recommended:
  1. In a first execution, the optimization is done; that is, optimal parameter estimates are computed, and the results are saved in an **OUTEST=** data set.
  2. In a subsequent execution, the optimal parameter estimates in the previous **OUTEST=** data set are read in an **INEST=** data set and used with **TECH=NONE** to compute further results, such as analytical second-order derivatives or some kind of covariance matrix.
- to restart the procedure using parameter estimates as initial values
- to split a time-consuming optimization problem into a series of smaller problems using intermediate results as initial values in subsequent runs. (Refer to the **MAXTIME=**, **MAXIT=**, and **MAXFUNC=** options to trigger stopping.)
- to write the value of the objective function, the parameter estimates, the time in seconds starting at the beginning of the optimization process and (if available) the gradient to the **OUTEST=** data set during the iterations. After the PROC NLP run is completed, the convergence progress can be inspected by graphically displaying the iterative information. (Refer to the **OUTITER** option.)

The variables of the **OUTEST=** data set are

- the BY variables that are used in a **DATA=** input data set
- a character variable **\_TECH\_** naming the optimization technique used
- a character variable **\_TYPE\_** specifying the type of the observation
- a character variable **\_NAME\_** naming the observation. For a linear constraint, the **\_NAME\_** variable indicates whether the constraint is active at the solution. For the initial observations, the **\_NAME\_** variable indicates if the number in the **\_RHS\_** variable corresponds to the number of positive, negative, or zero eigenvalues.
- $n$  numeric variables with the parameter names used in the **DECVAR** statement. These variables contain a point  $x$  of the parameter space, lower or upper bound constraints, or the coefficients of linear constraints.
- a numeric variable **\_RHS\_** (right-hand side) that is used for the right-hand-side value  $b_i$  of a linear constraint or for the value  $f = f(x)$  of the objective function at a point  $x$  of the parameter space
- a numeric variable **\_ITER\_** that is zero for initial values, equal to the iteration number for the **OUTITER** output, and missing for the result output

The `_TYPE_` variable identifies how to interpret the observation. If `_TYPE_` is

- **PARMS** then parameter-named variables contain the coordinates of the resulting point  $x^*$ . The `_RHS_` variable contains  $f(x^*)$ .
- **INITIAL** then parameter-named variables contain the feasible starting point  $x^{(0)}$ . The `_RHS_` variable contains  $f(x^{(0)})$ .
- **GRIDPNT** then (if the **OUTGRID** option is specified) parameter-named variables contain the coordinates of any point  $x^{(k)}$  used in the grid search. The `_RHS_` variable contains  $f(x^{(k)})$ .
- **GRAD** then parameter-named variables contain the gradient at the initial or final estimates.
- **STDERR** then parameter-named variables contain the approximate standard errors (square roots of the diagonal elements of the covariance matrix) if the **COV=** option is specified.
- **\_NOBS\_** then (if the **COV=** option is specified) all parameter variables contain the value of `_NOBS_` used in computing the  $\sigma^2$  value in the formula of the covariance matrix.
- **UPPERBD | UB** then (if there are boundary constraints) the parameter variables contain the upper bounds.
- **LOWERBD | LB** then (if there are boundary constraints) the parameter variables contain the lower bounds.
- **NACTBC** then all parameter variables contain the number  $n_{abc}$  of active boundary constraints at the solution  $x^*$ .
- **ACTBC** then (if there are active boundary constraints) the observation indicate which parameters are actively constrained, as follows:

`_NAME_=GE` the active lower bounds

`_NAME_=LE` the active upper bounds

`_NAME_=EQ` the active equality constraints

- **NACTLC** then all parameter variables contain the number  $n_{alc}$  of active linear constraints that are recognized as linearly independent.
- **NLDACTLC** then all parameter variables contain the number of active linear constraints that are recognized as linearly dependent.
- **LE** then (if there are linear constraints) the observation contains the  $i$ th linear constraint  $\sum_j a_{ij}x_j \leq b_i$ . The parameter variables contain the coefficients  $a_{ij}$ ,  $j = 1, \dots, n$ , and the `_RHS_` variable contains  $b_i$ . If the constraint  $i$  is active at the solution  $x^*$ , then `_NAME_=ACTLC` or `_NAME_=LDACTLC`.
- **GE** then (if there are linear constraints) the observation contains the  $i$ th linear constraint  $\sum_j a_{ij}x_j \geq b_i$ . The parameter variables contain the coefficients  $a_{ij}$ ,  $j = 1, \dots, n$ , and the `_RHS_` variable contains  $b_i$ . If the constraint  $i$  is active at the solution  $x^*$ , then `_NAME_=ACTLC` or `_NAME_=LDACTLC`.
- **EQ** then (if there are linear constraints) the observation contains the  $i$ th linear constraint  $\sum_j a_{ij}x_j = b_i$ . The parameter variables contain the coefficients  $a_{ij}$ ,  $j = 1, \dots, n$ , the `_RHS_` variable contains  $b_i$ , and `_NAME_=ACTLC` or `_NAME_=LDACTLC`.

- LAGRANGE then (if at least one of the linear constraints is an equality constraint or an active inequality constraint) the observation contains the vector of Lagrange multipliers. The Lagrange multipliers of active boundary constraints are listed first followed by those of active linear constraints and those of active nonlinear constraints. Lagrange multipliers are available only for the set of linearly independent active constraints.
- PROJGRAD then (if there are linear constraints) the observation contains the  $n - n_{act}$  values of the projected gradient  $g_Z = Z^T g$  in the variables corresponding to the first  $n - n_{act}$  parameters.
- JACOBIAN then (if the **PJACOBI** or **OUTJAC** option is specified) the  $m$  observations contain the  $m$  rows of the  $m \times n$  Jacobian matrix. The **\_RHS\_** variable contains the row number  $l$ ,  $l = 1, \dots, m$ .
- HESSIAN then the first  $n$  observations contain the  $n$  rows of the (symmetric) Hessian matrix. The **\_RHS\_** variable contains the row number  $j$ ,  $j = 1, \dots, n$ , and the **\_NAME\_** variable contains the corresponding parameter name.
- PROJHESS then the first  $n - n_{act}$  observations contain the  $n - n_{act}$  rows of the projected Hessian matrix  $Z^T G Z$ . The **\_RHS\_** variable contains the row number  $j$ ,  $j = 1, \dots, n - n_{act}$ , and the **\_NAME\_** variable is blank.
- CRPJAC then the first  $n$  observations contain the  $n$  rows of the (symmetric) crossproduct Jacobian matrix at the solution. The **\_RHS\_** variable contains the row number  $j$ ,  $j = 1, \dots, n$ , and the **\_NAME\_** variable contains the corresponding parameter name.
- PROJCRPJ then the first  $n - n_{act}$  observations contain the  $n - n_{act}$  rows of the projected crossproduct Jacobian matrix  $Z^T (J^T J) Z$ . The **\_RHS\_** variable contains the row number  $j$ ,  $j = 1, \dots, n - n_{act}$ , and the **\_NAME\_** variable is blank.
- COV1, COV2, COV3, COV4, COV5, or COV6 then (depending on the **COV=** option) the first  $n$  observations contain the  $n$  rows of the (symmetric) covariance matrix of the parameter estimates. The **\_RHS\_** variable contains the row number  $j$ ,  $j = 1, \dots, n$ , and the **\_NAME\_** variable contains the corresponding parameter name.
- DETERMIN contains the determinant  $\det = a \times 10^b$  of the matrix specified by the value of the **\_NAME\_** variable where  $a$  is the value of the first variable in the **DECVAR** statement and  $b$  is in **\_RHS\_**.
- NEIGPOS, NEIGNEG, or NEIGZER then the **\_RHS\_** variable contains the number of positive, negative, or zero eigenvalues of the matrix specified by the value of the **\_NAME\_** variable.
- COVRANK then the **\_RHS\_** variable contains the rank of the covariance matrix.
- SIGSQ then the **\_RHS\_** variable contains the scalar factor of the covariance matrix.
- **\_TIME\_** then (if the **OUTITER** option is specified) the **\_RHS\_** variable contains the number of seconds passed since the start of the optimization.
- TERMINAT then if optimization terminated at a point satisfying one of the termination criteria, an abbreviation of the corresponding criteria is given to the **\_NAME\_** variable. Otherwise **\_NAME\_=PROBLEMS**.

If for some reason the procedure does not terminate successfully (for example, no feasible initial values can be computed or the function value or derivatives at the starting point cannot be computed), the **OUTEST=** data set may contain only part of the observations (usually only the **PARMS** and **GRAD** observation).

**NOTE:** Generally you can use an **OUTEST=** data set as an **INEST=** data set in a further run of PROC NLP. However, be aware that the **OUTEST=** data set also contains the boundary and general linear constraints specified in the previous run of PROC NLP. When you are using this **OUTEST=** data set without changes as an **INEST=** data set, PROC NLP adds the constraints from the data set to the constraints specified by a **BOUNDS** or **LINCON** statement. Although PROC NLP automatically eliminates multiple identical constraints you should avoid specifying the same constraint twice.

### Output of Profiles

The following observations are written to the **OUTEST=** data set only when the **PROFILE** statement or **CLPARM** option is specified.

**Table 8.4** Output of Profiles

| <b>_TYPE_</b> | <b>_NAME_</b> | <b>_RHS_</b> | <b>Meaning of Observation</b>  |
|---------------|---------------|--------------|--|
| PLC_LOW       | parname       | y value      | coordinates of lower CL for $\alpha$                                 |
| PLC_UPP       | parname       | y value      | coordinates of upper CL for $\alpha$                                 |
| WALD_CL       | LOWER         | y value      | lower Wald CL for $\alpha$ in <b>_ALPHA_</b>                         |
| WALD_CL       | UPPER         | y value      | upper Wald CL for $\alpha$ in <b>_ALPHA_</b>                         |
| PL_CL         | LOWER         | y value      | lower PL CL for $\alpha$ in <b>_ALPHA_</b>                           |
| PL_CL         | UPPER         | y value      | upper PL CL for $\alpha$ in <b>_ALPHA_</b>                           |
| PROFILE       | L(THETA)      | missing      | y value corresponding to $x$<br>in following <b>_NAME_=THETA</b>     |
| PROFILE       | THETA         | missing      | $x$ value corresponding to $y$<br>in previous <b>_NAME_=L(THETA)</b> |

Assume that the **PROFILE** statement specifies  $n_p$  parameters and  $n_\alpha$  confidence levels. For **CLPARM**,  $n_p = n$  and  $n_\alpha = 4$ .

- **\_TYPE\_=PLC\_LOW** and **\_TYPE\_=PLC\_UPP**:

If the **CLPARM=** option or the **PROFILE** statement with the **OUTTABLE** option is specified, then the complete set  $\theta$  of parameter estimates (rather than only the confidence limit  $x = \theta_j$ ) is written to the **OUTEST=** data set for each side of the confidence interval. This output may be helpful for further analyses on how small changes in  $x = \theta_j$  affect the changes in the other  $\theta_i, i \neq j$ . The **\_ALPHA\_** variable contains the corresponding value of  $\alpha$ . There should be no more than  $2n_\alpha n_p$  observations. If the confidence limit cannot be computed, the corresponding observation is not available.

- **\_TYPE\_=WALD\_CL**:

If **CLPARM=WALD**, **CLPARM=BOTH**, or the **PROFILE** statement with  $\alpha$  values is specified, then the Wald confidence limits are written to the **OUTEST=** data set for each of the default or specified values of  $\alpha$ . The **\_ALPHA\_** variable contains the corresponding value of  $\alpha$ . There should be  $2n_\alpha$  observations.

- **\_TYPE\_=PL\_CL:**  
If **CLPARM=PL**, **CLPARM=BOTH**, or the **PROFILE** statement with  $\alpha$  values is specified, then the PL confidence limits are written to the **OUTEST=** data set for each of the default or specified values of  $\alpha$ . The **\_ALPHA\_** variable contains the corresponding values of  $\alpha$ . There should be  $2n_\alpha$  observations; some observations may have missing values.
- **\_TYPE\_=PROFILE:**  
If **CLPARM=PL**, **CLPARM=BOTH**, or the **CLPARM=** statement with or without  $\alpha$  values is specified, then a set of  $(x, y)$  point coordinates in two adjacent observations with **\_NAME\_=L(THETA)** ( $y$  value) and **\_NAME\_=THETA** ( $x$  value) is written to the **OUTEST=** data set. The **\_RHS\_** and **\_ALPHA\_** variables are not used (are set to missing). The number of observations depends on the difficulty of the optimization problems.

## OUTMODEL= Output Data Set

The program statements for objective functions, nonlinear constraints, and derivatives can be saved into an **OUTMODEL=** output data set. This data set can be used in an **INCLUDE** program statement or as a **MODEL=** input data set in subsequent calls of PROC NLP. The **OUTMODEL=** option is similar to the option used in PROC MODEL in SAS/ETS software.

### Storing Programs in Model Files

Models can be saved to and recalled from SAS catalog files. SAS catalogs are special files which can store many kinds of data structures as separate units in one SAS file. Each separate unit is called an entry, and each entry has an entry type that identifies its structure to the SAS system.

In general, to save a model, use the **OUTMODEL=name** option in the PROC NLP statement, where *name* is specified as *libref.catalog.entry*, *libref.entry*, or *entry*. The *libref*, *catalog*, and *entry* names must be valid SAS names no more than 8 characters long. The *catalog* name is restricted to 7 characters on the CMS operating system. If not given, the *catalog* name defaults to MODELS, and the *libref* defaults to WORK. The entry type is always MODEL. Thus, **OUTMODEL=X** writes the model to the file WORK.MODELS.X.MODEL.

The **MODEL=** option is used to read in a model. A list of model files can be specified in the **MODEL=** option, and a range of names with numeric suffixes can be given, as in **MODEL=(MODEL1-MODEL10)**. When more than one model file is given, the list must be placed in parentheses, as in **MODEL=(A B C)**. If more than one model file is specified, the files are combined in the order listed in the **MODEL=** option.

When the **MODEL=** option is specified in the PROC NLP statement and model definition statements are also given later in the PROC NLP step, the model files are read in first, in the order listed, and the model program specified in the PROC NLP step is appended after the model program read from the **MODEL=** files.

The **INCLUDE** statement can be used to append model code to the current model code. The contents of the model files are inserted into the current model at the position where the **INCLUDE** statement appears.

Note that the following statements are not part of the program code that is written to an **OUTMODEL=** data set: **MIN**, **MAX**, **LSQ**, **MINQUAD**, **MAXQUAD**, **DECVAR**, **BOUNDS**, **BY**, **CRPJAC**, **GRADIENT**, **HESSIAN**, **JACNLC**, **JACOBIAN**, **LABEL**, **LINCON**, **MATRIX**, and **NLINCON**.

## Displayed Output

### ***Procedure Initialization***

After the procedure has processed the problem, it displays summary information about the problem and the options that you have selected. It may also display a list of linearly dependent constraints and other information about the constraints and parameters.

### ***Optimization Start***

At the start of optimization the procedure displays

- the number of constraints that are active at the starting point, or more precisely, the number of constraints that are currently members of the working set. If this number is followed by a plus sign, there are more active constraints, of which at least one is temporarily released from the working set due to negative Lagrange multipliers.
- the value of the objective function at the starting point
- if the (projected) gradient is available, the value of the largest absolute (projected) gradient element
- for the TRUREG and LEVMAR subroutines, the initial radius of the trust region around the starting point

### ***Iteration History***

In general, the iteration history consists of one line of output containing the most important information for each iteration. The iteration-extensive Nelder-Mead simplex method, however, displays only one line for several internal iterations. This technique skips the output for some iterations because

- some of the termination tests (size and standard deviation) are rather time-consuming compared to the simplex operations and are done once every five simplex operations
- the resulting history output is smaller

The `_LIST_` variable (refer to the section “[Program Statements](#)” on page 620) also enables you to display the parameter estimates  $x^{(k)}$  and the gradient  $g^{(k)}$  in all or some selected iterations  $k$ .

The iteration history always includes the following (the words in parentheses indicate the column header output):

- the iteration number (iter)
- the number of iteration restarts (nrest)
- the number of function calls (nfun)
- the number of active constraints (act)
- the value of the optimization criterion (optcrit)
- the difference between adjacent function values (difcrit)

- the maximum of the absolute (projected) gradient components (maxgrad)

An apostrophe trailing the number of active constraints indicates that at least one of the active constraints was released from the active set due to a significant Lagrange multiplier.

The optimization history is displayed by default because it is important to check for possible convergence problems.

### Optimization Termination

The output of the optimization history ends with a short output of information concerning the optimization result:

- the number of constraints that are active at the final point, or more precisely, the number of constraints that are currently members of the working set. When this number is followed by a plus sign, it indicates that there are more active constraints of which at least one is temporarily released from the working set due to negative Lagrange multipliers.
- the value of the objective function at the final point
- if the (projected) gradient is available, the value of the largest absolute (projected) gradient element
- other information that is specific for the optimization technique

The **NOPRINT** option suppresses all output to the list file and only errors, warnings, and notes are displayed to the log file. The **PALL** option sets a large group of some of the commonly used specific displaying options, the **PSHORT** option suppresses some, and the **PSUMMARY** option suppresses almost all of the default output. The following table summarizes the correspondence between the general and the specific print options.

**Table 8.5** Optimization Termination

| Output Options   | <b>PALL</b> | default | <b>PSHORT</b> | <b>PSUMMARY</b> | Output                     |
|------------------|-------------|---------|---------------|-----------------|----------------------------|
|                  | y           | y       | y             | y               | Summary of optimization    |
|                  | y           | y       | y             | n               | Parameter estimates        |
|                  | y           | y       | y             | n               | Gradient of objective func |
| <b>PHISTORY</b>  | y           | y       | y             | n               | Iteration history          |
| <b>PINIT</b>     | y           | y       | n             | n               | Setting of initial values  |
|                  | y           | y       | n             | n               | Listing of constraints     |
| <b>PGRID</b>     | y           | n       | n             | n               | Results of grid search     |
| <b>PNLCJAC</b>   | y           | n       | n             | n               | Jacobian nonlin. constr.   |
| <b>PFUNCTION</b> | y           | n       | n             | n               | Values of functions        |
| <b>PEIGVAL</b>   | y           | n       | n             | n               | Eigenvalue distribution    |
| <b>PCRPIAC</b>   | y           | n       | n             | n               | Crossproduct Jacobian      |
| <b>PHESSIAN</b>  | y           | n       | n             | n               | Hessian matrix             |
| <b>PSTDERR</b>   | y           | n       | n             | n               | Approx. standard errors    |
| <b>PCOV</b>      | y           | n       | n             | n               | Covariance matrices        |
| <b>PJACOBI</b>   | n           | n       | n             | n               | Jacobian                   |
| <b>LIST</b>      | n           | n       | n             | n               | Model program, variables   |
| <b>LISTCODE</b>  | n           | n       | n             | n               | Compiled model program     |



### Convergence Status

Upon termination, the NLP procedure creates an ODS table called “ConvergenceStatus.” You can use this name to reference the table when using the Output Delivery System (ODS) to select tables and create output data sets. Within the “ConvergenceStatus” table there are two variables, “Status” and “Reason,” which contain the status of the optimization run. For the “Status” variable, a value of zero indicates that one of the convergence criteria is satisfied; a nonzero value indicates otherwise. In all cases, an explicit interpretation of the status code is displayed as a string stored in the “Reason” variable. For more information about ODS, see *SAS Output Delivery System: User’s Guide*.

## Missing Values

### Missing Values in Program Statements

There is one very important reason for using missing values in program statements specifying the values of the objective functions and derivatives: it may not be possible to evaluate the program statements for a particular point  $x$ . For example, the extrapolation formula of one of the line-search algorithms may generate large  $x$  values for which the EXP function cannot be evaluated without floating point overflow. The compiler of the program statements may check for such situations automatically, but it would be safer if you check the feasibility of your program statements. In some cases, the specification of boundary or linear constraints for parameters can avoid such situations. In many other cases, you can indicate that  $x$  is a *bad* point simply by returning a missing value for the objective function. In such cases the optimization algorithms in PROC NLP shorten the step length  $\alpha$  or reduce the trust region radius so that the next point will be closer to the point that was already successfully evaluated at the last iteration. Note that the starting point  $x^{(0)}$  must be a point for which the program statements can be evaluated.

### Missing Values in Input Data Sets

Observations with missing values in the **DATA=** data set for variables used in the objective function can lead to a missing value of the objective function implying that the corresponding **BY** group of data is not processed. The **NOMISS** option can be used to skip those observations of the **DATA=** data set for which relevant variables have missing values. Relevant variables are those that are referred to in program statements.

There can be different reasons to include observations with missing values in the **INEST=** data set. The value of the **\_RHS\_** variable is not used in some cases and can be missing. Missing values for the variables corresponding to parameters in the **\_TYPE\_** variable are as follows:

- **PARMS** observations cause those parameters to have initial values assigned by the **DECVAR** statement or by the **RANDOM=** or **INITIAL=** option.
- **UPPERBD** or **LOWERBD** observations cause those parameters to be unconstrained by upper or lower bounds.
- **LE**, **GE**, or **EQ** observations cause those parameters to have zero values in the constraint.

In general, missing values are treated as zeros.



## Computational Resources

Since nonlinear optimization is an iterative process that depends on many factors, it is difficult to estimate how much computer time is necessary to compute an optimal solution satisfying one of the termination criteria. The `MAXTIME=`, `MAXITER=`, and `MAXFUNC=` options can be used to restrict the amount of real time, the number of iterations, and the number of function calls in a single run of PROC NLP.

In each iteration  $k$ , the NRRIDG and LEVMAR techniques use symmetric Householder transformations to decompose the  $n \times n$  Hessian (crossproduct Jacobian) matrix  $G$ ,

$$G = V^T T V, \quad V \text{ orthogonal}, \quad T \text{ tridiagonal}$$

to compute the (Newton) search direction  $s$ :

$$s^{(k)} = -G^{(k-1)} g^{(k)}, \quad k = 1, 2, 3, \dots$$

The QUADAS, TRUREG, NEWRAP, and HYQUAN techniques use the Cholesky decomposition to solve the same linear system while computing the search direction. The QUANEW, DBLDOG, CONGRA, and NMSIMP techniques do not need to invert or decompose a Hessian or crossproduct Jacobian matrix and thus require fewer computational resources than the first group of techniques.

The larger the problem, the more time is spent computing function values and derivatives. Therefore, many researchers compare optimization techniques by counting and comparing the respective numbers of function, gradient, and Hessian (crossproduct Jacobian) evaluations. You can save computer time and memory by specifying derivatives (using the `GRADIENT`, `JACOBIAN`, `CRPJAC`, or `HESSIAN` statement) since you will typically produce a more efficient representation than the internal derivative compiler.

Finite-difference approximations of the derivatives are expensive since they require additional function or gradient calls.

- Forward-difference formulas:
  - First-order derivatives:  $n$  additional function calls are needed.
  - Second-order derivatives based on function calls only: for a dense Hessian,  $n(n+3)/2$  additional function calls are needed.
  - Second-order derivatives based on gradient calls:  $n$  additional gradient calls are needed.
- Central-difference formulas:
  - First-order derivatives:  $2n$  additional function calls are needed.
  - Second-order derivatives based on function calls only: for a dense Hessian,  $2n(n+1)$  additional function calls are needed.
  - Second-order derivatives based on gradient:  $2n$  additional gradient calls are needed.

Many applications need considerably more time for computing second-order derivatives (Hessian matrix) than for first-order derivatives (gradient). In such cases, a (dual) quasi-Newton or conjugate gradient technique is recommended, which does not require second-order derivatives.

The following table shows for each optimization technique which derivatives are needed (FOD: first-order derivatives; SOD: second-order derivatives), what kinds of constraints are supported (BC: boundary constraints; LIC: linear constraints), and the minimal memory (number of double floating point numbers) required. For various reasons, there are additionally about  $7n + m$  double floating point numbers needed.

| Quadratic Programming | FOD | SOD | BC | LIC | Memory           |
|-----------------------|-----|-----|----|-----|------------------|
| LICOMP                | -   | -   | x  | x   | $18n + 3nn$      |
| QUADAS                | -   | -   | x  | x   | $1n + 2nn/2$     |
| General Optimization  | FOD | SOD | BC | LIC | Memory           |
| TRUREG                | x   | x   | x  | x   | $4n + 2nn/2$     |
| NEWRAP                | x   | x   | x  | x   | $2n + 2nn/2$     |
| NRRIDG                | x   | x   | x  | x   | $6n + nn/2$      |
| QUANEW                | x   | -   | x  | x   | $1n + nn/2$      |
| DBLDOG                | x   | -   | x  | x   | $7n + nn/2$      |
| CONGRA                | x   | -   | x  | x   | $3n$             |
| NMSIMP                | -   | -   | x  | x   | $4n + nn$        |
| Least Squares         | FOD | SOD | BC | LIC | Memory           |
| LEVMAR                | x   | -   | x  | x   | $6n + nn/2$      |
| HYQUAN                | x   | -   | x  | x   | $2n + nn/2 + 3m$ |

**Notes:**

- Here,  $n$  denotes the number of parameters,  $nn$  the squared number of parameters, and  $nn/2 := n(n + 1)/2$ .
- The value of  $m$  is the product of the number of functions specified in the **MIN**, **MAX**, or **LSQ** statement and the maximum number of observations in each **BY** group of a **DATA=** input data set. The following table also contains the number  $v$  of variables in the **DATA=** data set that are used in the program statements.
- For a diagonal Hessian matrix, the  $nn/2$  term in QUADAS, TRUREG, NEWRAP, and NRRIDG is replaced by  $n$ .
- If the TRUREG, NRRIDG, or NEWRAP method is used to minimize a least squares problem, the second derivatives are replaced by the crossproduct Jacobian matrix.
- The memory needed by the **TECH=NONE** specification depends on the output specifications (typically, it needs  $3n + nn/2$  double floating point numbers and an additional  $mn$  if the Jacobian matrix is required).

The total amount of memory needed to run an optimization technique consists of the technique-specific memory listed in the preceding table, plus additional blocks of memory as shown in the following table.

|                           | double                       | int  | long | 8byte   |
|---------------------------|------------------------------|------|------|---------|
| Basic Requirement         | $7n + m$                     | $n$  | $3n$ | $n + m$ |
| <b>DATA=</b> data set     | $v$                          | -    | -    | $v$     |
| <b>JACOBIAN</b> statement | $m(n + 2)$                   | -    | -    | -       |
| <b>CRPJAC</b> statement   | $nn/2$                       | -    | -    | -       |
| <b>HESSIAN</b> statement  | $nn/2$                       | -    | -    | -       |
| <b>COV=</b> option        | $(2*)nn/2 + n$               | -    | -    | -       |
| Scaling vector            | $n$                          | -    | -    | -       |
| <b>BOUNDS</b> statement   | $2n$                         | $n$  | -    | -       |
| Bounds in <b>INEST=</b>   | $2n$                         | -    | -    | -       |
| <b>LINCON</b> and TRUREG  | $c(n + 1) + nn + nn/2 + 4n$  | $3c$ | -    | -       |
| <b>LINCON</b> and other   | $c(n + 1) + nn + 2nn/2 + 4n$ | $3c$ | -    | -       |

**Notes:**

- For **TECH=LICOMP**, the total amount of memory needed for the linear or boundary constrained case is  $18(n + c) + 3(n + c)(n + c)$ , where  $c$  is the number of constraints.
- The amount of memory needed to specify derivatives with a **GRADIENT**, **JACOBIAN**, **CRPJAC**, or **HESSIAN** statement (shown in this table) is small compared to that needed for using the internal function compiler to compute the derivatives. This is especially so for second-order derivatives.
- If the CONGRA technique is used, specifying the **GRADCHECK=DETAIL** option requires an additional  $nn/2$  double floating point numbers to store the finite-difference Hessian matrix.

---

## Memory Limit

The system option MEMSIZE sets a limit on the amount of memory used by the SAS System. If you do not specify a value for this option, then the SAS System sets a default memory limit. Your operating environment determines the actual size of the default memory limit, which is sufficient for many applications. However, to solve most realistic optimization problems, the NLP procedure might require more memory. Increasing the memory limit can reduce the chance of an out-of-memory condition.

**NOTE:** The MEMSIZE system option is not available in some operating environments. See the documentation for your operating environment for more information.

You can specify -MEMSIZE 0 to indicate all available memory should be used, but this setting should be used with caution. In most operating environments, it is better to specify an adequate amount of memory than to specify -MEMSIZE 0. For example, if you are running PROC OPTLP to solve LP problems with only a few hundred thousand variables and constraints, -MEMSIZE 500M might be sufficient to enable the procedure to run without an out-of-memory condition. When problems have millions of variables, -MEMSIZE 1000M or higher might be needed. These are “rules of thumb”—problems with atypical structure, density, or other characteristics can increase the optimizer’s memory requirements.

The MEMSIZE option can be specified at system invocation, on the SAS command line, or in a configuration file. The syntax is described in the SAS Companion for your operating environment.

To report a procedure’s memory consumption, you can use the FULLSTIMER option. The syntax is described in the SAS Companion for your operating environment.

---

## Examples: NLP Procedure

---

### Example 8.1: Using the DATA= Option

This example illustrates the use of the **DATA=** option. The Bard function (refer to Moré, Garbow, and Hillstom (1981)) is a least squares problem with  $n = 3$  parameters and  $m = 15$  functions  $f_k$ :

$$f(x) = \frac{1}{2} \sum_{k=1}^{15} f_k^2(x), \quad x = (x_1, x_2, x_3)$$

where

$$f_k(x) = y_k - \left( x_1 + \frac{u_k}{v_k x_2 + w_k x_3} \right)$$

with  $u_k = k$ ,  $v_k = 16 - k$ ,  $w_k = \min(u_k, v_k)$ , and

$$y = (.14, .18, .22, .25, .29, .32, .35, .39, .37, .58, .73, .96, 1.34, 2.10, 4.39)$$

The minimum function value  $f(x^*) = 4.107\text{E}-3$  is at the point  $(0.08, 1.13, 2.34)$ . The starting point  $x^0 = (1, 1, 1)$  is used.

The following is the naive way of specifying the objective function.

```
proc nlp tech=levmar;
  lsq y1-y15;
  parms x1-x3 = 1;
  tmp1 = 15 * x2 + min(1,15) * x3;
  y1 = 0.14 - (x1 + 1 / tmp1);
  tmp1 = 14 * x2 + min(2,14) * x3;
  y2 = 0.18 - (x1 + 2 / tmp1);
  tmp1 = 13 * x2 + min(3,13) * x3;
  y3 = 0.22 - (x1 + 3 / tmp1);
  tmp1 = 12 * x2 + min(4,12) * x3;
  y4 = 0.25 - (x1 + 4 / tmp1);
  tmp1 = 11 * x2 + min(5,11) * x3;
  y5 = 0.29 - (x1 + 5 / tmp1);
  tmp1 = 10 * x2 + min(6,10) * x3;
  y6 = 0.32 - (x1 + 6 / tmp1);
  tmp1 = 9 * x2 + min(7,9) * x3;
  y7 = 0.35 - (x1 + 7 / tmp1);
  tmp1 = 8 * x2 + min(8,8) * x3;
  y8 = 0.39 - (x1 + 8 / tmp1);
  tmp1 = 7 * x2 + min(9,7) * x3;
  y9 = 0.37 - (x1 + 9 / tmp1);
  tmp1 = 6 * x2 + min(10,6) * x3;
  y10 = 0.58 - (x1 + 10 / tmp1);
  tmp1 = 5 * x2 + min(11,5) * x3;
  y11 = 0.73 - (x1 + 11 / tmp1);
  tmp1 = 4 * x2 + min(12,4) * x3;
  y12 = 0.96 - (x1 + 12 / tmp1);
  tmp1 = 3 * x2 + min(13,3) * x3;
  y13 = 1.34 - (x1 + 13 / tmp1);
  tmp1 = 2 * x2 + min(14,2) * x3;
  y14 = 2.10 - (x1 + 14 / tmp1);
  tmp1 = 1 * x2 + min(15,1) * x3;
  y15 = 4.39 - (x1 + 15 / tmp1);
run;
```

A more economical way to program this problem uses the `DATA=` option to input the 15 terms in  $f(x)$ .

```
data bard;
  input r @@;
  w1 = 16. - _n_;
  w2 = min(_n_ , 16. - _n_);
```

```

      datalines;
.14 .18 .22 .25 .29 .32 .35 .39
.37 .58 .73 .96 1.34 2.10 4.39
;

proc nlp data=bard tech=levmar;
  lsq y;
  parms x1-x3 = 1.;
  y = r - (x1 + _obs_ / (w1 * x2 + w2 * x3));
run;

```

Another way you can specify the objective function uses the [ARRAY](#) statement and an explicit do loop, as in the following code.

```

proc nlp tech=levmar;
  array r[15] .14 .18 .22 .25 .29 .32 .35 .39 .37 .58
             .73 .96 1.34 2.10 4.39 ;
  array y[15] y1-y15;
  lsq y1-y15;
  parms x1-x3 = 1.;
  do i = 1 to 15;
    w1 = 16. - i;
    w2 = min(i , w1);
    w3 = w1 * x2 + w2 * x3;
    y[i] = r[i] - (x1 + i / w3);
  end;
run;

```

---

## Example 8.2: Using the INQUAD= Option

This example illustrates the [INQUAD=](#) option for specifying a quadratic programming problem:

$$\min f(x) = \frac{1}{2}x^T Gx + g^T x + c, \quad \text{with } G^T = G$$

Suppose that  $c = -100$ ,  $G = \text{diag}(.4, 4)$  and  $2 \leq x_1 \leq 50$ ,  $-50 \leq x_2 \leq 50$ , and  $10 \leq 10x_1 - x_2$ .

You specify the constant  $c$  and the Hessian  $G$  in the data set QUAD1. Notice that the `_TYPE_` variable contains the keywords that identify how the procedure should interpret the observations.

```

data quad1;
  input _type_ $ _name_ $ x1 x2;
  datalines;
const . -100 -100
quad x1 0.4 0
quad x2 0 4
;

```

You specify the QUAD1 data set with the [INQUAD=](#) option. Notice that the names of the variables in the QUAD1 data set and the `_NAME_` variable match the names of the parameters in the [PARMS](#) statement.

```

proc nlp inquad=quad1 all;
  min ;
  parms x1 x2 = -1;
  bounds 2 <= x1 <= 50,
         -50 <= x2 <= 50;
  lincon 10 <= 10 * x1 - x2;
run;

```

Alternatively, you can use a sparse format for specifying the  $G$  matrix, eliminating the zeros. You use the special variables `_ROW_`, `_COL_`, and `_VALUE_` to give the nonzero row and column names and value.

```

data quad2;
  input _type_ $ _row_ $ _col_ $ _value_;
  datalines;
const . . -100
quad x1 x1 0.4
quad x2 x2 4
;

```

You can also include the constraints in the QUAD data set. Notice how the `_TYPE_` variable contains keywords that identify how the procedure is to interpret the values in each observation.

```

data quad3;
  input _type_ $ _name_ $ x1 x2 _rhs_;
  datalines;
const . -100 -100 .
quad x1 0.02 0 .
quad x2 0.00 2 .
parms . -1 -1 .
lowerbd . 2 -50 .
upperbd . 50 50 .
ge . 10 -1 10
;

proc nlp inquad=quad3;
  min ;
  parms x1 x2;
run;

```

---

### Example 8.3: Using the INEST=Option

This example illustrates the use of the `INEST=` option for specifying a starting point and linear constraints. You name a data set with the `INEST=` option. The format of this data set is similar to the format of the QUAD data set described in the previous example.

Consider the Hock and Schittkowski (1981) Problem # 24:

$$\min f(x) = \frac{((x_1 - 3)^2 - 9)x_2^3}{27\sqrt{3}}$$

subject to:

$$\begin{aligned} 0 &\leq x_1, x_2 \\ 0 &\leq .57735x_1 - x_2 \\ 0 &\leq x_1 + 1.732x_2 \\ 6 &\geq x_1 + 1.732x_2 \end{aligned}$$

with minimum function value  $f(x^*) = -1$  at  $x^* = (3, \sqrt{3})$ . The feasible starting point is  $x^0 = (1, .5)$ .

You can specify this model in **PROC NLP** as follows:

```
proc nlp tech=trureg outest=res;
  min y;
  parms x1 = 1,
        x2 = .5;
  bounds 0 <= x1-x2;
  lincon  .57735 * x1 -          x2 >= 0,
          x1 + 1.732 * x2 >= 0,
          -x1 - 1.732 * x2 >= -6;
  y = ((x1 - 3)**2 - 9.) * x2**3 / (27 * sqrt(3));
run;
```

Note that none of the data for this model are in a data set. Alternatively, you can save the starting point (1, .5) and the linear constraints in a data set. Notice that the `_TYPE_` variable contains keywords that identify how the procedure is to interpret each of the observations and that the parameters in the problems X1 and X2 are variables in the data set. The observation with `_TYPE_=LOWERBD` gives the lower bounds on the parameters. The observation with `_TYPE_=GE` gives the coefficients for the first constraint. Similarly, the subsequent observations contain specifications for the other constraints. Also notice that the special variable `_RHS_` contains the right-hand-side values.

```
data betts1(type=est);
  input _type_ $ x1 x2 _rhs_;
  datalines;
parms      1          .5          .
lowerbd    0          0          .
ge         .57735     -1          .
ge         1          1.732        .
le         1          1.732        6
;
```

Now you can solve this problem with the following code. Notice that you specify the objective function and the parameters.

```
proc nlp inest=betts1 tech=trureg;
  min y;
  parms x1 x2;
  y = ((x1 - 3)**2 - 9) * x2**3 / (27 * sqrt(3));
run;
```

You can even include any constants used in the program statements in the `INEST=` data set. In the following code the variables A, B, C, and D contain some of the constants used in calculating the objective function Y.

```

data betts2(type=est);
  input _type_ $ x1    x2    _rhs_    a    b    c    d;
  datalines;
parms      1          .5          .      3    9   27    3
lowerbd    0          0           .      .    .    .    .
ge         .57735     -1          0      .    .    .    .
ge         1          1.732        0      .    .    .    .
le         1          1.732        6      .    .    .    .
;

```

Notice that in the program statement for calculating Y, the constants are replaced by the A, B, C, and D variables.

```

proc nlp inest=betts2 tech=trureg;
  min y;
  parms x1 x2;
  y = (((x1 - a)**2 - b) * x2**3) / (c * sqrt(d));
run;

```



## Example 8.4: Restarting an Optimization

This example shows how you can restart an optimization problem using the `OUTEST=`, `INEST=`, `OUTMODEL=`, and `MODEL=` options and how to save output into an `OUT=` data set. The least squares solution of the Rosenbrock function using the trust region method is used.

The following code solves the problem and saves the model in the `MODEL` data set and the solution in the `EST` and `OUT1` data sets.

```
proc nlp tech=trureg outmodel=model outest=est out=out1;
  lsq y1 y2;
  parms x1 = -1.2 ,
        x2 = 1.;
  y1 = 10. * (x2 - x1 * x1);
  y2 = 1. - x1;
run;

proc print data=out1;
run;
```

The final parameter estimates  $x^* = (1, 1)$  and the values of the functions  $f_1 = Y1$  and  $f_2 = Y2$  are written into an `OUT=` data set, shown in [Output 8.4.1](#). Since `OUTDER=0` is the default, the `OUT=` data set does not contain the Jacobian matrix.

**Output 8.4.1** Solution in an `OUT=` Data Set

| Obs | _OBS_ | _TYPE_ | y1 | y2          | x2 | x1 |
|-----|-------|--------|----|-------------|----|----|
| 1   | 1     |        | 0  | -2.2204E-16 | 1  | 1  |

Next, the procedure reads the optimal parameter estimates from the `EST` data set and the model from the `MODEL` data set. It does not do any optimization (`TECH=NONE`), but it saves the Jacobian matrix to the `OUT=OUT2` data set because of the option `OUTDER=1`. It also displays the Jacobian matrix because of the option `PJAC`; the Jacobian matrix is shown in [Output 8.4.2](#). [Output 8.4.3](#) shows the contents of the `OUT2` data set, which also contains the Jacobian matrix.

```
proc nlp tech=none model=model inest=est out=out2 outder=1 pjac PHISTORY;
  lsq y1 y2;
  parms x1 x2;
run;

proc print data=out2;
run;
```

**Output 8.4.2** Jacobian Matrix Output

| PROC NLP: Least Squares Minimization |    |
|--------------------------------------|----|
| Jacobian Matrix                      |    |
| x1                                   | x2 |
| -20                                  | 10 |
| -1                                   | 0  |

**Output 8.4.3** Jacobian Matrix in an OUT= Data Set

| Obs | _OBS_ | _TYPE_   | y1  | y2 | _WRT_ | x2 | x1 |
|-----|-------|----------|-----|----|-------|----|----|
| 1   | 1     |          | 0   | -0 |       | 1  | 1  |
| 2   | 1     | ANALYTIC | 10  | 0  | x2    | 1  | 1  |
| 3   | 1     | ANALYTIC | -20 | -1 | x1    | 1  | 1  |

**Example 8.5: Approximate Standard Errors**

The NLP procedure provides a variety of ways for estimating parameters in nonlinear statistical models and for obtaining approximate standard errors and covariance matrices for the estimators. These methods are illustrated by estimating the mean of a random sample from a normal distribution with mean  $\mu$  and standard deviation  $\sigma$ . The simplicity of the example makes it easy to compare the results of different methods in NLP with the usual estimator, the sample mean.

The following data step is used:

```
data x;
  input x @@;
datalines;
1 3 4 5 7
;
```

The standard error of the mean, computed with  $n - 1$  degrees of freedom, is 1. The usual maximum-likelihood approximation to the standard error of the mean, using a variance divisor of  $n$  rather than  $n - 1$ , is 0.894427.

The sample mean is a least squares estimator, so it can be computed using an LSQ statement. Moreover, since this model is linear, the Hessian matrix and crossproduct Jacobian matrix are identical, and all three versions of the **COV=** option yield the same variance and standard error of the mean. Note that **COV=j** means that the crossproduct Jacobian is used. This is chosen because it requires the least computation.

```
proc nlp data=x cov=j pstderr pshort PHISTORY;
  lsq resid;
  parms mean=0;
  resid=x-mean;
run;
```

The results are the same as the usual estimates.

### Output 8.5.1 Parameter Estimates

| PROC NLP: Least Squares Minimization |                                   |                   |          |                   |
|--------------------------------------|-----------------------------------|-------------------|----------|-------------------|
| Optimization Results                 |                                   |                   |          |                   |
| Parameter Estimates                  |                                   |                   |          |                   |
| N Parameter                          | Estimate                          | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                               | 4.000000                          | 1.000000          | 4.000000 | 0.016130          |
| Optimization Results                 |                                   |                   |          |                   |
| Parameter Estimates                  |                                   |                   |          |                   |
| N Parameter                          | Gradient<br>Objective<br>Function |                   |          |                   |
| 1 mean                               | 8.881784E-15                      |                   |          |                   |
| Value of Objective Function = 10     |                                   |                   |          |                   |

PROC NLP can also compute maximum-likelihood estimates of  $\mu$  and  $\sigma$ . In this case it is convenient to minimize the negative log likelihood. To get correct standard errors for maximum-likelihood estimators, the **SIGSQ=1** option is required. The following program shows **COV=1** but the output that follows has **COV=2** and **COV=3**.

```
proc nlp data=x cov=1 sigsq=1 pstderr phes pcov pshort;
  min nloglik;
  parms mean=0, sigma=1;
  bounds 1e-12 < sigma;
  nloglik=.5*((x-mean)/sigma)**2 + log(sigma);
run;
```

The variance divisor is  $n$  instead of  $n - 1$ , so the standard error of the mean is 0.894427 instead of 1. The standard error of the mean is the same with all six types of covariance matrix, but the standard error of the standard deviation varies. The sampling distribution of the standard deviation depends on the higher moments of the population distribution, so different methods of estimation can produce markedly different estimates of the standard error of the standard deviation.

Output 8.5.2 shows the output when COV=1, Output 8.5.3 shows the output when COV=2, and Output 8.5.4 shows the output when COV=3.

**Output 8.5.2** Solution for COV=1

| PROC NLP: Nonlinear Minimization                         |                                   |                   |          |                   |
|--|-----------------------------------|-------------------|----------|-------------------|
| Optimization Results                                     |                                   |                   |          |                   |
| Parameter Estimates                                      |                                   |                   |          |                   |
| N Parameter  | Estimate                          | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean   | 4.000000                          | 0.894427          | 4.472136 | 0.006566          |
| 2 sigma  | 2.000000                          | 0.458258          | 4.364358 | 0.007260          |
| Optimization Results                                     |                                   |                   |          |                   |
| Parameter Estimates                                      |                                   |                   |          |                   |
| N Parameter  | Gradient<br>Objective<br>Function |                   |          |                   |
| 1 mean   | 1.331492E-10                      |                   |          |                   |
| 2 sigma  | -5.606415E-9                      |                   |          |                   |
| Value of Objective Function = 5.9657359028               |                                   |                   |          |                   |
| Hessian Matrix   |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean   | 1.2500000028                      | -1.33149E-10      |          |                   |
| sigma  | -1.33149E-10                      | 2.500000014       |          |                   |
| Determinant = 3.1250000245                               |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues                     |                                   |                   |          |                   |
| Covariance Matrix 1: M = (NOBS/d)<br>inv(G) JJ(f) inv(G) |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean   | 0.8                               | 1.906775E-11      |          |                   |
| sigma  | 1.906775E-11                      | 0.2099999991      |          |                   |
| Factor sigm = 1  |                                   |                   |          |                   |
| Determinant = 0.1679999993                               |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues                     |                                   |                   |          |                   |

**Output 8.5.3** Solution for COV=2

| PROC NLP: Nonlinear Minimization           |                                   |                   |          |                   |
|--|-----------------------------------|-------------------|----------|-------------------|
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Estimate                          | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                                     | 4.000000                          | 0.894427          | 4.472136 | 0.006566          |
| 2 sigma                                    | 2.000000                          | 0.632456          | 3.162278 | 0.025031          |
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Gradient<br>Objective<br>Function |                   |          |                   |
| 1 mean                                     | 1.331492E-10                      |                   |          |                   |
| 2 sigma                                    | -5.606415E-9                      |                   |          |                   |
| Value of Objective Function = 5.9657359028 |                                   |                   |          |                   |
| Hessian Matrix                             |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean                                       | 1.2500000028                      | -1.33149E-10      |          |                   |
| sigma                                      | -1.33149E-10                      | 2.500000014       |          |                   |
| Determinant = 3.1250000245                 |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues       |                                   |                   |          |                   |
| Covariance Matrix 2: H = (NOBS/d) inv(G)   |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean                                       | 0.7999999982                      | 4.260769E-11      |          |                   |
| sigma                                      | 4.260769E-11                      | 0.3999999978      |          |                   |
| Factor sigm = 1                            |                                   |                   |          |                   |
| Determinant = 0.3199999975                 |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues       |                                   |                   |          |                   |

**Output 8.5.4** Solution for COV=3

| PROC NLP: Nonlinear Minimization           |                                   |                   |          |                   |
|--|-----------------------------------|-------------------|----------|-------------------|
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Estimate                          | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                                     | 4.000000                          | 0.509136          | 7.856442 | 0.000537          |
| 2 sigma                                    | 2.000000                          | 0.419936          | 4.762634 | 0.005048          |
| Optimization Results                       |                                   |                   |          |                   |
| Parameter Estimates                        |                                   |                   |          |                   |
| N Parameter                                | Gradient<br>Objective<br>Function |                   |          |                   |
| 1 mean                                     | 1.338402E-10                      |                   |          |                   |
| 2 sigma                                    | -5.940302E-9                      |                   |          |                   |
| Value of Objective Function = 5.9657359028 |                                   |                   |          |                   |
| Hessian Matrix                             |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean                                       | 1.2500000028                      | -1.33149E-10      |          |                   |
| sigma                                      | -1.33149E-10                      | 2.500000014       |          |                   |
| Determinant = 3.1250000245                 |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues       |                                   |                   |          |                   |
| Covariance Matrix 3: J = (1/d) inv(W)      |                                   |                   |          |                   |
|  | mean                              | sigma             |          |                   |
| mean                                       | 0.2592197879                      | 1.091093E-11      |          |                   |
| sigma                                      | 1.091093E-11                      | 0.1763460041      |          |                   |
| Factor sigm = 0.2                          |                                   |                   |          |                   |
| Determinant = 0.0457123738                 |                                   |                   |          |                   |
| Matrix has Only Positive Eigenvalues       |                                   |                   |          |                   |

Under normality, the maximum-likelihood estimators of  $\mu$  and  $\sigma$  are independent, as indicated by the diagonal Hessian matrix in the previous example. Hence, the maximum-likelihood estimate of  $\mu$  can be obtained by using any fixed value for  $\sigma$ , such as 1. However, if the fixed value of  $\sigma$  differs from the actual maximum-likelihood estimate (in this case 2), the model is misspecified and the standard errors obtained with **COV=2** or **COV=3** are incorrect. It is therefore necessary to use **COV=1**, which yields consistent estimates of the standard errors under a variety of forms of misspecification of the error distribution.

```
proc nlp data=x cov=1 sigsq=1 pstderr pcov pshort;
  min sqresid;
  parms mean=0;
  sqresid=.5*(x-mean)**2;
run;
```

This formulation produces the same standard error of the mean, 0.894427 (see [Output 8.5.5](#)).

**Output 8.5.5** Solution for Fixed  $\sigma$  and COV=1

| PROC NLP: Nonlinear Minimization |          |                   |          |                   |
|----------------------------------|----------|-------------------|----------|-------------------|
| Optimization Results             |          |                   |          |                   |
| Parameter Estimates              |          |                   |          |                   |
| N Parameter                      | Estimate | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                           | 4.000000 | 0.894427          | 4.472136 | 0.006566          |
| Optimization Results             |          |                   |          |                   |
| Parameter Estimates              |          |                   |          |                   |
|                                  |          | Gradient          |          |                   |
|                                  |          | Objective         |          |                   |
| N Parameter                      |          | Function          |          |                   |
| 1 mean                           |          | 0                 |          |                   |
| Value of Objective Function = 10 |          |                   |          |                   |
| Covariance Matrix                |          |                   |          |                   |
| 1: M = (NOBS/d) inv(G)           |          |                   |          |                   |
| JJ(f) inv(G)                     |          |                   |          |                   |
|                                  |          | mean              |          |                   |
| mean                             |          | 0.8               |          |                   |
| Factor sigm = 1                  |          |                   |          |                   |

The maximum-likelihood formulation with fixed  $\sigma$  is actually a least squares problem. The objective function, parameter estimates, and Hessian matrix are the same as those in the first example in this section using the **LSQ** statement. However, the Jacobian matrix is different, each row being multiplied by twice the residual.

To treat this formulation as a least squares problem, the `SIGSQ=1` option can be omitted. But since the Jacobian is not the same as in the formulation using the `LSQ` statement, the `COV=1 | M` and `COV=3 | J` options, which use the Jacobian, do not yield correct standard errors. The correct standard error is obtained with `COV=2 | H`, which uses only the Hessian matrix:

```
proc nlp data=x cov=2 pstderr pcov pshort;
  min sqresid;
  parms mean=0;
  sqresid=.5*(x-mean)**2;
run;
```

The results are the same as in the first example.

Output 8.5.6 Solution for Fixed  $\sigma$  and COV=2

| PROC NLP: Nonlinear Minimization |          |                   |          |                   |
|----------------------------------|----------|-------------------|----------|-------------------|
| Optimization Results             |          |                   |          |                   |
| Parameter Estimates              |          |                   |          |                   |
| N Parameter                      | Estimate | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 mean                           | 4.000000 | 0.500000          | 8.000000 | 0.001324          |
| Optimization Results             |          |                   |          |                   |
| Parameter Estimates              |          |                   |          |                   |
|                                  |          | Gradient          |          |                   |
|                                  |          | Objective         |          |                   |
| N Parameter                      |          | Function          |          |                   |
| 1 mean                           |          | 0                 |          |                   |
| Value of Objective Function = 10 |          |                   |          |                   |
| Covariance Matrix 2:             |          |                   |          |                   |
| H = (NOBS/d) inv(G)              |          |                   |          |                   |
|                                  |          | mean              |          |                   |
| mean                             |          | 0.25              |          |                   |
| Factor sigm = 1.25               |          |                   |          |                   |

In summary, to obtain appropriate standard errors for least squares estimates, you can use the `LSQ` statement with any of the `COV=` options, or you can use the `MIN` statement with `COV=2`. To obtain appropriate standard errors for maximum-likelihood estimates, you can use the `MIN` statement with the negative log likelihood or the `MAX` statement with the log likelihood, and in either case you can use any of the `COV=` options provided that you specify `SIGSQ=1`. You can also use a log-likelihood function with a misspecified scale parameter provided that you use `SIGSQ=1` and `COV=1`. For nonlinear models, all of these methods yield approximations based on asymptotic theory, and should therefore be interpreted cautiously.



## Example 8.6: Maximum Likelihood Weibull Estimation

### Two-Parameter Weibull Estimation

The following data are taken from Lawless (1982, p. 193) and represent the number of days it took rats painted with a carcinogen to develop carcinoma. The last two observations are censored data from a group of 19 rats:

```
data pike;
  input days cens @@;
  datalines;
143 0 164 0 188 0 188 0
190 0 192 0 206 0 209 0
213 0 216 0 220 0 227 0
230 0 234 0 246 0 265 0
304 0 216 1 244 1
;
```

Suppose that you want to show how to compute the maximum likelihood estimates of the scale parameter  $\sigma$  ( $\alpha$  in Lawless), the shape parameter  $c$  ( $\beta$  in Lawless), and the location parameter  $\theta$  ( $\mu$  in Lawless). The observed likelihood function of the three-parameter Weibull transformation (Lawless 1982, p. 191) is

$$L(\theta, \sigma, c) = \frac{c^m}{\sigma^m} \prod_{i \in D} \left( \frac{t_i - \theta}{\sigma} \right)^{c-1} \prod_{i=1}^p \exp \left( - \left( \frac{t_i - \theta}{\sigma} \right)^c \right)$$

and the log likelihood is

$$l(\theta, \sigma, c) = m \log c - mc \log \sigma + (c - 1) \sum_{i \in D} \log(t_i - \theta) - \sum_{i=1}^p \left( \frac{t_i - \theta}{\sigma} \right)^c$$

The log likelihood function can be evaluated only for  $\sigma > 0$ ,  $c > 0$ , and  $\theta < \min_i t_i$ . In the estimation process, you must enforce these conditions using lower and upper boundary constraints. The three-parameter Weibull estimation can be numerically difficult, and it usually pays off to provide good initial estimates. Therefore, you first estimate  $\sigma$  and  $c$  of the two-parameter Weibull distribution for constant  $\theta = 0$ . You then use the optimal parameters  $\hat{\sigma}$  and  $\hat{c}$  as starting values for the three-parameter Weibull estimation.

Although the use of an `INEST=` data set is not really necessary for this simple example, it illustrates how it is used to specify starting values and lower boundary constraints:

```
data par1(type=est);
  keep _type_ sig c theta;
  _type_='parms'; sig = .5;
  c = .5; theta = 0; output;
  _type_='lb'; sig = 1.0e-6;
  c = 1.0e-6; theta = .; output;
run;
```

The following **PROC NLP** call specifies the maximization of the log likelihood function for the two-parameter Weibull estimation for constant  $\theta = 0$ :

```
proc nlp data=pike tech=tr inest=par1 outest=opar1
    outmodel=model cov=2 vardef=n pcov phes;
    max logf;
    parms sig c;
    profile sig c / alpha = .9 to .1 by -.1 .09 to .01 by -.01;

    x_th = days - theta;
    s     = - (x_th / sig)**c;
    if cens=0 then s + log(c) - c*log(sig) + (c-1)*log(x_th);
    logf = s;
run;
```

After a few iterations you obtain the solution given in [Output 8.6.1](#).

**Output 8.6.1** Optimization Results

| PROC NLP: Nonlinear Maximization           |                                   |                   |           |                   |
|--|-----------------------------------|-------------------|-----------|-------------------|
| Optimization Results                       |                                   |                   |           |                   |
| Parameter Estimates                        |                                   |                   |           |                   |
| N Parameter                                | Estimate                          | Approx<br>Std Err | t Value   | Approx<br>Pr >  t |
| 1 sig                                      | 234.318611                        | 9.645908          | 24.292021 | 9.050475E-16      |
| 2 c  | 6.083147                          | 1.068229          | 5.694611  | 0.000017269       |
| Optimization Results                       |                                   |                   |           |                   |
| Parameter Estimates                        |                                   |                   |           |                   |
| N Parameter                                | Gradient<br>Objective<br>Function |                   |           |                   |
| 1 sig                                      | 1.3372183E-9                      |                   |           |                   |
| 2 c  | -7.859277E-9                      |                   |           |                   |
| Value of Objective Function = -88.23273515 |                                   |                   |           |                   |

Since the gradient has only small elements and the Hessian (shown in [Output 8.6.2](#)) is negative definite (has only negative eigenvalues), the solution defines an isolated maximum point.

#### Output 8.6.2 Hessian Matrix at $x^*$

| PROC NLP: Nonlinear Maximization     |              |              |  |
|--------------------------------------|--------------|--------------|--|
| Hessian Matrix                       |              |              |  |
|                                      | sig          | c            |  |
| sig                                  | -0.011457556 | 0.0257527577 |  |
| c                                    | 0.0257527577 | -0.934221388 |  |
| Determinant = 0.0100406894           |              |              |  |
| Matrix has Only Negative Eigenvalues |              |              |  |

The square roots of the diagonal elements of the approximate covariance matrix of parameter estimates are the approximate standard errors (ASE's). The covariance matrix is given in [Output 8.6.3](#).

#### Output 8.6.3 Covariance Matrix

```

PROC NLP: Nonlinear Maximization

Covariance Matrix 2:
H = (NOBS/d) inv(G)

              sig              c
sig    93.043549863    2.5648395794
c      2.5648395794    1.141112488

Factor sigm = 1

Determinant = 99.594754608

Matrix has 2 Positive Eigenvalue(s)

```

The confidence limits in [Output 8.6.4](#) correspond to the  $\alpha$  values in the [PROFILE](#) statement.

**Output 8.6.4** Confidence Limits

| PROC NLP: Nonlinear Maximization |           |            |          |   |            |
|----------------------------------|-----------|------------|----------|---|------------|
| Wald and PL Confidence Limits    |           |            |          |   |            |
| N                                | Parameter | Estimate   | Alpha    | Profile Likelihood<br>Confidence Limits |            |
| 1                                | sig       | 234.318611 | 0.900000 | 233.111324                              | 235.532695 |
| 1                                | sig       | .          | 0.800000 | 231.886549                              | 236.772876 |
| 1                                | sig       | .          | 0.700000 | 230.623280                              | 238.063824 |
| 1                                | sig       | .          | 0.600000 | 229.292797                              | 239.436639 |
| 1                                | sig       | .          | 0.500000 | 227.855829                              | 240.935290 |
| 1                                | sig       | .          | 0.400000 | 226.251597                              | 242.629201 |
| 1                                | sig       | .          | 0.300000 | 224.372260                              | 244.643392 |
| 1                                | sig       | .          | 0.200000 | 221.984557                              | 247.278423 |
| 1                                | sig       | .          | 0.100000 | 218.390824                              | 251.394102 |
| 1                                | sig       | .          | 0.090000 | 217.884162                              | 251.987489 |
| 1                                | sig       | .          | 0.080000 | 217.326988                              | 252.645278 |
| 1                                | sig       | .          | 0.070000 | 216.708814                              | 253.383546 |
| 1                                | sig       | .          | 0.060000 | 216.008815                              | 254.228034 |
| 1                                | sig       | .          | 0.050000 | 215.199301                              | 255.215496 |
| 1                                | sig       | .          | 0.040000 | 214.230116                              | 256.411041 |
| 1                                | sig       | .          | 0.030000 | 213.020874                              | 257.935686 |
| 1                                | sig       | .          | 0.020000 | 211.369067                              | 260.066128 |
| 1                                | sig       | .          | 0.010000 | 208.671091                              | 263.687174 |
| 2                                | c         | 6.083147   | 0.900000 | 5.950029                                | 6.217752   |
| 2                                | c         | .          | 0.800000 | 5.815559                                | 6.355576   |
| 2                                | c         | .          | 0.700000 | 5.677909                                | 6.499187   |
| 2                                | c         | .          | 0.600000 | 5.534275                                | 6.651789   |
| 2                                | c         | .          | 0.500000 | 5.380952                                | 6.817880   |
| 2                                | c         | .          | 0.400000 | 5.212344                                | 7.004485   |
| 2                                | c         | .          | 0.300000 | 5.018784                                | 7.225733   |
| 2                                | c         | .          | 0.200000 | 4.776379                                | 7.506166   |
| 2                                | c         | .          | 0.100000 | 4.431310                                | 7.931669   |
| 2                                | c         | .          | 0.090000 | 4.382687                                | 7.991457   |
| 2                                | c         | .          | 0.080000 | 4.327815                                | 8.056628   |
| 2                                | c         | .          | 0.070000 | 4.270773                                | 8.129238   |
| 2                                | c         | .          | 0.060000 | 4.207130                                | 8.211221   |
| 2                                | c         | .          | 0.050000 | 4.134675                                | 8.306218   |
| 2                                | c         | .          | 0.040000 | 4.049531                                | 8.418782   |
| 2                                | c         | .          | 0.030000 | 3.945037                                | 8.559677   |
| 2                                | c         | .          | 0.020000 | 3.805759                                | 8.749130   |
| 2                                | c         | .          | 0.010000 | 3.588814                                | 9.056751   |

**Output 8.6.4** *continued*

PROC NLP: Nonlinear Maximization

Wald and PL Confidence Limits

Wald Confidence Limits

|            |            |
|------------|------------|
| 233.106494 | 235.530729 |
| 231.874849 | 236.762374 |
| 230.601846 | 238.035377 |
| 229.260292 | 239.376931 |
| 227.812545 | 240.824678 |
| 226.200410 | 242.436813 |
| 224.321270 | 244.315953 |
| 221.956882 | 246.680341 |
| 218.452504 | 250.184719 |
| 217.964960 | 250.672263 |
| 217.431654 | 251.205569 |
| 216.841087 | 251.796136 |
| 216.176649 | 252.460574 |
| 215.412978 | 253.224245 |
| 214.508337 | 254.128885 |
| 213.386118 | 255.251105 |
| 211.878873 | 256.758350 |
| 209.472398 | 259.164825 |
| 5.948912   | 6.217382   |
| 5.812514   | 6.353780   |
| 5.671537   | 6.494757   |
| 5.522967   | 6.643327   |
| 5.362638   | 6.803656   |
| 5.184103   | 6.982191   |
| 4.975999   | 7.190295   |
| 4.714157   | 7.452137   |
| 4.326067   | 7.840227   |
| 4.272075   | 7.894220   |
| 4.213014   | 7.953280   |
| 4.147612   | 8.018682   |
| 4.074029   | 8.092265   |
| 3.989457   | 8.176837   |
| 3.889274   | 8.277021   |
| 3.764994   | 8.401300   |
| 3.598076   | 8.568219   |
| 3.331572   | 8.834722   |

**Three-Parameter Weibull Estimation**

You now prepare for the three-parameter Weibull estimation by using PROC UNIVARIATE to obtain the smallest data value for the upper boundary constraint for  $\theta$ . For this small problem, you can do this much more simply by just using a value slightly smaller than the minimum data value 143.

```

/* Calculate upper bound for theta parameter */
proc univariate data=pike noprint;
  var days;
  output out=stats n=nobs min=minx range=range;
run;

data stats;
  set stats;
  keep _type_ theta;

  /* 1. write parms observation */
  theta = minx - .1 * range;
  if theta < 0 then theta = 0;
  _type_ = 'parms';
  output;

  /* 2. write ub observation */
  theta = minx * (1 - 1e-4);
  _type_ = 'ub';
  output;
run;

```

The data set PAR2 specifies the starting values and the lower and upper bounds for the three-parameter Weibull problem:

```

proc sort data=opar1;
  by _type_;
run;

data par2(type=est);
  merge opar1(drop=theta) stats;
  by _type_;
  keep _type_ sig c theta;
  if _type_ in ('parms' 'lowerbd' 'ub');
run;

```

The following [PROC NLP](#) call uses the [MODEL=](#) input data set containing the log likelihood function that was saved during the two-parameter Weibull estimation:

```

proc nlp data=pike tech=tr inest=par2 outest=opar2
  model=model cov=2 vardef=n pcov phes;
  max logf;
  parms sig c theta;
  profile sig c theta / alpha = .5 .1 .05 .01;
run;

```

After a few iterations, you obtain the solution given in [Output 8.6.5](#).

#### Output 8.6.5 Optimization Results

| PROC NLP: Nonlinear Maximization           |            |                   |          |                   |
|--|------------|-------------------|----------|-------------------|
| Optimization Results                       |            |                   |          |                   |
| Parameter Estimates                        |            |                   |          |                   |
| N Parameter                                | Estimate   | Approx<br>Std Err | t Value  | Approx<br>Pr >  t |
| 1 sig                                      | 108.382729 | 32.573390         | 3.327340 | 0.003540          |
| 2 c  | 2.711477   | 1.058759          | 2.560995 | 0.019108          |
| 3 theta                                    | 122.025945 | 28.692434         | 4.252896 | 0.000430          |
| Optimization Results                       |            |                   |          |                   |
| Parameter Estimates                        |            |                   |          |                   |
|  |            | Gradient          |          |                   |
|  |            | Objective         |          |                   |
| N Parameter                                |            | Function          |          |                   |
| 1 sig                                      |            | -2.43159E-10      |          |                   |
| 2 c  |            | -3.770071E-8      |          |                   |
| 3 theta                                    |            | -5.235252E-9      |          |                   |
| Value of Objective Function = -87.32424712 |            |                   |          |                   |

From inspecting the first- and second-order derivatives at the optimal solution, you can verify that you have obtained an isolated maximum point. The Hessian matrix is shown in [Output 8.6.6](#).

#### Output 8.6.6 Hessian Matrix

| PROC NLP: Nonlinear Maximization     |              |              |              |
|--------------------------------------|--------------|--------------|--------------|
| Hessian Matrix                       |              |              |              |
|                                      | sig          | c            | theta        |
| sig                                  | -0.010639974 | 0.045388785  | -0.010033749 |
| c                                    | 0.045388785  | -4.078687998 | -0.083026335 |
| theta                                | -0.010033749 | -0.083026335 | -0.014752091 |
| Determinant = 0.0000502116           |              |              |              |
| Matrix has Only Negative Eigenvalues |              |              |              |

The square roots of the diagonal elements of the approximate covariance matrix of parameter estimates are the approximate standard errors. The covariance matrix is given in [Output 8.6.7](#).

**Output 8.6.7** Covariance Matrix

| PROC NLP: Nonlinear Maximization                   |              |              |              |
|--|--------------|--------------|--------------|
| Covariance Matrix 2: $H = (NOBS/d) \text{ inv}(G)$ |              |              |              |
|  | sig          | c            | theta        |
| sig  | 1061.0261315 | 29.926259653 | -890.0933623 |
| c  | 29.926259653 | 1.1209710444 | -26.66352288 |
| theta  | -890.0933623 | -26.66352288 | 823.25607986 |
| Factor $\text{sigm} = 1$                           |              |              |              |
| Determinant = 19915.723197                         |              |              |              |
| Matrix has 3 Positive Eigenvalue(s)                |              |              |              |



The difference between the Wald and profile CLs for parameter PHI2 are remarkable, especially for the upper 95% and 99% limits, as shown in [Output 8.6.8](#).

**Output 8.6.8** Confidence Limits

| PROC NLP: Nonlinear Maximization |           |            |            |   |            |
|----------------------------------|-----------|------------|------------|---|------------|
| Wald and PL Confidence Limits    |           |            |            |   |            |
| N                                | Parameter | Estimate   | Alpha      | Profile Likelihood<br>Confidence Limits |            |
| 1                                | sig       | 108.382665 | 0.500000   | 91.811561                               | 141.564605 |
| 1                                | sig       | .          | 0.100000   | 76.502372                               | .          |
| 1                                | sig       | .          | 0.050000   | 72.215849                               | .          |
| 1                                | sig       | .          | 0.010000   | 64.262384                               | .          |
| 2                                | c         | 2.711475   | 0.500000   | 2.139297                                | 3.704052   |
| 2                                | c         | .          | 0.100000   | 1.574162                                | 9.250073   |
| 2                                | c         | .          | 0.050000   | 1.424853                                | 19.517943  |
| 2                                | c         | .          | 0.010000   | 1.163096                                | 19.542452  |
| 3                                | theta     | 122.026005 | 0.500000   | 91.027145                               | 135.095454 |
| 3                                | theta     | .          | 0.100000   | .                                       | 141.833769 |
| 3                                | theta     | .          | 0.050000   | .                                       | 142.512603 |
| 3                                | theta     | .          | 0.010000   | .                                       | 142.967407 |
| Wald and PL Confidence Limits    |           |            |            |   |            |
| Wald Confidence Limits           |           |            |            |   |            |
|                                  |           | 86.412324  | 130.353006 |   |            |
|                                  |           | 54.804393  | 161.960937 |   |            |
|                                  |           | 44.540216  | 172.225114 |   |            |
|                                  |           | 24.479464  | 192.285865 |   |            |
|                                  |           | 1.997355   | 3.425595   |   |            |
|                                  |           | 0.969976   | 4.452974   |   |            |
|                                  |           | 0.636351   | 4.786599   |   |            |
|                                  |           | -0.015700  | 5.438650   |   |            |
|                                  |           | 102.673331 | 141.378680 |   |            |
|                                  |           | 74.831341  | 142.985700 |   |            |
|                                  |           | 65.790094  | 142.985700 |   |            |
|                                  |           | 48.119490  | 142.985700 |   |            |

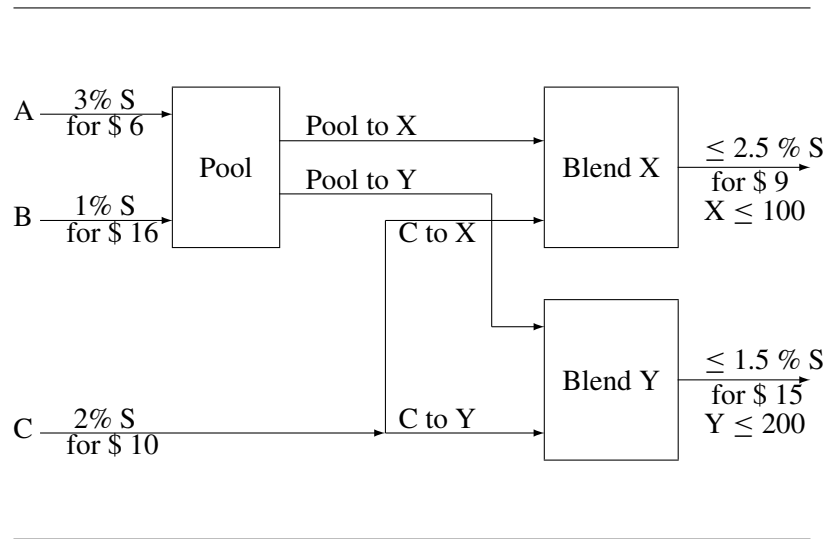
## Example 8.7: Simple Pooling Problem

The following optimization problem is discussed in Haverly (1978) and in Liebman et al. (1986, pp. 127–128). Two liquid chemicals,  $X$  and  $Y$ , are produced by the pooling and blending of three input liquid chemicals,  $A$ ,  $B$ , and  $C$ . You know the sulfur impurity amounts of the input chemicals, and you have to respect upper limits of the sulfur impurity amounts of the output chemicals. The sulfur concentrations and the prices of the input and output chemicals are:

- Chemical  $A$ : Concentration = 3%, Price = \$6
- Chemical  $B$ : Concentration = 1%, Price = \$16

- Chemical *C*: Concentration = 2%, Price= \$10
- Chemical *X*: Concentration  $\leq 2.5\%$ , Price= \$9
- Chemical *Y*: Concentration  $\leq 1.5\%$ , Price= \$15

The problem is complicated by the fact that the two input chemicals *A* and *B* are available only as a mixture (they are either shipped together or stored together). Because the amounts of *A* and *B* are unknown, the sulfur concentration of the mixture is also unknown.



You know customers will buy no more than 100 units of *X* and 200 units of *Y*. The problem is determining how to operate the pooling and blending of the chemicals to maximize the profit. The objective function for the profit is

$$\begin{aligned} \text{profit} &= \text{cost}(x) \times \text{amount}(x) + \text{cost}(y) \times \text{amount}(y) \\ &\quad - \text{cost}(a) \times \text{amount}(a) - \text{cost}(b) \times \text{amount}(b) - \text{cost}(c) \times \text{amount}(c) \end{aligned}$$

There are three groups of constraints:

1. The first group of constraint functions is the mass balance restrictions illustrated by the graph. These are four linear equality constraints:
  - $\text{amount}(a) + \text{amount}(b) = \text{pool\_to\_x} + \text{pool\_to\_y}$
  - $\text{pool\_to\_x} + c\_to\_x = \text{amount}(x)$
  - $\text{pool\_to\_y} + c\_to\_y = \text{amount}(y)$
  - $\text{amount}(c) = c\_to\_x + c\_to\_y$
2. You introduce a new variable,  $\text{pool\_s}$ , that represents the sulfur concentration of the pool. Using  $\text{pool\_s}$  and the sulfur concentration of *C* (2%), you obtain two nonlinear inequality constraints for the sulfur concentrations of *X* and *Y*, one linear equality constraint for the sulfur balance, and lower and upper boundary restrictions for  $\text{pool\_s}$ :

- $pool\_s \times pool\_to\_x + 2\ c\_to\_x \leq 2.5\ amount(x)$
- $pool\_s \times pool\_to\_y + 2\ c\_to\_y \leq 1.5\ amount(y)$
- $3\ amount(a) + 1\ amount(b) = pool\_s \times (amount(a) + amount(b))$
- $1 \leq pool\_s \leq 3$

3. The last group assembles the remaining boundary constraints. First, you do not want to produce more than you can sell; and finally, all variables must be nonnegative:

- $amount(x) \leq 100, \quad amount(y) \leq 200$
- $amount(a), amount(b), amount(c), amount(x), amount(y) \geq 0$
- $pool\_to\_x, pool\_to\_y, c\_to\_x, c\_to\_y \geq 0$

There exist several local optima to this problem that can be found by specifying different starting points. Using the starting point with all variables equal to 1 (specified with a [PARMS](#) statement), PROC NLP finds a solution with  $profit = 400$ :

```
proc nlp all;
  parms amountx amounty amounta amountb amountc
        pooltox pooltoy ctox ctoy pools = 1;
        bounds 0 <= amountx amounty amounta amountb amountc,
        amountx <= 100,
        amounty <= 200,
        0 <= pooltox pooltoy ctox ctoy,
        1 <= pools <= 3;
  lincon amounta + amountb = pooltox + pooltoy,
        pooltox + ctox = amountx,
        pooltoy + ctoy = amounty,
        ctox + ctoy      = amountc;
  nlincon nlc1-nlc2 >= 0.,
        nlc3 = 0.;
  max f;
  costa = 6; costb = 16; costc = 10;
  costx = 9; costy = 15;
  f = costx * amountx + costy * amounty
      - costa * amounta - costb * amountb - costc * amountc;
  nlc1 = 2.5 * amountx - pools * pooltox - 2. * ctox;
  nlc2 = 1.5 * amounty - pools * pooltoy - 2. * ctoy;
  nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
run;
```

The specified starting point was not feasible with respect to the linear equality constraints; therefore, a starting point is generated that satisfies linear and boundary constraints. [Output 8.7.1](#) gives the starting parameter estimates.

## Output 8.7.1 Starting Estimates

| PROC NLP: Nonlinear Maximization           |                              |                                   |                                  |                              |
|--|------------------------------|-----------------------------------|----------------------------------|------------------------------|
| Optimization Start<br>Parameter Estimates  |                              |                                   |                                  |                              |
| N Parameter                                | Estimate                     | Gradient<br>Objective<br>Function | Gradient<br>Lagrange<br>Function | Lower<br>Bound<br>Constraint |
| 1 amountx                                  | 1.363636                     | 9.000000                          | -0.843698                        | 0                            |
| 2 amounty                                  | 1.363636                     | 15.000000                         | -0.111882                        | 0                            |
| 3 amounta                                  | 0.818182                     | -6.000000                         | -0.430733                        | 0                            |
| 4 amountb                                  | 0.818182                     | -16.000000                        | -0.542615                        | 0                            |
| 5 amountc                                  | 1.090909                     | -10.000000                        | 0.017768                         | 0                            |
| 6 pooltox                                  | 0.818182                     | 0                                 | -0.669628                        | 0                            |
| 7 pooltoy                                  | 0.818182                     | 0                                 | -0.303720                        | 0                            |
| 8 cttox                                    | 0.545455                     | 0                                 | -0.174070                        | 0                            |
| 9 cttoy                                    | 0.545455                     | 0                                 | 0.191838                         | 0                            |
| 10 pools                                   | 2.000000                     | 0                                 | 0.068372                         | 1.000000                     |
| Optimization Start<br>Parameter Estimates  |                              |                                   |                                  |                              |
| N Parameter                                | Upper<br>Bound<br>Constraint |                                   |                                  |                              |
| 1 amountx                                  | 100.000000                   |                                   |                                  |                              |
| 2 amounty                                  | 200.000000                   |                                   |                                  |                              |
| 3 amounta                                  | .                            |                                   |                                  |                              |
| 4 amountb                                  | .                            |                                   |                                  |                              |
| 5 amountc                                  | .                            |                                   |                                  |                              |
| 6 pooltox                                  | .                            |                                   |                                  |                              |
| 7 pooltoy                                  | .                            |                                   |                                  |                              |
| 8 cttox                                    | .                            |                                   |                                  |                              |
| 9 cttoy                                    | .                            |                                   |                                  |                              |
| 10 pools                                   | 3.000000                     |                                   |                                  |                              |
| Value of Objective Function = 3.8181818182 |                              |                                   |                                  |                              |
| Value of Lagrange Function = -2.866739915  |                              |                                   |                                  |                              |

**Output 8.7.1** *continued*

| PROC NLP: Nonlinear Maximization |              |                                   |                                  |                               |        |
|----------------------------------|--------------|-----------------------------------|----------------------------------|-------------------------------|--------|
| Optimization Results             |              |                                   |                                  |                               |        |
| Parameter Estimates              |              |                                   |                                  |                               |        |
| N Parameter                      | Estimate     | Gradient<br>Objective<br>Function | Gradient<br>Lagrange<br>Function | Active<br>Bound<br>Constraint |        |
| 1 amountx                        | -1.40474E-11 | 9.000000                          | 0                                | Lower BC                      |        |
| 2 amounty                        | 200.000000   | 15.000000                         | 0                                | Upper BC                      |        |
| 3 amounta                        | 1.027701E-16 | -6.000000                         | 0                                | Lower BC                      |        |
| 4 amountb                        | 100.000000   | -16.000000                        | -1.77636E-15                     |                               |        |
| 5 amountc                        | 100.000000   | -10.000000                        | 1.776357E-15                     |                               |        |
| 6 pooltox                        | 7.024003E-12 | 0                                 | 0                                | Lower BC                      |        |
| 7 pooltoy                        | 100.000000   | 0                                 | -1.06581E-14                     |                               |        |
| 8 ctox                           | -2.10714E-11 | 0                                 | 5.329071E-15                     | Lower BC                      | LinDep |
| 9 ctoy                           | 100.000000   | 0                                 | 1.776357E-15                     |                               |        |
| 10 pools                         | 1.000000     | 0                                 | 0                                | Lower BC                      | LinDep |

The starting point satisfies the four equality constraints, as shown in [Output 8.7.2](#). The nonlinear constraints are given in [Output 8.7.3](#).

**Output 8.7.2** Linear Constraints

| PROC NLP: Nonlinear Maximization |                    |        |                    |                  |  |
|----------------------------------|--------------------|--------|--------------------|------------------|--|
| Linear Constraints               |                    |        |                    |                  |  |
| 1                                | -3.331E-16 : ACT   | 0 == + | 1.0000 * amounta + | 1.0000 * amountb |  |
|                                  | - 1.0000 * pooltox | -      | 1.0000 * pooltoy   |                  |  |
| 2                                | 1.1102E-16 : ACT   | 0 == - | 1.0000 * amountx + | 1.0000 * pooltox |  |
|                                  | + 1.0000 * ctox    |        |                    |                  |  |
| 3                                | 1.1102E-16 : ACT   | 0 == - | 1.0000 * amounty + | 1.0000 * pooltoy |  |
|                                  | + 1.0000 * ctoy    |        |                    |                  |  |
| 4                                | 1.1102E-16 : ACT   | 0 == - | 1.0000 * amountc + | 1.0000 * ctox    |  |
|                                  | + 1.0000 * ctoy    |        |                    |                  |  |

**Output 8.7.3** Nonlinear Constraints

| PROC NLP: Nonlinear Maximization |  |         |          |                        |              |
|----------------------------------|--|---------|----------|------------------------|--------------|
| Values of Nonlinear Constraints  |  |         |          |                        |              |
| Constraint                       |  | Value   | Residual | Lagrange<br>Multiplier |              |
| [ 5 ] nlc3                       |  | 0       | 0        | 4.9441                 | Active NLEC  |
| [ 6 ] nlc1_G                     |  | 0.6818  | 0.6818   | .                      |              |
| [ 7 ] nlc2_G                     |  | -0.6818 | -0.6818  | -9.8046                | Violat. NLIC |

**Output 8.7.3** *continued*

| PROC NLP: Nonlinear Maximization |        |          |          |            |        |      |        |
|----------------------------------|--------|----------|----------|------------|--------|------|--------|
| Values of Nonlinear Constraints  |        |          |          |            |        |      |        |
|                                  |        |          |          | Lagrange   |        |      |        |
| Constraint                       |        | Value    | Residual | Multiplier |        |      |        |
| [ 5 ]                            | nlc3   | 0        | 0        | 6.0000     | Active | NLEC |        |
| [ 6 ]                            | nlc1_G | 4.04E-16 | 4.04E-16 | .          | Active | NLIC | LinDep |
| [ 7 ]                            | nlc2_G | -284E-16 | -284E-16 | -6.0000    | Active | NLIC |        |

Output 8.7.4 shows the settings of some important PROC NLP options.

**Output 8.7.4** Options

| PROC NLP: Nonlinear Maximization         |              |
|--|--------------|
| Minimum Iterations                       | 0            |
| Maximum Iterations                       | 200          |
| Maximum Function Calls                   | 500          |
| Iterations Reducing Constraint Violation | 20           |
| ABSGCONV Gradient Criterion              | 0.00001      |
| GCONV Gradient Criterion                 | 1E-8         |
| ABSFCONV Function Criterion              | 0            |
| FCONV Function Criterion                 | 2.220446E-16 |
| FCONV2 Function Criterion                | 1E-6         |
| FSIZE Parameter                          | 0            |
| ABSXCONV Parameter Change Criterion      | 0            |
| XCONV Parameter Change Criterion         | 0            |
| XSIZE Parameter                          | 0            |
| ABSCONV Function Criterion               | 1.340781E154 |
| Line Search Method                       | 2            |
| Starting Alpha for Line Search           | 1            |
| Line Search Precision LSPRECISION        | 0.4          |
| DAMPSTEP Parameter for Line Search       | .            |
| FD Derivatives: Accurate Digits in Obj.F | 15.653559775 |
| FD Derivatives: Accurate Digits in NLCon | 15.653559775 |
| Singularity Tolerance (SINGULAR)         | 1E-8         |
| Constraint Precision (LCEPS)             | 1E-8         |
| Linearly Dependent Constraints (LCSING)  | 1E-8         |
| Releasing Active Constraints (LCDEACT)   | .            |

The iteration history, given in [Output 8.7.5](#), does not show any problems.

### Output 8.7.5 Iteration History

| PROC NLP: Nonlinear Maximization                           |  |  |  |  |  |  |  |
|--|--|--|--|--|--|--|--|
| Dual Quasi-Newton Optimization                             |  |  |  |  |  |  |  |
| Modified VMCWD Algorithm of Powell (1978, 1982)            |  |  |  |  |  |  |  |
| Dual Broyden - Fletcher - Goldfarb - Shanno Update (DBFGS) |  |  |  |  |  |  |  |
| Lagrange Multiplier Update of Powell(1982)                 |  |  |  |  |  |  |  |
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The optimal solution in [Output 8.7.6](#) shows that to obtain the maximum profit of \$400, you need only to produce the maximum 200 units of blending *Y* and no units of blending *X*.

**Output 8.7.6** Optimization Solution

| PROC NLP: Nonlinear Maximization  |              |                                   |                                  |                               |        |
|-----------------------------------|--------------|-----------------------------------|----------------------------------|-------------------------------|--------|
| Optimization Results              |              |                                   |                                  |                               |        |
| Parameter Estimates               |              |                                   |                                  |                               |        |
| N Parameter                       | Estimate     | Gradient<br>Objective<br>Function | Gradient<br>Lagrange<br>Function | Active<br>Bound<br>Constraint |        |
| 1 amountx                         | -1.40474E-11 | 9.000000                          | 0                                | Lower BC                      |        |
| 2 amounty                         | 200.000000   | 15.000000                         | 0                                | Upper BC                      |        |
| 3 amounta                         | 1.027701E-16 | -6.000000                         | 0                                | Lower BC                      |        |
| 4 amountb                         | 100.000000   | -16.000000                        | -1.77636E-15                     |                               |        |
| 5 amountc                         | 100.000000   | -10.000000                        | 1.776357E-15                     |                               |        |
| 6 pooltox                         | 7.024003E-12 | 0                                 | 0                                | Lower BC                      |        |
| 7 pooltoy                         | 100.000000   | 0                                 | -1.06581E-14                     |                               |        |
| 8 cttox                           | -2.10714E-11 | 0                                 | 5.329071E-15                     | Lower BC                      | LinDep |
| 9 cttoy                           | 100.000000   | 0                                 | 1.776357E-15                     |                               |        |
| 10 pools                          | 1.000000     | 0                                 | 0                                | Lower BC                      | LinDep |
| Value of Objective Function = 400 |              |                                   |                                  |                               |        |
| Value of Lagrange Function = 400  |              |                                   |                                  |                               |        |

The constraints are satisfied at the solution, as shown in [Output 8.7.7](#)

**Output 8.7.7** Linear and Nonlinear Constraints at the Solution

| PROC NLP: Nonlinear Maximization         |                  |          |                    |                        |             |
|--|------------------|----------|--------------------|------------------------|-------------|
| Linear Constraints Evaluated at Solution |                  |          |                    |                        |             |
| 1 ACT                                    | 0 =              | 0 +      | 1.0000 * amounta + | 1.0000 * amountb       |             |
| -  | 1.0000 * pooltox | -        | 1.0000 * pooltoy   |                        |             |
| 2 ACT                                    | -4.481E-17 =     | 0 -      | 1.0000 * amountx + | 1.0000 * pooltox       |             |
| +  | 1.0000 * cttox   |          |                    |                        |             |
| 3 ACT                                    | 0 =              | 0 -      | 1.0000 * amounty + | 1.0000 * pooltoy       |             |
| +  | 1.0000 * cttoy   |          |                    |                        |             |
| 4 ACT                                    | 0 =              | 0 -      | 1.0000 * amountc + | 1.0000 * cttox         |             |
| +  | 1.0000 * cttoy   |          |                    |                        |             |
| Values of Nonlinear Constraints          |                  |          |                    |                        |             |
| Constraint                               |                  | Value    | Residual           | Lagrange<br>Multiplier |             |
| [ 5 ] nlc3                               |                  | 0        | 0                  | 6.0000 Active          | NLEC        |
| [ 6 ] nlc1_G                             | 4.04E-16         | 4.04E-16 |                    | . Active               | NLIC LinDep |
| [ 7 ] nlc2_G                             | -284E-16         | -284E-16 |                    | -6.0000 Active         | NLIC        |



## Output 8.7.7 continued

| Linearly Dependent Active Boundary Constraints               |    |          |
|--|----|----------|
| Parameter  | N  | Kind     |
| ctox   | 8  | Lower BC |
| pools  | 10 | Lower BC |
| Linearly Dependent Gradients of Active Nonlinear Constraints |    |          |
| Parameter  | N  |          |
| nlc3   | 6  |          |

The same problem can be specified in many different ways. For example, the following specification uses an **INEST**= data set containing the values of the starting point and of the constants COST, COSTB, COSTC, COSTX, COSTY, CA, CB, CC, and CD:

```
data init1(type=est);
  input _type_ $ amountx amounty amounta amountb
        amountc pooltox pooltoy ctox ctoy pools
        _rhs_ costa costb costc costx costy
        ca cb cc cd;
  datalines;
parms 1 1 1 1 1 1 1 1 1 1
      . 6 16 10 9 15 2.5 1.5 2. 3.
;

proc nlp inest=init1 all;
  parms amountx amounty amounta amountb amountc
        pooltox pooltoy ctox ctoy pools;
  bounds 0 <= amountx amounty amounta amountb amountc,
         amountx <= 100,
         amounty <= 200,
         0 <= pooltox pooltoy ctox ctoy,
         1 <= pools <= 3;
  lincon amounta + amountb = pooltox + pooltoy,
        pooltox + ctox = amountx,
        pooltoy + ctoy = amounty,
        ctox + ctoy = amountc;
  nlincon nlc1-nlc2 >= 0.,
         nlc3 = 0.;
  max f;
  f = costx * amountx + costy * amounty
      - costa * amounta - costb * amountb - costc * amountc;
  nlc1 = ca * amountx - pools * pooltox - cc * ctox;
  nlc2 = cb * amounty - pools * pooltoy - cc * ctoy;
  nlc3 = cd * amounta + amountb - pools * (amounta + amountb);
run;
```

The third specification uses an `INEST=` data set containing the boundary and linear constraints in addition to the values of the starting point and of the constants. This specification also writes the model specification into an `OUTMOD=` data set:

```
data init2(type=est);
  input _type_ $ amountx amounty amounta amountb amountc
          pooltox pooltoy cttox cttoy pools
          _rhs_ costa costb costc costx costy;
  datalines;
parms      1      1      1      1      1      1      1      1      1
           .      6 16 10      9      15 2.5 1.5      2      3
lowerbd    0      0      0      0      0      0      0      0      0      1
           .      .      .      .      .      .      .      .      .      .
upperbd    100 200      .      .      .      .      .      .      .      3
           .      .      .      .      .      .      .      .      .      .
eq          .      .      1      1      .      -1      -1      .      .      .
           0      .      .      .      .      .      .      .      .      .
eq          1      .      .      .      .      -1      .      -1      .      .
           0      .      .      .      .      .      .      .      .      .
eq          .      1      .      .      .      .      -1      .      -1      .
           0      .      .      .      .      .      .      .      .      .
eq          .      .      .      .      1      .      .      -1      -1      .
           0      .      .      .      .      .      .      .      .      .
;

proc nlp inest=init2 outmod=model all;
  parms amountx amounty amounta amountb amountc
          pooltox pooltoy cttox cttoy pools;
  nlincon nlc1-nlc2 >= 0.,
          nlc3 = 0.;
  max f;
  f = costx * amountx + costy * amounty
      - costa * amounta - costb * amountb - costc * amountc;
  nlc1 = 2.5 * amountx - pools * pooltox - 2. * cttox;
  nlc2 = 1.5 * amounty - pools * pooltoy - 2. * cttoy;
  nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
run;
```

The fourth specification not only reads the `INEST=INIT2` data set, it also uses the model specification from the `MODEL` data set that was generated in the last specification. The `PROC NLP` call now contains only the defining variable statements:

```
proc nlp inest=init2 model=model all;
  parms amountx amounty amounta amountb amountc
          pooltox pooltoy cttox cttoy pools;
  nlincon nlc1-nlc2 >= 0.,
          nlc3 = 0.;
  max f;
run;
```

All four specifications start with the same starting point of all variables equal to 1 and generate the same results. However, there exist several local optima to this problem, as is pointed out in Liebman et al. (1986, p. 130).

```

proc nlp inest=init2 model=model all;
  parms amountx amounty amounta amountb amountc
    pooltox pooltoy ctox ctoy = 0,
    pools = 2;
  nlincon nlc1-nlc2 >= 0.,
    nlc3 = 0.;
  max f;
run;

```

This starting point with all variables equal to 0 is accepted as a local solution with  $profit = 0$ , which minimizes rather than maximizes the profit.

---

## Example 8.8: Chemical Equilibrium

The following example is used in many test libraries for nonlinear programming and was taken originally from Bracken and McCormick (1968).

The problem is to determine the composition of a mixture of various chemicals satisfying its chemical equilibrium state. The second law of thermodynamics implies that a mixture of chemicals satisfies its chemical equilibrium state (at a constant temperature and pressure) when the free energy of the mixture is reduced to a minimum. Therefore the composition of the chemicals satisfying its chemical equilibrium state can be found by minimizing the function of the free energy of the mixture.

### Notation:

- $m$  number of chemical elements in the mixture
- $n$  number of compounds in the mixture
- $x_j$  number of moles for compound  $j$ ,  $j = 1, \dots, n$
- $s$  total number of moles in the mixture ( $s = \sum_{j=1}^n x_j$ )
- $a_{ij}$  number of atoms of element  $i$  in a molecule of compound  $j$
- $b_i$  atomic weight of element  $i$  in the mixture

### Constraints for the Mixture:

- The number of moles must be positive:

$$x_j > 0, \quad j = 1, \dots, n$$

- There are  $m$  mass balance relationships,

$$\sum_{j=1}^n a_{ij} x_j = b_i, \quad i = 1, \dots, m$$

**Objective Function: Total Free Energy of Mixture**

$$f(x) = \sum_{j=1}^n x_j \left[ c_j + \ln \left( \frac{x_j}{s} \right) \right]$$

with

$$c_j = \left( \frac{F^\circ}{RT} \right)_j + \ln P$$

where  $F^\circ/RT$  is the model standard free energy function for the  $j$ th compound (found in tables) and  $P$  is the total pressure in atmospheres.

**Minimization Problem:**

Determine the parameters  $x_j$  that minimize the objective function  $f(x)$  subject to the nonnegativity and linear balance constraints.

**Numeric Example:**

Determine the equilibrium composition of compound  $\frac{1}{2}N_2H_4 + \frac{1}{2}O_2$  at temperature  $T = 3500^\circ\text{K}$  and pressure  $P = 750\text{psi}$ .

| $j$ | Compound | $(F^\circ/RT)_j$ | $c_j$   | $a_{ij}$ |         |         |
|-----|----------|------------------|---------|----------|---------|---------|
|     |          |                  |         | $i = 1$  | $i = 2$ | $i = 3$ |
|     |          |                  | $H$     | $N$      | $O$     |         |
| 1   | $H$      | -10.021          | -6.089  | 1        |         |         |
| 2   | $H_2$    | -21.096          | -17.164 | 2        |         |         |
| 3   | $H_2O$   | -37.986          | -34.054 | 2        |         | 1       |
| 4   | $N$      | -9.846           | -5.914  |          | 1       |         |
| 5   | $N_2$    | -28.653          | -24.721 |          | 2       |         |
| 6   | $NH$     | -18.918          | -14.986 | 1        | 1       |         |
| 7   | $NO$     | -28.032          | -24.100 |          | 1       | 1       |
| 8   | $O$      | -14.640          | -10.708 |          |         | 1       |
| 9   | $O_2$    | -30.594          | -26.662 |          |         | 2       |
| 10  | $OH$     | -26.111          | -22.179 | 1        |         | 1       |

**Example Specification:**

```
proc nlp tech=tr pall;
  array c[10] -6.089 -17.164 -34.054 -5.914 -24.721
           -14.986 -24.100 -10.708 -26.662 -22.179;
  array x[10] x1-x10;
  min y;
  parms x1-x10 = .1;
  bounds 1.e-6 <= x1-x10;
  lincon 2. = x1 + 2. * x2 + 2. * x3 + x6 + x10,
         1. = x4 + 2. * x5 + x6 + x7,
         1. = x3 + x7 + x8 + 2. * x9 + x10;
  s = x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10;
  y = 0.;
```



Output 8.8.2 lists the optimal parameters with the gradient.

### Output 8.8.2 Optimization Results

| PROC NLP: Nonlinear Minimization           |          |                                   |
|--|----------|-----------------------------------|
| Optimization Results                       |          |                                   |
| Parameter Estimates                        |          |                                   |
| N Parameter                                | Estimate | Gradient<br>Objective<br>Function |
| 1 x1                                       | 0.040668 | -9.785055                         |
| 2 x2                                       | 0.147730 | -19.570110                        |
| 3 x3                                       | 0.783153 | -34.792170                        |
| 4 x4                                       | 0.001414 | -12.968921                        |
| 5 x5                                       | 0.485247 | -25.937841                        |
| 6 x6                                       | 0.000693 | -22.753976                        |
| 7 x7                                       | 0.027399 | -28.190984                        |
| 8 x8                                       | 0.017947 | -15.222060                        |
| 9 x9                                       | 0.037314 | -30.444120                        |
| 10 x10                                     | 0.096871 | -25.007115                        |
| Value of Objective Function = -47.76109086 |          |                                   |

The three equality constraints are satisfied at the solution, as shown in Output 8.8.3.

### Output 8.8.3 Linear Constraints at Solution

| PROC NLP: Nonlinear Minimization         |            |   |
|--|------------|---|
| Linear Constraints Evaluated at Solution |            |   |
| 1 ACT                                    | -3.608E-16 | = 2.0000 - 1.0000 * x1 - 2.0000 * x2 - 2.0000 * x3 - 1.0000 * x6 - 1.0000 * x10 |
| 2 ACT                                    | 2.2204E-16 | = 1.0000 - 1.0000 * x4 - 2.0000 * x5 - 1.0000 * x6 - 1.0000 * x7                |
| 3 ACT                                    | -1.943E-16 | = 1.0000 - 1.0000 * x3 - 1.0000 * x7 - 1.0000 * x8 - 2.0000 * x9 - 1.0000 * x10 |

The Lagrange multipliers are given in [Output 8.8.4](#).

#### Output 8.8.4 Lagrange Multipliers

| PROC NLP: Nonlinear Minimization |     |                     |
|----------------------------------|-----|---------------------|
| First Order Lagrange Multipliers |     |                     |
| Active Constraint                |     | Lagrange Multiplier |
| Linear EC                        | [1] | 9.785055            |
| Linear EC                        | [2] | 12.968921           |
| Linear EC                        | [3] | 15.222060           |

The elements of the projected gradient must be small to satisfy a necessary first-order optimality condition. The projected gradient is given in [Output 8.8.5](#).

#### Output 8.8.5 Projected Gradient

| PROC NLP: Nonlinear Minimization |                    |  |
|----------------------------------|--------------------|--|
| Projected Gradient               |                    |  |
| Free Dimension                   | Projected Gradient |  |
| 1                                | 4.5770108E-9       |  |
| 2                                | 6.868355E-10       |  |
| 3                                | -7.283013E-9       |  |
| 4                                | -0.000001864       |  |
| 5                                | -0.000001434       |  |
| 6                                | -0.000001361       |  |
| 7                                | -0.000000294       |  |

The projected Hessian matrix shown in [Output 8.8.6](#) is positive definite, satisfying the second-order optimality condition.

**Output 8.8.6** Projected Hessian Matrix

| PROC NLP: Nonlinear Minimization |              |              |              |              |
|----------------------------------|--------------|--------------|--------------|--------------|
| Projected Hessian Matrix         |              |              |              |              |
|                                  | X1           | X2           | X3           | X4           |
| X1                               | 20.903196985 | -0.122067474 | 2.6480263467 | 3.3439156526 |
| X2                               | -0.122067474 | 565.97299938 | 106.54631863 | -83.7084843  |
| X3                               | 2.6480263467 | 106.54631863 | 1052.3567179 | -115.230587  |
| X4                               | 3.3439156526 | -83.7084843  | -115.230587  | 37.529977667 |
| X5                               | -1.373829641 | -37.43971036 | 182.89278895 | -4.621642366 |
| X6                               | -1.491808185 | -36.20703737 | 175.97949593 | -4.574152161 |
| X7                               | 1.1462413516 | -16.635529   | -57.04158208 | 10.306551561 |
| Projected Hessian Matrix         |              |              |              |              |
|                                  | X5           | X6           | X7           |              |
| X1                               | -1.373829641 | -1.491808185 | 1.1462413516 |              |
| X2                               | -37.43971036 | -36.20703737 | -16.635529   |              |
| X3                               | 182.89278895 | 175.97949593 | -57.04158208 |              |
| X4                               | -4.621642366 | -4.574152161 | 10.306551561 |              |
| X5                               | 79.326057844 | 22.960487404 | -12.69831637 |              |
| X6                               | 22.960487404 | 66.669897023 | -8.121228758 |              |
| X7                               | -12.69831637 | -8.121228758 | 14.690478023 |              |

The following `PROC NLP` call uses a specified analytical gradient and the Hessian matrix is computed by finite-difference approximations based on the analytic gradient:

```
proc nlp tech=tr fdhessian all;
  array c[10] -6.089 -17.164 -34.054 -5.914 -24.721
           -14.986 -24.100 -10.708 -26.662 -22.179;
  array x[10] x1-x10;
  array g[10] g1-g10;
  min y;
  parms x1-x10 = .1;
  bounds 1.e-6 <= x1-x10;
  lincon 2. = x1 + 2. * x2 + 2. * x3 + x6 + x10,
         1. = x4 + 2. * x5 + x6 + x7,
         1. = x3 + x7 + x8 + 2. * x9 + x10;
  s = x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10;
  y = 0.;
  do j = 1 to 10;
    y = y + x[j] * (c[j] + log(x[j] / s));
    g[j] = c[j] + log(x[j] / s);
  end;
run;
```

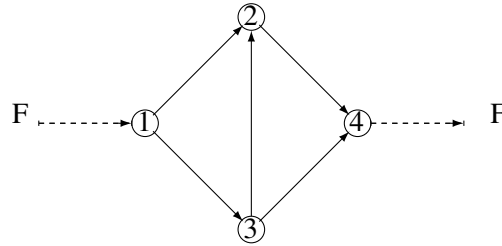
The results are almost identical to those of the previous run.



### Example 8.9: Minimize Total Delay in a Network

The following example is taken from the user's guide of GINO (Liebman et al. 1986). A simple network of five roads (arcs) can be illustrated by the path diagram:

**Figure 8.11** Simple Road Network



The five roads connect four intersections illustrated by numbered nodes. Each minute  $F$  vehicles enter and leave the network. Arc  $(i, j)$  refers to the road from intersection  $i$  to intersection  $j$ , and the parameter  $x_{ij}$  refers to the flow from  $i$  to  $j$ . The law that traffic flowing into each intersection  $j$  must also flow out is described by the linear equality constraint

$$\sum_i x_{ij} = \sum_i x_{ji}, \quad j = 1, \dots, n$$

In general, roads also have an upper capacity, which is the number of vehicles which can be handled per minute. The upper limits  $c_{ij}$  can be enforced by boundary constraints

$$0 \leq x_{ij} \leq c_{ij}, \quad i, j = 1, \dots, n$$

Finding the maximum flow through a network is equivalent to solving a simple linear optimization problem, and for large problems, **PROC LP** or **PROC NETFLOW** can be used. The objective function is

$$\max \quad f = x_{24} + x_{34}$$

and the constraints are

$$\begin{aligned} x_{13} &= x_{32} + x_{34} \\ x_{12} + x_{32} &= x_{24} \\ x_{12} + x_{13} &= x_{24} + x_{34} \\ 0 \leq x_{12}, x_{32}, x_{34} &\leq 10 \\ 0 \leq x_{13}, x_{24} &\leq 30 \end{aligned}$$

The three linear equality constraints are linearly dependent. One of them is deleted automatically by the **PROC NLP** subroutines. Even though the default technique is used for this small example, any optimization subroutine can be used.

```
proc nlp all initial=.5;
  max y;
  parms x12 x13 x32 x24 x34;
  bounds x12 <= 10,
         x13 <= 30,
         x32 <= 10,
         x24 <= 30,
         x34 <= 10;

  /* what flows into an intersection must flow out */
  lincon x13 = x32 + x34,
         x12 + x32 = x24,
         x24 + x34 = x12 + x13;
  y = x24 + x34 + 0*x12 + 0*x13 + 0*x32;
run;
```

The iteration history is given in [Output 8.9.1](#), and the optimal solution is given in [Output 8.9.2](#).

### Output 8.9.1 Iteration History

```

PROC NLP: Nonlinear Maximization

Newton-Raphson Ridge Optimization

Without Parameter Scaling


```

| Iter | Rest<br>arts | Func<br>Calls | Act<br>Con | Objective<br>Function | Obj Fun<br>Change | Max Abs<br>Gradient<br>Element | Ridge  | Actual<br>Over<br>Pred<br>Change |
|------|--------------|---------------|------------|-----------------------|-------------------|--------------------------------|--------|----------------------------------|
| 1*   | 0            | 2             | 4          | 20.25000              | 19.2500           | 0.5774                         | 0.0313 | 0.860                            |
| 2*   | 0            | 3             | 5          | 30.00000              | 9.7500            | 0                              | 0.0313 | 1.683                            |

```

Optimization Results

Iterations                2  Function Calls                4
Hessian Calls             3  Active Constraints            5
Objective Function        30  Max Abs Gradient Element      0
Ridge                     0  Actual Over Pred Change      1.6834532374

All parameters are actively constrained.  Optimization cannot proceed.

```

**Output 8.9.2** Optimization Results

| PROC NLP: Nonlinear Maximization |           |                                   |                               |
|----------------------------------|-----------|-----------------------------------|-------------------------------|
| Optimization Results             |           |                                   |                               |
| Parameter Estimates              |           |                                   |                               |
| N Parameter                      | Estimate  | Gradient<br>Objective<br>Function | Active<br>Bound<br>Constraint |
| 1 x12                            | 10.000000 | 0                                 | Upper BC                      |
| 2 x13                            | 20.000000 | 0                                 |                               |
| 3 x32                            | 10.000000 | 0                                 | Upper BC                      |
| 4 x24                            | 20.000000 | 1.000000                          |                               |
| 5 x34                            | 10.000000 | 1.000000                          | Upper BC                      |
| Value of Objective Function = 30 |           |                                   |                               |

Finding a traffic pattern that minimizes the total delay to move  $F$  vehicles per minute from node 1 to node 4 introduces nonlinearities that, in turn, demand nonlinear optimization techniques. As traffic volume increases, speed decreases. Let  $t_{ij}$  be the travel time on arc  $(i, j)$  and assume that the following formulas describe the travel time as decreasing functions of the amount of traffic:

$$\begin{aligned}
 t_{12} &= 5 + 0.1x_{12}/(1 - x_{12}/10) \\
 t_{13} &= x_{13}/(1 - x_{13}/30) \\
 t_{32} &= 1 + x_{32}/(1 - x_{32}/10) \\
 t_{24} &= x_{24}/(1 - x_{24}/30) \\
 t_{34} &= 5 + 0.1x_{34}/(1 - x_{34}/10)
 \end{aligned}$$

These formulas use the road capacities (upper bounds), assuming  $F = 5$  vehicles per minute have to be moved through the network. The objective function is now

$$\min f = t_{12}x_{12} + t_{13}x_{13} + t_{32}x_{32} + t_{24}x_{24} + t_{34}x_{34}$$

and the constraints are

$$\begin{aligned}
 x_{13} &= x_{32} + x_{34} \\
 x_{12} + x_{32} &= x_{24} \\
 x_{24} + x_{34} &= F = 5 \\
 0 \leq x_{12}, x_{32}, x_{34} &\leq 10 \\
 0 \leq x_{13}, x_{24} &\leq 30
 \end{aligned}$$



**Output 8.9.4** Optimization Results

| PROC NLP: Nonlinear Minimization           |              |                                   |                               |
|--|--------------|-----------------------------------|-------------------------------|
| Optimization Results                       |              |                                   |                               |
| Parameter Estimates                        |              |                                   |                               |
| N Parameter                                | Estimate     | Gradient<br>Objective<br>Function | Active<br>Bound<br>Constraint |
| 1 x12                                      | 2.500000     | 5.777778                          |                               |
| 2 x13                                      | 2.500000     | 5.702479                          |                               |
| 3 x32                                      | -2.77556E-17 | 1.000000                          | Lower BC                      |
| 4 x24                                      | 2.500000     | 5.702479                          |                               |
| 5 x34                                      | 2.500000     | 5.777778                          |                               |
| Value of Objective Function = 40.303030303 |              |                                   |                               |

The active constraints and corresponding Lagrange multiplier estimates (costs) are given in [Output 8.9.5](#) and [Output 8.9.6](#), respectively.

**Output 8.9.5** Linear Constraints at Solution

| PROC NLP: Nonlinear Minimization         |              |  |  |
|--|--------------|--|--|
| Linear Constraints Evaluated at Solution |              |  |  |
| 1 ACT                                    | 0 =          | 0 + 1.0000 * x13 - 1.0000 * x32 - 1.0000 * x34 |  |
| 2 ACT                                    | 4.4409E-16 = | 0 + 1.0000 * x12 + 1.0000 * x32 - 1.0000 * x24 |  |
| 3 ACT                                    | 0 =          | -5.0000 + 1.0000 * x24 + 1.0000 * x34          |  |

**Output 8.9.6** Lagrange Multipliers at Solution

| PROC NLP: Nonlinear Minimization |     |                        |
|----------------------------------|-----|------------------------|
| First Order Lagrange Multipliers |     |                        |
| Active Constraint                |     | Lagrange<br>Multiplier |
| Lower BC                         | x32 | 0.924702               |
| Linear EC                        | [1] | 5.702479               |
| Linear EC                        | [2] | 5.777778               |
| Linear EC                        | [3] | 11.480257              |

Output 8.9.7 shows that the projected gradient is very small, satisfying the first-order optimality criterion.

**Output 8.9.7** Projected Gradient at Solution

| PROC NLP: Nonlinear Minimization |                       |
|----------------------------------|-----------------------|
| Projected Gradient               |                       |
| Free<br>Dimension                | Projected<br>Gradient |
| 1                                | 4.440892E-16          |

The projected Hessian matrix (shown in Output 8.9.8) is positive definite, satisfying the second-order optimality criterion.

**Output 8.9.8** Projected Hessian at Solution

| PROC NLP: Nonlinear Minimization |             |
|----------------------------------|-------------|
| Projected Hessian<br>Matrix      |             |
|                                  | X1          |
| X1                               | 1.535309013 |

## Rewriting NLP Models for PROC OPTMODEL

This section covers techniques for converting NLP procedure models to OPTMODEL procedure models. For information about the OPTMODEL procedure, see Chapter 5, “The OPTMODEL Procedure” (*SAS/OR User’s Guide: Mathematical Programming*).

To illustrate the basics, consider the following first version of the NLP model for Example 8.7:

```

/*****
/* Rewriting NLP Models for PROC OPTMODEL          */
/*****/

proc nlp all;
  parms amountx amounty amounta amountb amountc
    pooltox pooltoy ctox ctoy pools = 1;
  bounds 0 <= amountx amounty amounta amountb amountc,
         amountx <= 100,
         amounty <= 200,
         0 <= pooltox pooltoy ctox ctoy,
         1 <= pools <= 3;

```

```

lincon amounta + amountb = pooltox + pooltoy,
      pooltox + ctox = amountx,
      pooltoy + ctoy = amounty,
      ctox + ctoy      = amountc;
nlincon nlc1-nlc2 >= 0.,
      nlc3 = 0.;
max f;
costa = 6; costb = 16; costc = 10;
costx = 9; costy = 15;
f = costx * amountx + costy * amounty
  - costa * amounta - costb * amountb - costc * amountc;
nlc1 = 2.5 * amountx - pools * pooltox - 2. * ctox;
nlc2 = 1.5 * amounty - pools * pooltoy - 2. * ctoy;
nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
run;

```

These statements define a model that has bounds, linear constraints, nonlinear constraints, and a simple objective function. The following statements are a straightforward conversion of the PROC NLP statements to PROC OPTMODEL form:

```

proc optmodel;
  var amountx init 1 >= 0 <= 100,
      amounty init 1 >= 0 <= 200;
  var amounta init 1 >= 0,
      amountb init 1 >= 0,
      amountc init 1 >= 0;
  var pooltox init 1 >= 0,
      pooltoy init 1 >= 0;
  var ctox init 1 >= 0,
      ctoy init 1 >= 0;
  var pools init 1 >= 1 <= 3;
  con amounta + amountb = pooltox + pooltoy,
      pooltox + ctox = amountx,
      pooltoy + ctoy = amounty,
      ctox + ctoy      = amountc;
  number costa, costb, costc, costx, costy;
  costa = 6; costb = 16; costc = 10;
  costx = 9; costy = 15;
  max f = costx * amountx + costy * amounty
        - costa * amounta - costb * amountb - costc * amountc;
  con nlc1: 2.5 * amountx - pools * pooltox - 2. * ctox >= 0,
      nlc2: 1.5 * amounty - pools * pooltoy - 2. * ctoy >= 0,
      nlc3: 3 * amounta + amountb - pools * (amounta + amountb)
            = 0;
  solve;
  print amountx amounty amounta amountb amountc
        pooltox pooltoy ctox ctoy pools;

```

The PROC OPTMODEL variable declarations are split into individual declarations because PROC OPTMODEL does not permit name lists in its declarations. In the OPTMODEL procedure, variable bounds are part of the variable declaration instead of a separate BOUNDS statement. The PROC NLP statements are as follows:

```
parms amountx amounty amounta amountb amountc
```

```

pooltox pooltoy ctox ctoy pools = 1;
bounds 0 <= amountx amounty amounta amountb amountc,
        amountx <= 100,
        amounty <= 200,
0 <= pooltox pooltoy ctox ctoy,
1 <= pools <= 3;

```

The following PROC OPTMODEL statements are equivalent to the PROC NLP statements:

```

var amountx init 1 >= 0 <= 100,
    amounty init 1 >= 0 <= 200;
var amounta init 1 >= 0,
    amountb init 1 >= 0,
    amountc init 1 >= 0;
var pooltox init 1 >= 0,
    pooltoy init 1 >= 0;
var ctox init 1 >= 0,
    ctoy init 1 >= 0;
var pools init 1 >= 1 <= 3;

```

The linear constraints are declared in the NLP model with the following statement:

```

lincon amounta + amountb = pooltox + pooltoy,
    pooltox + ctox = amountx,
    pooltoy + ctoy = amounty,
    ctox + ctoy      = amountc;

```

The following linear constraint declarations in the PROC OPTMODEL model are quite similar to the PROC NLP LINCON declarations:

```

con amounta + amountb = pooltox + pooltoy,
    pooltox + ctox = amountx,
    pooltoy + ctoy = amounty,
    ctox + ctoy      = amountc;

```

But PROC OPTMODEL provides much more flexibility in defining linear constraints. For example, coefficients can be named parameters or any other expression that evaluates to a constant.

The cost parameters are declared explicitly in the PROC OPTMODEL model. Unlike the DATA step or PROC NLP, PROC OPTMODEL requires names to be declared before they are used. There are multiple ways to set the values of these parameters. The preceding example used assignments. The values could have been made part of the declaration by using the INIT *expression* clause or the = *expression* clause. The values could also have been read from a data set with the READ DATA statement.

Note in the original NLP statements that the assignment to a parameter such as *costa* occurs every time the objective function is evaluated. However, the assignment occurs just once in the PROC OPTMODEL code, when the assignment statement is processed. This works because the values are constant. But the PROC OPTMODEL statements permit the parameters to be reassigned later to interactively modify the model.



The following statements define the objective *f* in the NLP model:

```
max f;
. . .
f = costx * amountx + costy * amounty
   - costa * amounta - costb * amountb - costc * amountc;
```

The PROC OPTMODEL version of the objective is defined with the same expression text, as follows:

```
max f = costx * amountx + costy * amounty
      - costa * amounta - costb * amountb - costc * amountc;
```

But in PROC OPTMODEL the MAX statement and the assignment to the name *f* in the PROC NLP statements are combined. There are advantages and disadvantages to this approach. The PROC OPTMODEL formulation is much closer to the mathematical formulation of the model. However, if there are multiple intermediate variables being used to structure the objective, then multiple IMPVAR declarations are required.

In the PROC NLP model the nonlinear constraints use the following syntax:

```
nlincon nlc1-nlc2 >= 0.,
        nlc3 = 0.;
. . .
nlc1 = 2.5 * amountx - pools * pooltox - 2. * ctox;
nlc2 = 1.5 * amounty - pools * pooltoy - 2. * ctoy;
nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
```

In the PROC OPTMODEL model the equivalent statements are as follows:

```
con nlc1: 2.5 * amountx - pools * pooltox - 2. * ctox >= 0,
    nlc2: 1.5 * amounty - pools * pooltoy - 2. * ctoy >= 0,
    nlc3: 3 * amounta + amountb - pools * (amounta + amountb)
        = 0;
```

The nonlinear constraints in PROC OPTMODEL use the same syntax as linear constraints. In fact, if the variable *pools* were declared as a parameter, then all the preceding constraints would be linear. The nonlinear constraint in PROC OPTMODEL combines the NLINCON statement of PROC NLP with the assignment in the PROC NLP statements. As in objective expressions, objective names can be used in nonlinear constraint expressions to structure the formula.

The PROC OPTMODEL model does not use a RUN statement to invoke the solver. Instead the solver is invoked interactively by the SOLVE statement in PROC OPTMODEL. By default, the OPTMODEL procedure prints much less data about the optimization process. Generally these data consist of messages from the solver (such as the termination reason) in addition to a short status display. The PROC OPTMODEL statements add a PRINT statement in order to display the variable estimates from the solver.

The model for [Example 8.8](#) illustrates how to convert PROC NLP statements that handle arrays into PROC OPTMODEL form. The PROC NLP model is as follows:

```
proc nlp tech=tr pall;
  array c[10] -6.089 -17.164 -34.054 -5.914 -24.721
           -14.986 -24.100 -10.708 -26.662 -22.179;
  array x[10] x1-x10;
  min y;
  parms x1-x10 = .1;
  bounds 1.e-6 <= x1-x10;
  lincon 2. = x1 + 2. * x2 + 2. * x3 + x6 + x10,
         1. = x4 + 2. * x5 + x6 + x7,
         1. = x3 + x7 + x8 + 2. * x9 + x10;
  s = x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10;
  y = 0.;
  do j = 1 to 10;
    y = y + x[j] * (c[j] + log(x[j] / s));
  end;
run;
```

The model finds an equilibrium state for a mixture of chemicals. The following statements show a corresponding PROC OPTMODEL model:

```
proc optmodel;
  set CMP = 1..10;
  number c{CMP} = [-6.089 -17.164 -34.054 -5.914 -24.721
                  -14.986 -24.100 -10.708 -26.662 -22.179];
  var x{CMP} init 0.1 >= 1.e-6;
  con 2. = x[1] + 2. * x[2] + 2. * x[3] + x[6] + x[10],
       1. = x[4] + 2. * x[5] + x[6] + x[7],
       1. = x[3] + x[7] + x[8] + 2. * x[9] + x[10];

  /* replace the variable s in the NLP model */
  impvar s = sum{i in CMP} x[i];

  min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));
  solve;
  print x y;
```

The PROC OPTMODEL model uses the set CMP to represent the set of compounds, which are numbered 1 to 10 in the example. The array c was initialized by using the equivalent PROC OPTMODEL syntax. The individual array locations could also have been initialized by assignment or READ DATA statements.

The VAR declaration for variable x combines the VAR and BOUNDS statements of the PROC NLP model. The index set of the array is based on the set of compounds CMP, to simplify changes to the model.

The linear constraints are similar in form to the PROC NLP model. However, the PROC OPTMODEL version uses the array form of the variable names because the OPTMODEL procedure treats arrays as distinct variables, not as aliases of lists of scalar variables.

The implicit variable s replaces the intermediate variable of the same name in the PROC NLP model. This is an example of translating an intermediate variable from the other models to PROC OPTMODEL. An alternative way is to use an additional constraint for every intermediate variable. In the preceding statements, instead of declaring objective s, you can use the following statements:

```

. . .
var s;
con s = sum{i in CMP} x[i];
. . .

```

Note that this alternative formulation passes an extra variable and constraint to the solver. This formulation can sometimes be solved more efficiently, depending on the characteristics of the model.

The PROC OPTMODEL version uses a SUM operator over the set CMP, which enhances the flexibility of the model to accommodate possible changes in the set of compounds.

In the PROC NLP model the objective function  $y$  is determined by an explicit loop. With PROC OPTMODEL, the DO loop is replaced by a SUM aggregation operation. The accumulation in the PROC NLP model is now performed by PROC OPTMODEL with the SUM operator.

This PROC OPTMODEL model can be further generalized. Note that the array initialization and constraints assume a fixed set of compounds. You can rewrite the model to handle an arbitrary number of compounds and chemical elements. The new model loads the linear constraint coefficients from a data set along with the objective coefficients for the parameter  $c$ , as follows:

```

data comp;
  input c a_1 a_2 a_3;
  datalines;
-6.089   1 0 0
-17.164  2 0 0
-34.054  2 0 1
-5.914   0 1 0
-24.721  0 2 0
-14.986  1 1 0
-24.100  0 1 1
-10.708  0 0 1
-26.662  0 0 2
-22.179  1 0 1
;

data atom;
  input b @@;
  datalines;
2. 1. 1.
;

proc optmodel;
  set CMP;
  set ELT;
  number c{CMP};
  number a{ELT,CMP};
  number b{ELT};
  read data atom into ELT=[_n_] b;
  read data comp into CMP=[_n_]
    c {i in ELT} < a[i,_n_]=col("a_"||i) >;
  var x{CMP} init 0.1 >= 1.e-6;
  con bal{i in ELT}: b[i] = sum{j in CMP} a[i,j]*x[j];
  impvar s = sum{i in CMP} x[i];
  min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));

```



In the preceding model the chemical elements and compounds are designated by numbers. So in the PRINT output, for example, the row that is labeled “3” represents the amount of the compound H<sub>2</sub>O. PROC OPTMODEL is capable of using more symbolic strings to designate array indices. The following version of the model uses strings to index arrays:

```
data comp;
    input name $ c a_h a_n a_o;
    datalines;
H      -6.089    1 0 0
H2     -17.164   2 0 0
H2O    -34.054   2 0 1
N      -5.914    0 1 0
N2     -24.721   0 2 0
NH     -14.986   1 1 0
NO     -24.100   0 1 1
O      -10.708   0 0 1
O2     -26.662   0 0 2
OH     -22.179   1 0 1
;
data atom;
    input name $ b;
    datalines;
H 2.
N 1.
O 1.
;
proc optmodel;
    set<string> CMP;
    set<string> ELT;
    number c{CMP};
    number a{ELT,CMP};
    number b{ELT};
    read data atom into ELT=[name] b;
    read data comp into CMP=[name]
        c {i in ELT} < a[i,name]=col("a_"||i) >;
    var x{CMP} init 0.1 >= 1.e-6;
    con bal{i in ELT}: b[i] = sum{j in CMP} a[i,j]*x[j];
    impvar s = sum{i in CMP} x[i];
    min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));
    solve;
    print x;
```

In this model, the sets CMP and ELT are now sets of strings. The data sets provide the names of the compounds and elements. The names of the data set variables for atom counts in the data set COMP now include the chemical element symbol as part of their spelling. For example, the atom count for element H (hydrogen) is named a\_h. Note that these changes did not require any modification to the specifications of the linear constraints or the objective.

The PRINT statement in the preceding statements produces the results shown in [Output 8.9.10](#). The indices of variable x are now strings that represent the actual compounds.

**Output 8.9.10** PROC OPTMODEL Output with Strings

| The OPTMODEL Procedure |            |
|------------------------|------------|
| [1]                    | x          |
| H                      | 0.04066848 |
| H2                     | 0.14773067 |
| H2O                    | 0.78315260 |
| N                      | 0.00141459 |
| N2                     | 0.48524616 |
| NH                     | 0.00069358 |
| NO                     | 0.02739955 |
| O                      | 0.01794757 |
| O2                     | 0.03731444 |
| OH                     | 0.09687143 |

---

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