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Combined Use of Optimization and Simulation Technologies to Design an Optimal Logistics Network

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Abstract

Use of optimization methodologies for supply chain network design has had a significant impact on developing cost-efficient capital investment and replenishment strategies across many industries. Less understood is the impact dynamic simulation modeling can have on determining the success of a particular network design in meeting its operating objectives. This paper provides an understanding of the methods and appropriate usage of a dynamic simulation modeling tool coupled with a logistics network optimization tool. We will discuss how coupling these tools can provide insight into the structure of a supply chain, as well as the robustness of that structure through immediate testing via dynamic simulation modeling.

COMBINED USE OF OPTIMIZATION AND SIMULATION TECHNOLOGIES TO DESIGN AN OPTIMAL LOGISTICS NETWORK

Overview

Procter & Gamble has actively pursued understanding supply chain design issues and strategies for a number of years. The concept was first introduced internally in 1995. The "Ultimate Supply System" sought to understand the impact of tightly coupling supply chain partners to integrate information, physical material and product flow, and financial activities. This had the potential to significantly increase sales, reduce costs, increase cash flow and, ultimately, to provide the right product at the right time at the right price to our consumers.

P&G's internal operations research group, Global Analytics, has been involved with this initiative from the start. The group has contributed a number of unique modeling and analysis approaches to help business units understand and leverage the key drivers in efficient supply chain design and execution. By utilizing optimization, simulation, and other methodologies, we leverage our resources broadly across all of the company's business units.

Until recently most supply chain design projects we supported utilized either network optimization or simulation modeling, but interactively with two separate modeling tools. We will discuss how we found coupling these two technologies together on a specific project has led to deeper insights and, more importantly, more efficient supply chains with a higher degree of confidence that those efficiencies will be realized. We will review the advantages and limitations of each technology in the context of supply chain design, then explore the opportunities that can be realized through a marriage of the two.

Procter & Gamble and Its Diverse Businesses

Founded in 1837 in Cincinnati, Ohio, Procter & Gamble has grown to a $40 Billion company with 100,000 employees and operations in over 72 countries, including over 120 manufacturing facilities. Through a portfolio of 300 brands grouped into 35 product categories, P&G represents a number of industries and as such, provides a rich test bed of supply chain design opportunities.

Business Unit	Manufacturing	Supply	Logistics	Other
Pharmaceutical	Small Batch Mixing	Exotic materials	Airfreight	Highly regulated
Laundry Detergent	Liquids and Dry Powder	Agglomerates (2-stage making)	Bulk container, super sacks, full truck, ocean container, rail	
Paper making	Web-based, high speed, continuous, capital intensive	Pulp (commodity)	Rail, High-cube trailers, containers	High capacity utilization required to make money

Industrial Chemicals	Process-based	Fatty acids, alcohols	Bulk liquid, tanker truck, rail	Make, Buy, Sell planning decisions
Cosmetics	Small batch, high labor intensity	Contract manufacturing for components	Small package freight	High SKU complexity, 12-18 month line turnover

Table 1. Examples of Procter & Gamble's different supply networks.

The Ultimate Supply System

In 1995, the Vice President of P&G's Product Supply function, which covers all activities from procurement through to delivery of finished product to our customer's docks, laid out a plan for capitalizing on efficiencies found in what is now known as the supply chain.

The idea was simple: close-couple all the supply chain partners, from the store shelf back to our supplier's supplier, and synchronize the reactions between the players beginning when a consumer's product selection is scanned at a retailer's checkout line. We were interested in understanding three aspects of these transactions: 1) the transmittal of information back through the supply chain, 2) the effective flow of materials and products through the physical supply chain to replenish the store shelves and 3) how do we speed up the financial flow of cash?

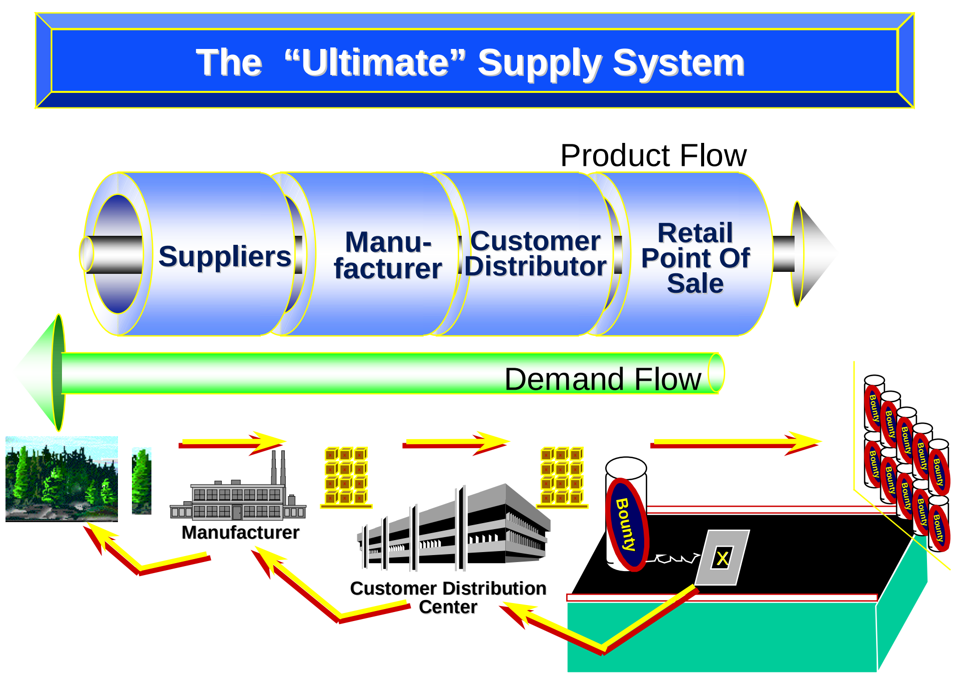

Figure 1. Conceptual view of The Ultimate Supply System

One aspect of supply chain interaction that has been identified is supply chain 'bullwhip', and what causes it to take place. Once a product is scanned at a retail store, a natural delay occurs in the transmittal of the signal that triggers a replenishment event to take place. Delays occur for a number of reasons, and the longer the delay, the greater the uncertainty upstream supply chain partners experience. That uncertainty translates into those partners taking measures to guard against stock outages, in the form of larger safety stocks. As that demand signal, and its delay, moves further away from its source, the larger the amplitude, or uncertainty becomes. That uncertainty impacts planning cycles, and their lead times, within and between the supply chain partners. In this way, distance and time become more and more critical to building an effective and efficient supply chain.

In addition, there are compounding factors that occur due to the *nature* of that initial demand signal the supply chain receives. The circumstances that cause a consumer to walk into a specific store and purchase a particular SKU of Bounty paper towels are of interest in understanding supply chains. It could just be the normal weekly shopping run, which results in a demand signal that is relatively easy to predict and manage. Problems arise when product promotions take place. The consumer might have made a purchase because of a coupon event, a store ad placed in a local paper, or via an in-store event. These events can cause disruptions in the supply chain, and far too frequently are mis-communicated to the supply chain partners.

New product initiatives are another form of disruption in the supply chain. A new initiative, perhaps a new product, or variation on an existing product, requires decisions on pre-launch production timing, and pre-building and staging inventory to meet anticipated demand for the products.

The location and amount of inventories and production capability plays a direct impact on the ability to respond to these types of supply chain demand-creating events, further leading to improving our understanding of how physical location and work processes are inherently linked in efficient supply chain design. And while these problems exist in scale in the U.S., they are further exacerbated when dealing with international trade.

Motivation

Several years ago, as a direct outcome of thinking about developing more efficient and effective supply chains, senior management at P&G wanted to test an idea: Redesign the distribution network in one of our key markets to improve the ability to respond to our customer’s orders as quickly as possible.

The approach required not only changing the way we handle the order fulfillment process, but to dramatically change the location of our physical inventories, by product and order type. The first question needing to be answered was: Where do we locate warehousing throughout the market in order to have the right selection of P&G products available such that we can guarantee a specific order delivery cycle time to our customers?

The Global Analytics group was asked to develop a traditional distribution network design model, utilizing mathematical optimization methods, to suggest a potential layout of warehousing required to meet this need. To accomplish this, work processes and policies would need to be substantially changed. How successfully those changes were managed, and how effective the resulting processes were in achieving the objectives, was partially dependent on where and how inventory was physically deployed in the network. This led us to support the development of a dynamic simulation model to adequately represent the processing of a supply chain's work processes and operating policies against the supply chain's primary driver: demand.

This leads to an important point: If a supply chain's design incorporates not only a structural question (Where and how many piles of inventory?), but also one of work process (inventory deployment, replenishment policies, operating policies), the two issues are inherently linked and must be solved together.

As we investigated different operating policies within the warehouse structure proposed by the optimization models, we found that in certain instances that we would not be able to achieve the service levels we had intended. This learning from the simulation modeling fed back into the optimization model, in terms of new constraints required to determine a feasible warehousing structure. That, in turn, created a new scenario to test within the simulation environment. In the course of the work, we realized that an easier process to move back and forth between the two technologies would be useful.

About Supply Chain Network Design

Network design focuses on the location-specific aspects of a supply chain, such as the location of production and warehousing facilities to best meet customer demand replenishment locations. Included in that analysis is determining not only the location, but also the replenishment linkages from a facility to its downstream supply chain partners.

Supply Network design normally utilizes optimization technology, which develops a constrained, least cost network. An optimization model can be constrained by capacity limitations on facilities, and also by limiting the length of replenishment links. This type of constraint attempts to address time-based aspects of a supply chain, normally by using distance as a surrogate for time. However, this type of constraint is a crude representation of lead time, as many factors beyond just distance contribute to a facility's timely ability to react to a demand signal.

The power of using optimization technology on network design problems is the technology's ability to effectively select from among thousands of options simultaneously to determine a supply chain structure. The macro nature of this analysis best suits itself to structural, location problems.

Within large organizations, a central planning group usually is responsible for commissioning a network design analysis. This can be accomplished by either in-house resources, with specially licensed or even proprietary tools, or through a consulting firm retained to perform some or all aspects of the analysis.

Key Drivers in Network Design

An effective supply chain network design begins with forward-looking projections of demand for the businesses being studied. This can require estimates as far ahead as 10 years. From a financial analysis standpoint, for potential bricks-and-mortar investments, the overall analysis is driven by an NPV analysis where an evaluation of capital investments vs. savings realized over a five- to ten-year basis. The predominant driver of the size of the investment and of the associated savings is the projected demand. Multiple model runs are made with different demand scenarios to test the sensitivity of a particular network structure.

Other key drivers include: transportation costs between supply chain facilities, facility variable and fixed costs, and on an international basis, duties and in certain instances, taxes, can be significant drivers.

Limitations

While optimization-based network design, linked with appropriate financial analysis, provides a sound basis for investment and structural changes, there are limitations to its use in supply chain design.

First, the broad brush-strokes required to represent the full scope of a supply chain fails to capture the execution effectiveness of a particular network design. Secondly, the large-scale optimization models often forsake the time element crucial to understanding capacity-inventory balance questions and lead-time vs. production or replenishment cycles issues. While optimization technology has recently taken great strides to close this gap (via advances in problem formulation, solver capabilities and raw computing power), it is, by its nature, incapable of dealing with execution level details that can make or break a supply chain structure.

Next, optimization requires aggregating a number of elements of a supply chain. For example, rarely will a network optimization model include SKU-level analysis. Instead, whole product families are normally representative of a number of SKUs. This loss of granularity can hide critical elements of execution-level capability required to make a supply chain work effectively.

Finally, network optimization models are, by their nature, highly data intensive. Modeling and data gathering technologies have come a long way over the last 10-15 years, allowing rough-cut models to be constructed relatively quickly. However, as previously mentioned, the forward-looking nature of this analysis requires that forward-looking data models be developed. It is simply not adequate, nor appropriate, to develop a recommendation for a supply chain design based on yesterday's performance data and cost structures.

Supply Chain Simulation Modeling

Simulation modeling allows time-based, execution-level events to be represented, analyzed, and understood. Simulation provides a rich environment for experimenting with different approaches to operating strategies that may be effective. Until recently, simulation has extensively been used to examine manufacturing operations for removing throughput bottlenecks, improving operating efficiencies, testing sequences of operations, material handling design, etc. More instances of utilizing simulation technology on broader supply chain issues are being reported.

Within the context of supply chains, simulation allows close analysis of inventory positions, their deployment and how they are affected by changes in downstream demand signals, and the re-order policies in place to respond to those signals. Synchronizing planning cycles and production schedules with up- and down-stream supply chain partners, as well as understanding capacity utilization issues in response to closer coupling of supply chains are issues that can be addressed with simulation modeling.

In this way, supply chain simulation modeling allows testing of a proposed network design to understand how robust that design is under the rigors of the day-to-day order processing and replenishment.

Because simulation has historically found its place in operations-level issues, in-house capability for this technology is often found in a process engineering organization.

Key Drivers in Supply Chain Simulation Modeling

As in network design, the primary driver of understanding process related issues in a supply chain is the demand. However, in simulation modeling the timing and size of individual demand events (orders) for specific SKUs, rather than an aggregated product-family level representation of demand, is the driver. The uncertainty in forecasting or otherwise anticipating what that order stream will be has a profound effect on inventory, production capacity, transportation requirements, staffing, staging space, dock utilization, or other resource contention issues.

Although simulation modeling has the capability to capture other stochastic characteristics of a supply chain (e.g. transportation arrival times), we have found the biggest driver overall in determining supply chain capability has been effectively responding to the initial demand signal.

Limitations

As discussed, simulation's greatest strength is allowing detailed testing of a particular design for it's relative strengths and weaknesses. This also points out its limitation: each change in a supply chain's structure needs to be modeled and tested individually. It does not inherently select from a number of different structural possibilities to determine the "best", in terms of efficiency, costs, responsiveness, etc. Unless explicitly modeled to take a decision based on cost or efficiency (e.g. develop a production schedule "real time", re-allocate inventory piles across a supply chain), simulation's role is to test the strength of a design against its environment.
Like network design, simulation modeling is equally data-intensive in its requirements. However, the data requirements are different in nature. In network optimization, the unit of measure is cost, whereas in simulation modeling, it is time. Detailed information on orders, when they occur, what SKUs, what quantities, etc., is required, as well as information on planning and production cycles and schedules.

Applications on the Supply Chain

There are numerous potential applications for applying both network design and simulation modeling in conjunction with each other to develop an efficient and robust supply chain design. While end-to-end supply chain models are possible, and often required to gain a full understanding of a particular design's impact, in the following sections we will focus on partner-to-partner interrelationships as we step back into the supply chain, beginning with our most important partner – our consumers.

Consumer Fulfillment

In the consumer goods industry, retailers are most interested in designing an efficient network of distribution centers to service their retail stores. A network design not only encompasses the location and number of stocking locations, but the mission of that location, in terms of type of product stocked, and perhaps separating slow-moving from fast-moving, as well as seasonal goods. Some of the operational issues encountered while attempting to validate a particular network design might be:

- Will this have an impact on improving the out-of-stocks that take place?
- What would be the staffing that is required at the DC's as well as at the stores to unload and to stock?
- What amount and kind of staging space would be required?
- Would the design be able to eliminate back room inventory as a result?
- What is the reorder policy?
- What's the order delivery cycle time?
- For limited shelf life products, how do you cycle product through quickly?

Customer Fulfillment

For consumer goods manufacturers, supply chain network design normally covers the location and number of distribution centers required to service a geographic market area. As with retailers, what products are stocked, as well as what issues dictate customer ordering policy (product restrictions, minimum order quantity), will drive the locations and their service areas. In addition, when necessary, allocation of production capacity can be considered in conjunction with warehousing. From an execution standpoint, we are interested in:

- Determining safety inventory requirements at each stocking location given the variability in customer orders.
- Determining cycle stock to cover transportation and order lead-times, and production cycles given the distance to customer markets, and from production locations.
- Synchronizing the planning activities of customers, warehouses, and production.
- Developing policy decisions on whether a push, pull, or a combination replenishment strategy is appropriate for the products, customers and warehouses involved.
- Addressing concepts, such as late-stage production (or packaging) differentiation, dynamics fulfillment by servicing a customer from multiple sites, cross DC shipping, fast and slow mover separation

Plant Capacity

Plant capacity, particularly regarding the number and type of production lines required, is often driven by external supply chain factors. A network optimization model can effectively help determine what increments of capacity are required at a plant location, when supplier and customer partner locations are key considerations. Once a rough plan is determined, execution issues need to be considered, such as:

- Utilization of that capacity (dedicated vs. swing production lines),
- Different technology choices – while network design can help address increments of capacity required from a cost-efficiency basis, it may be more beneficial from a responsiveness and service standpoint to have smaller increments of capacity available at more locations, rather than less.

Supplier – Plant
In a network design analysis, identifying where your key materials may be most effectively located to service your plants is of interest. To understand how to best utilize the capacity available, would require deeper analysis into:

- Appropriate safety stock levels at the supplier and manufacturing site.
- The effect of coordinated planning cycles and production schedules on overcoming distance disadvantages.

Integrating Optimization and Simulation
P&G has been the catalyst in marrying the two technologies of optimization and simulation. At present, the capability allows a network design to be generated from Insight's GSCM optimization product and then read into Simulation Dynamics' Supply Chain Builder simulation product. The end-result of the optimization is both a network design and a database file. The database file is then read into Supply Chain Builder to create a simulation model. In Supply Chain Builder, about 90% of the structure of a supply chain can be represented by this database. The database must be augmented with additional data needed by a supply chain simulation, such as additional demand data and policy parameters.

Example of Supply Chain Simulation
The example pictured below illustrates how a system with a customer, plant, and supplier responds to a 10-day promotion involving a tripling of demand.

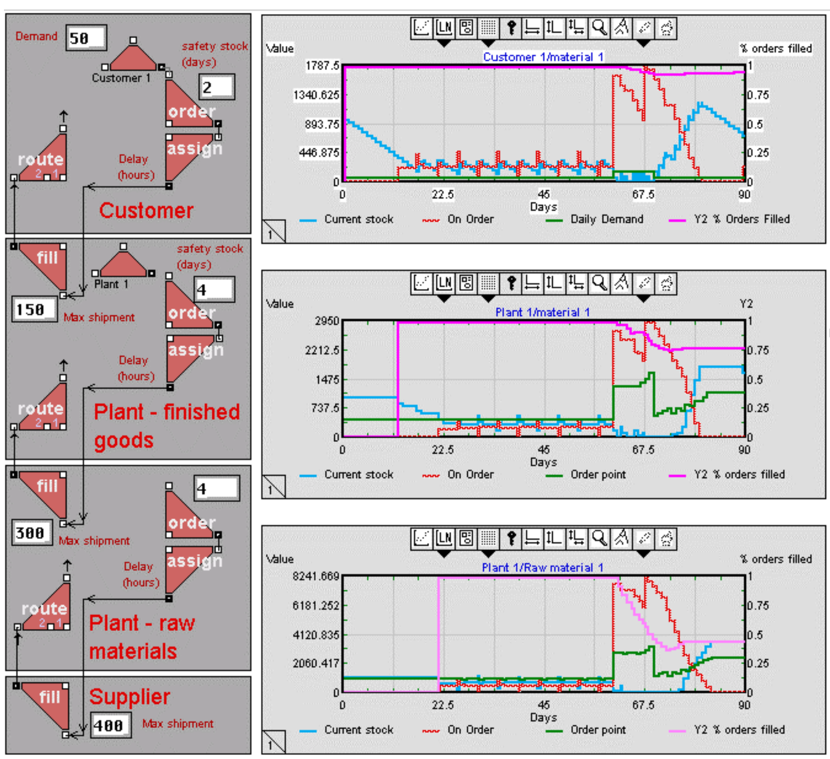

Figure 2. Example Supply Chain Simulation

In this example, there is a constant demand of 50 cases per day until day 60. Between day 60 and day 70, demand is tripled to 150 cases per day. This continues until day 70, when demand returns to 50 per day. Even with transportation lead times held constant, we observe very dynamic behavior. Notice that it takes about 30 days for the system to settle down following the 10-day promotion. We can derive vastly different behavior as we change forecast policies and ordering parameters (safeties, targets) at each location.

While a typical simulation would have a much more detailed demand picture, this simple example illustrates the behavior we are trying to understand. As discussed before, simulation modeling has the capability to capture stochastic characteristics. However, the biggest overall benefit has been increased understanding of the nature of our systems in responding to demand.

Outputs of Simulation

A typical simulation has many SKUs, each with its own pattern of demand, and potentially each with its own ordering policies. At a high level, we want to measure the total cases that are in the system and the overall percent orders filled, across multiple locations and SKUs. An example of this is shown below. For cases in system, we want to know whether those cases are in our inventories or our customers' inventories, or if they are in the pipeline (on trucks). Percent orders filled can be measured at a number of places in a supply chain. A challenge is in determining how this relates to our objectives, because, as indicated in Figure 2, percent orders filled can be very different, depending on where it is measured.

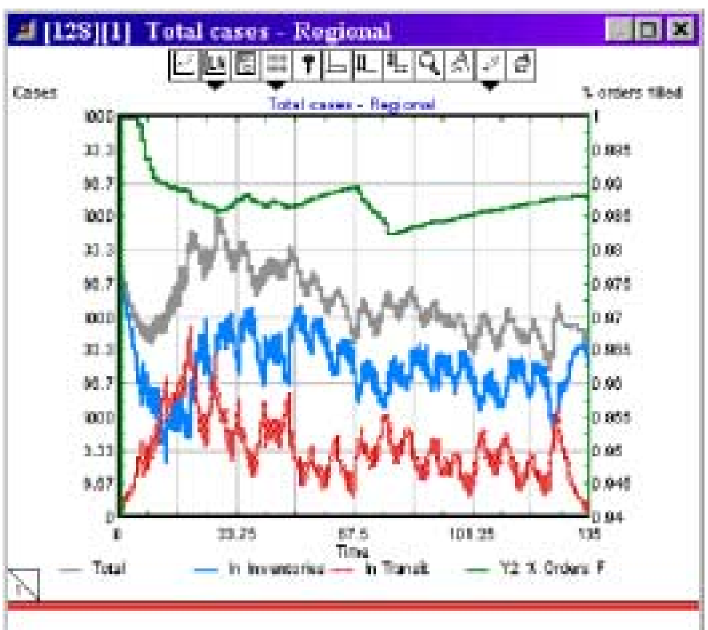

Figure 3. Sample Output from Supply Chain Simulation

In addition to these performance measures, inventory age and costs can also be reported. Performance is also presented in summary reports, by SKUs, locations, classes of SKU or classes of location. Simulation analysis relies on summary plots and reports; however, it is important to note that critical discoveries are made when we are led to drill down and plot individual SKUs, either at a single location or across multiple locations.

In a classical simulation study, we develop understanding of a system performance curve that is theoretically like the one shown below. This theory assumes that policies leading to greater material (e.g., cases) in a system also correspond to lower percent out of stock, and therefore greater customer satisfaction. A maximum percent out of stock goal is established. Higher out of stock percentages are deemed unacceptable. If we achieve lower out of stock percentages it is "icing on the cake".

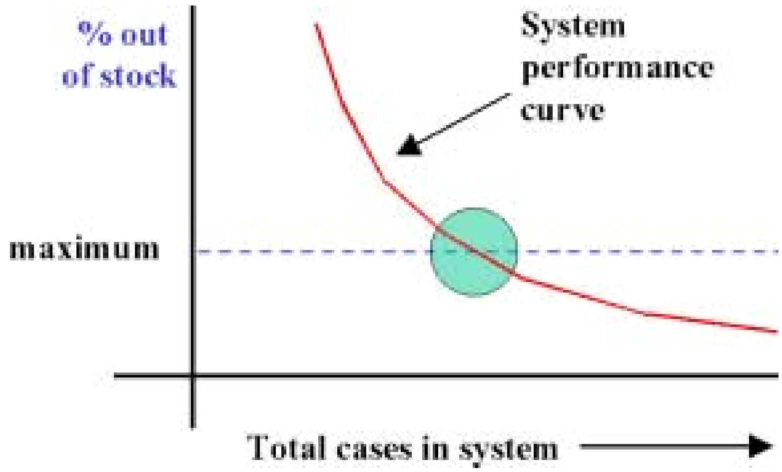

Figure 4. Simulation Performance Measures

Using simulation allows us to "do the limbo" by discovering how low we can go with total cases in system while achieving our objective for percent out of stock. With a given network design, we are trying to understand as much as we can about the circle in the middle of this picture. Within this green circle, we are able to explore various policies (e.g., forecast, manufacturing, ordering, assignment) to fine-tune both our understanding and our operational system.

Implementation Issues
Several issues exist when trying to utilize both network optimization and simulation technologies to evaluate supply chain design.

User Overload. With network optimization technology, the art of putting together a model correctly and being able to analyze options correctly within it requires a high level of experience in both the technology itself and in analysis procedures. The same applies to simulation modeling. However, it's rare to find expertise residing in an organization or individual who understands how to operate both of these methods effectively.

Data sourcing. The commitment to perform both network design and simulation modeling requires an understanding that the true cost of this type of analysis is in the intensity of data collection required. Network design is driven by cost unit-based data, while simulation requires time unit-based data. The time required to gather this information can easily double the effort necessary for completing an analysis.

Scoping. The scope of a network design model may differ from that of its companion simulation model. The output from a network design model may include tens of warehousing facilities, servicing hundreds of customer regions with dozens of product family groups. This reflects the macro level of model detail appropriate for determining the overall structure of a supply chain. Simulation modeling may only look at the work processes, inventory stocking targets and order fulfillment policies of a single warehousing facility and its customers. Therefore, the network design model can provide the overall structure, but not the operating details required for a simulation. It provides a first step to get started, but much more structure and information is required to successfully model execution-level processes.

Conclusions

In supply chains, time is the enemy. In the past, cost was the primary driver in supply network design. Today, higher accuracy performance measures require more rigorous planning and design of supply chain interactions. Using an optimization tool for Network design is appropriate for macro-level analysis to identify structural choices in a design, but time and service performance measures have become key drivers to good supply chain design and management. Simulation modeling helps in designing against these measures.

Demand is the primary driver in both macro supply network design and in work process and operating policy design. In network design, optimization tools are used to perform extensive sensitivity analysis to ensure that over-investment in capacity and facilities doesn’t occur. Simulation modeling allows finer analysis of how that capacity is utilized against daily, or even hourly, changes in downstream demand.

Past results do not guarantee future performance. Designing supply chains requires not only hindsight, but also foresight to understand where costs, time, and ultimately, the consumer are headed. It’s necessary to superimpose what the future is going to bring to you as a result of the system that you’re going to build. Within the network structure suggested by optimization, simulation modeling projects the impact and interaction of forecasted dynamic inputs.