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## Optimizing Supply Chain Robustness through Simulation and Machine Learning

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### ABSTRACT

This paper introduces a supply chain simulator that has been built using SAS® Simulation Studio. The key features of the SAS® simulation technology, which enable the development of digital supply chains and the analysis of thousands of scenarios to perform risk-and-return tradeoff, are discussed. The paper concludes with a description of how computational efficiencies can be achieved through an integrated use of SAS Simulation Studio and SAS® Visual Data Mining and Machine Learning.

### INTRODUCTION

Managing supply chain network operations is one of the key challenges faced by many companies. SAS recognizes the importance of overcoming this challenge and presents an analytical solution that equips you with the power to predict the future performance of your supply chain network operations. At the heart of this solution lies a flexible, data-driven, and scalable supply chain simulation. There are three main features of this simulation:

- It mimicks the flow of thousands of products starting as production orders and ending as finished goods inventory through a supply chain network of manufacturing plants, supply warehouses, mixing centers, and customers with fleets of transporters operating between all pairs of supply chain network components.
- It provides enhanced visibility into the future of supply chain network operations.
- It enables the analysis of thousands of scenarios to perform risk-and-return tradeoff and presents opportunity to enhance resilience of your supply chain with minimum cost.

This paper describes the SAS technology that has led to the development of a supply chain network simulation with these three key features. Specifically, this technology is the SAS Simulation Studio, which enables you to represent, simulate, and analyze any large-scale and dynamic industrial system and its operations, regardless of whether you are in manufacturing, service, or communications. SAS Simulation Studio captures the supply chain flow logic (at the level of detail that is needed for the strategic, tactical, or operational problem you want to solve), represents all supply chain input risks, and provides predictions of your supply chain performance indicators (KPIs). The indicators can range from service-level measurements to cost calculations.

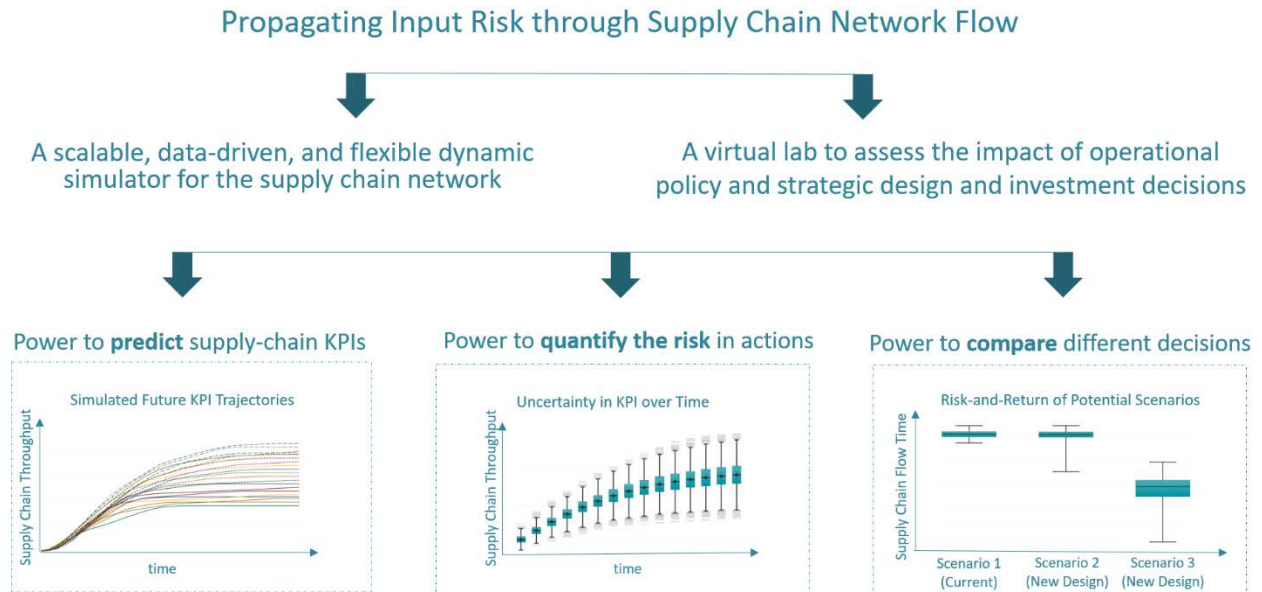


**Figure 1: Logic and Input Risk to Drive Supply Chain Simulation to Produce KPI Predictions**

The resulting scalable, data-driven, and flexible dynamic supply chain simulator serves as a virtual laboratory to assess the impact of various operational policy and design decisions. It serves as a decision-support tool by presenting you

- the power to predict supply-chain KPIs,
- the power to quantify the risk in actions, and
- the power to compare different supply chain network design and policy decisions.

These benefits are illustrated in Figure 2.



**Figure 2: Benefits of the SAS Supply Chain Network Simulation**

This paper discusses how SAS Simulation Studio creates flexible, scalable, and data-driven discrete-event stochastic simulation models of large-scale and dynamic supply chains that are exposed to various levels of uncertainty. While you are not restricted by any assumptions on your supply chain network flow logic, we use an example supply chain process to convey the key features of the SAS supply chain simulator. This example supply chain logic is presented in the next section.

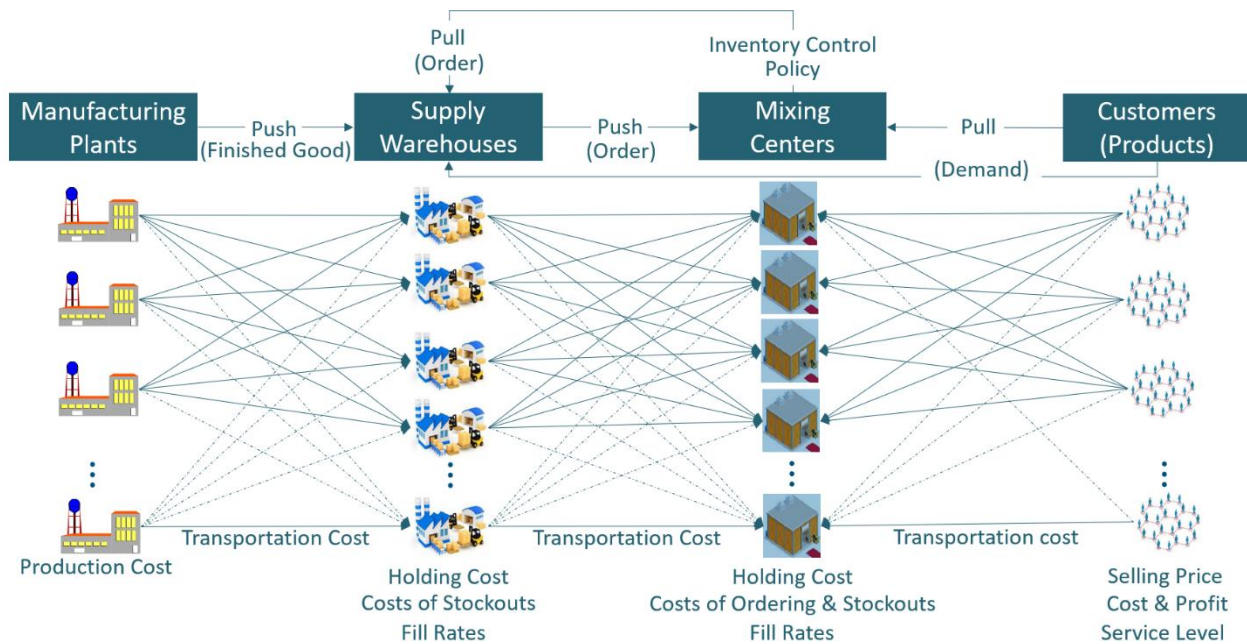
## AN EXAMPLE SUPPLY CHAIN PROCESS

This section provides the supply chain configuration and assumptions on which the supply chain simulation of this paper is built. This configuration consists of four different components:

- production plants
- supply warehouses
- mixing centers (regional warehouses)
- transportation from supply warehouses to mixing centers

Each plant is assumed to consist of a variety of manufacturing lines with machinery equipped to process certain types of products. Each production line has its production order to follow on a minute-level basis. Customer demand may be received both at supply warehouses and mixing centers. The finished goods, which are produced at the plants, are placed into the supply warehouses. Based on their own inventory management policies, each day mixing centers pull inventory from supply warehouses through the creation of replenishment orders. The replenishment orders arrive at the supply warehouses, are filled from the on-site inventory, and are loaded onto the trucks. The loaded trucks transport the inventory from supply warehouses to mixing centers, where they are used to fulfill customer orders. At any supply warehouse, meeting customer demand has higher priority than replenishing orders

received from the mixing centers. This description is the supply chain network flow logic that is used to develop a digital supply chain model in SAS Simulation Studio. (see Figure 1.) A detailed illustration of this flow is presented in Figure 3.



**Figure 3: SAS End-To-End Supply Chain Network Simulation**

The other key component of the simulation development is the supply chain input risk. (see Figure 1.) In this step, the sources of uncertainty in the supply chain network flow are identified, their risk profiles are characterized by a rigorous statistical analysis, and the resulting input risk models are incorporated into the supply chain simulation model. These are examples of sources of uncertainty in a supply chain network flow:

- product demand
- duration of production
- duration of transportation
- asset failures and repairs

In Figure 3, an asset may correspond to a machine in a manufacturing plant or a truck in a transportation fleet. It is important to note that you can customize the SAS supply chain simulator to capture any other drivers of risk in your supply chain, such as supplier uncertainty, yield uncertainty, or availability of operators. Furthermore, input risk models can be as simple as a single probability distribution for a specific product that is assumed to exhibit no temporal behavior, or it can be as complex as a neural network providing the demand forecasts. SAS supply chain network simulation can accommodate any level of complexity embedded into the input risk models. Similarly, you can customize the resulting simulation to record outputs to be analyzed for the prediction of a wide variety of measures of performance, including but not limited to the following KPIs:

- profit, cost, and service level
- inventory, flow time, and throughput
- asset utilizations and operator utilizations

You can use the simulation to achieve these three major objectives:

1. KPI generation

2. risk modeling (for example, uncertainty quantification in the supply chain KPIs)
3. risk management (for example, identification of robust operational supply chain policies and strategic decisions under uncertainty).

The next section introduces SAS Simulation Studio and shows how the SAS supply chain simulator is data-driven and scalable, which ensures success in simulating supply chains of increasing complexity.

## SIMULATING SUPPLY CHAIN USING SAS SIMULATION STUDIO

SAS Simulation Studio is a Java application for building and working with discrete-event simulation models (Hughes, Pratt, and Biller 2018). SAS Simulation Studio models dynamic system operations as a discrete sequence of events, each of which occurs at a specific point in time and triggers a change in system state. Examples of such systems include call centers, supply chains, and emergency rooms. Other benefits of the resulting models are as follows:

- Modeling interdependent interactions that complicate system modeling and analysis.
- Capturing random elements such as timing of chance events and preferences.
- **Enabling users to ask “what if” questions and to observe system performance.**

By developing simulations, there is no need to build out real-world systems or physical models, which leads to significantly less cost and risk. You can study many alternate system configurations, and you can craft many alternate scenarios for each configuration. Furthermore, you can amass a large amount of data very quickly, and you can then take advantage of these simulation-generated data sets to obtain detailed insights into system performance and identify robust response to changes.

SAS Simulation Studio provides a graphical user interface to perform modeling and analysis. It offers drag-and-drop model construction to carry out a wide variety of tasks, such as data loading, entity creation, accounting for delays, managing resources, controlling flow via non-blocking queues and switch blocks, and creating, collecting and analyzing simulation output data. Furthermore, it allows the design of experiments to conduct scenario analysis. Objects move within the discrete-event simulation as entities. The eight types of entities present in the simulation of the supply chain flow that is illustrated in Figure 3 are listed below along with their high-level descriptions:

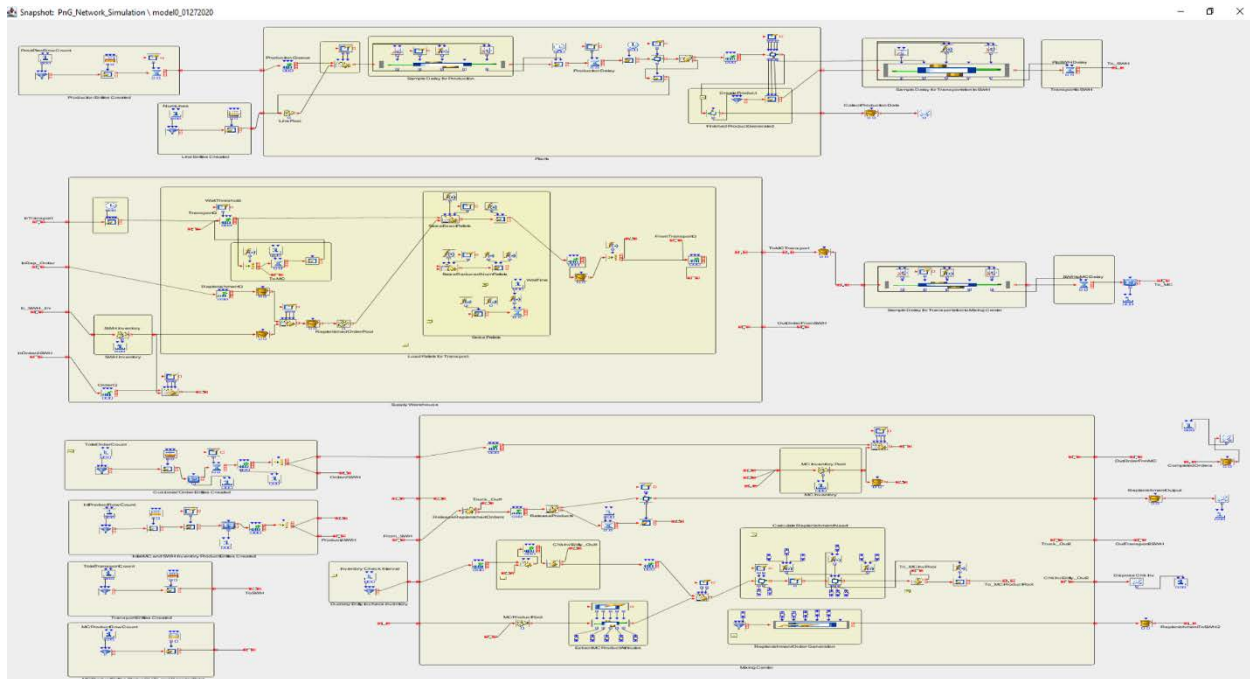
- Production Entity: production plan that has been created for the planning horizon
- Line Entity: descriptions of all the lines in the **supply chain’s** manufacturing plants
- Order Entity: demand received daily at the supply warehouses and mixing centers
- Product Entity: representation of the finished goods flowing through the supply chain
- Transport Entity: description of transporters (e.g., trucks) in the fleet of supply chain
- Replenishment Order Entity: description of request to pull inventory from warehouse
- Check Inventory Level Entity: signal recreated to activate inventory checks regularly
- Inventory Control Entity: specification of reorder points and order-up-to levels that are used to manage the inventory for the products which are stored at the mixing centers

These entities flow through the following five primary modules that make up the simulation model of the supply chain network flow in Figure 3:

- Daily Generation of Customer Demand to Arrive Warehouses and Mixing Centers
- Manufacturing Plant Module
- Supply Warehouse Logic

- Transportation Logic
- Mixing Center Logic

The dynamic update of the attributes of the entities as they flow through these modules produce the model view in Figure 4, which shows the graphical user interface of SAS Simulation Studio.



**Figure 4: Supply Chain Network Simulation Model View**

Figure 4 consists of three primary rows of blocks. The first row contains the manufacturing plant module. The second row contains supply warehouse logic and the transportation logic. The third row represents the mixing center logic where the majority of the customer demands and the truckloads of finished goods inventory arrive, the levels of inventory are daily checked for all products of the mixing centers, and the finished goods inventory is pulled from the supply warehouses through the creation of replenishment orders, which are driven by on-site inventory and assumptions of inventory control policies. It is important to note that the model view in Figure 4 remains the same independent of the scale of the supply chain network under consideration. The model view is the same for a single product or for 500 or more different products. The model view for a single production line containing a single plant, a single truck, and a single mixing center remains the same regardless of the number of production lines, manufacturing plants, supply warehouses, mixing centers, or trucks in the supply chain. This is the case because SAS supply chain network simulation is both data-driven and scalable. These two aspects of the supply chain network simulation are discussed in the next section.

## SUPPLY CHAIN SIMULATION IS DATA-DRIVEN AND SCALABLE

There are six different input data files that are uploaded into the model view of Figure 4. After you create these data sets and select the folder containing them in the [Input Data and Results](#) dialog box in SAS Simulation Studio, you would be ready to execute the simulation.

The first of these six data sets is the [Order.sas7bdat](#) input data file, which contains the customer orders that are received daily at the supply warehouses and at the mixing centers. The number of rows in this data file equals to the total number of customer orders received by the supply chain over the course of the supply chain simulation horizon. This input data

file contains eight different columns, each characterizing a specific attribute of a customer order:

- **Time of Arrival** of the customer order, represented by the number of hours passed since the start of the network simulation at time zero (in other words, 12AM real time)
- **Day** of the arrival, with 1 representing the first day of the simulation (for example, Monday)
- **Time of Shipment**, which is the target day by which customer order is to be fulfilled
- **Destination**, which indicates the location at which the customer order arrives
- **SWHId**, which is the index of the supply warehouse, if the **Destination** is a warehouse
- **MCIId**, which is the index of the mixing center, if the **Destination** is a mixing center
- **ProductId**, which is the unique identifier for the stock keeping unit (SKU)
- **Quantity**, which is the size (number of units) of the order arriving the supply chain

These column specifications contain the minimum information requirements needed to create customer order entities that flow through the supply chain network logic and produce a portion of the simulation output data to be used for KPI prediction and scenario analysis.

The following are the remaining input data files and their descriptions and attributes:

- **InitProduct.sas7bdat**, which contains the starting inventory for all products at all locations.
  - **Attributes** are Destination, SWHId, MCIId, ProductId, and Quantity.
  - **Quantity** represents the initial inventory (number of units available) at time 0.
- **Production.sas7bdat**, which contains the production plan for each of the lines.
  - **Attributes** are PlantId, LineId, ProductId, ArrTime, ProdTimeDist, Quantity, SWHId, SWHTransDelDist, ProdStartTime, ProductionDelay, and ProdEndTime.
  - **Quantity** represents planned production quantity for a specific line (**LineId**) in a specific plant (**PlantId**), which starts at the time of **ArrTime**, and lasting for an uncertain duration of time (specified by **ProdTimeDist**).
  - In addition to reading attribute characteristics from input data sets, each entity of the supply chain network simulation is tracked, and its history is recorded. For example, **ProdStartTime**, **ProductionDelay**, **ProdEndTime** are tracking data.
  - Completed production units are routed to the supply warehouse, which is specified by **SWHId**, and the uncertain transport duration to this warehouse is specified by **SWHTransDelDist**.
- **Line.sas7bdat**, which describes the production lines and plants in the supply chain.
  - **Attributes** are PlantId, LineId, and ProductId.
- **Transport.sas7bdat**, which contains descriptions of all the trucks in the supply chain.
  - **Attributes** are SWHId, MCIId, Truck Priority, and MCTransDelDist.
  - Each row of this dataset represents a specific truck operating between a supply warehouse (specified by **SWHId**) and a mixing center (specified by **MCIId**). The modeling of each truck can be modified to meet its **Minimum Load** and **Maximum Load** requirements before departing for its destination. Furthermore, if the truck has only met the **Minimum Load** requirement, then **Minimum Wait Time** may be additionally defined to specify the minimum

amount of time this truck should wait before departure. Finally, `MCTransDelDist` specifies the uncertain duration of transportation.

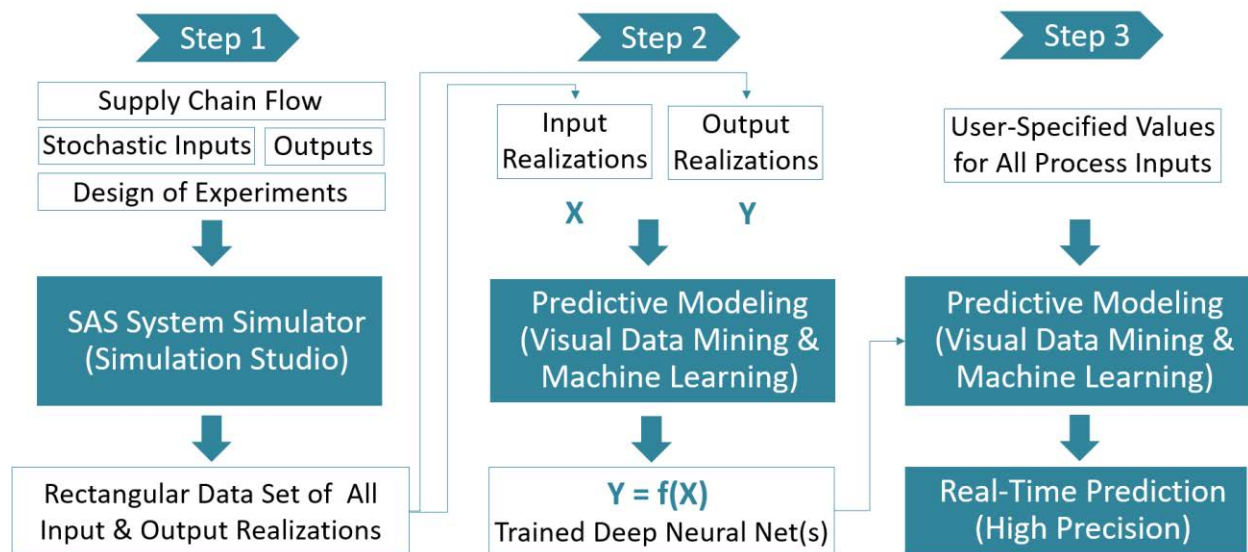
- `MCPProduct.sas7bdat`, which lists products stored at mixing centers and inventory control policies.
  - `Attributes` are `ProductId`, `MCIId`, `SWHId`, `Reorder Point`, `Order-Up-To Level`, and `Order Pending`.
  - The SAS supply chain simulator described in this paper assumes single sourcing. For example, product `ProductId`, which meets demand at the mixing center `MCIId`, is supplied only from the supply warehouse `SWHId`. However, if needed, SAS Simulation Studio has the flexibility to relax this assumption.

By dynamically updating the attributes of these data sets and utilizing the flexibility of the SAS Simulation Studio constructs, a scalable and data-driven simulation can be developed for the supply chain network illustrated in Figure 3. It is important to note that at this point we have not read in data files that are specifically allocated to the creation of Product and Replenishment Order entities. The data read from `InitProduct.sas7bdat` makes up the Product entities that represent the inventory sitting at the supply warehouses and the mixing centers. As soon as production is completed as specified in `Production.sas7bdat`, the finished goods are also recognized as Product entities. The Replenishment Order entity is created when the daily check of the inventory level indicates a value below a reorder point and there is no record of a replenishment order in transit for the same product at the same mixing center. Such creation of additional entities is embedded into the SAS supply chain simulation, taking advantage of the highly granular and flexible constructs.

## MACHINE LEARNING FOR ACCELERATING SCENARIO ANALYSIS

So far, this paper has described how SAS Simulation Studio can be used to obtain a scalable, data-driven, and flexible dynamic simulation for your supply chain. You can view this simulation as a large supply-chain data generation program. Therefore, you can accelerate your prediction of KPIs and scenario analyses through integration with machine learning, using SAS Visual Data Mining and Machine Learning.

For example, you might need a fast scenario-analysis capability for identifying the optimal inventory control policies for all products across all mixing centers to attain high service levels at minimal cost. For product `ProductId` stored at mixing center `MCIId`, the inventory control policy parameters are found in `MCPProduct.sas7bdat` input data file in columns `Reorder Point` and `Order-Up-To Level`. You can use the simulation output data generated across many pairs of these two columns to identify an improved control policy through the joint use of SAS supply chain simulator and SAS Visual Data Mining and Machine Learning. A high-level description of this integration is provided in Figure 5. You can find an example of this integration in the healthcare industry in Biller et al. (2019).



**Figure 5: A Three-Step Approach for Fast Scenario Analysis**

## CONCLUSIONS

This paper presents a high-level description for a computer simulation developed to manage your supply chain operations using SAS Simulation Studio, which is the discrete-event system simulation component of SAS Optimization. The key features of this software include object-oriented programming, tracking of objects and values, automated KPI collection, and smart decisioning and integration. These features are primary contributors to the successful creation of a scalable, data-driven, and flexible dynamic simulation for a supply chain network. Although this paper describes simulation development for a specific supply chain flow, the SAS simulation technology can be customized to meet your modeling requirements. SAS Simulation Studio is data-driven and scalable, which provides flexibility in implementation. Finally, you can use SAS Simulation Studio with SAS Visual Data Mining and Machine Learning for KPI prediction in real time and for fast scenario analysis.

## REFERENCES

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- Hughes, Ed, Pratt, Rob, and Billier, Bahar 2018. "Solving Business Problems with SAS Analytics and OPTMODEL." **Technology workshop presented at INFORMS Analytics Conference**, April 15–17, 2018, Baltimore, MD.

## RECOMMENDED READING

- SAS Institute Inc. 2018. *SAS Simulation Studio 15.1: User's Guide*. Cary, NC: SAS Institute Inc. Available <https://documentation.sas.com/?docsetId=simsug&docsetTarget=titlepage.htm&docsetVersion=15.1&locale=en> (accessed February 6, 2020).

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