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A FOUR STEP METHODOLOGY FOR USING SIMULATION AND OPTIMIZATION TECHNOLOGIES IN STRATEGIC SUPPLY CHAIN PLANNING

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ABSTRACT

Supply chains are real world systems that transform raw materials and resources into end products that are consumed by customers. Supply chains encompass a series of steps that add value through time, place, and material transformation. Each manufacturer or distributor has some subset of the supply chain that it must manage and run profitably and efficiently to survive and grow. Decisions about how to plan a company's supply chain operations can be operational, tactical, or strategic. Strategic decisions are the most far-reaching and difficult d to make. These decisions are characterized by complexity, interdependence, and uncertainty. Simulation and optimization modeling techniques are used to help make supply chain strategic decisions. The four-step methodology is a proposed approach to supply chain strategic planning that attempts to leverage the strength of multiple modeling techniques. Each step solves a different part of the master planning problem, using either optimization, simulation, or simulation-optimization. By using complementary modeling approaches together in the Four Step Methodology, the supply chain planner's activities and decisions can be greatly improved.

1 INTRODUCTION

Since its commercialization and proliferation as a viable industrial technology, discrete event simulation (DES) modeling has achieved a status of pre-eminence in the analysis of complex systems. DES offers analysts and decision-makers a means to replicate the behavior of complex systems as they operate over time. The most common applications of DES include plant floor operations, logistics systems, and human service delivery systems, although there are many different applications that do not fall neatly into one of these three headings.

As DES technology has matured, supporting methodologies and accepted practices have grown along with it, to provide a blueprint of how to successfully deploy it and avoid the pitfalls of past failed projects. However, while a core nucleus of dedicated experts and vendors has helped to further the development and maturation of DES technology, the task of clarifying the contextual borders which define the touch-points of DES with other alternative modeling technologies has largely been left to the user community. Many simulation experts focus on and promote the use of simulation technology with regard to the problems it can solve, but few have an agenda that includes defining what simulation can't do.

Aside from educators and a few leading edge researchers, it is the User Community itself that has been forced to take on the formidable task of defining when simulation is relevant, and when it is not. As many practitioners will attest, the most crucial stage of any project that involves problem solving and decision making is the formulation of the problem itself and the selection of which tools and technologies to attack the problem with. When one knows an issue is a "simulation" problem, one can proceed with established methodologies. When one knows it is not, one can select a different approach.

2 DOMAIN DEFINITION AND SUPPLY CHAIN STRATEGIC PLANNING

In recent years, the problem of "domain definition" has become more and more acute. As practitioners in industry continue to demand better solutions to their analytical and planning problems, they have pushed technologies such as DES towards the boundaries of what they can be expected to do. Simulation, once considered as a statistical sampling technique for selecting finished designs (preferably in a head to head comparison) are now being expected to provide projections, predictions, and even prescriptions about how a design can be improved or a problem should be solved.

These increased expectations resulted in a renewed effort by simulation industry experts to incorporate other techniques into their simulations, and in 1994, SimRunner, the first simulation-optimization package was released by Decision Science, Inc. In the five years that followed, nearly all of the major simulation vendors have incorporate some form of model optimization or improved output analysis into their tools.

Unfortunately, while improving the size of the DES problem-solving domain, these developments also had a deleterious effect on domain definition, causing the user community to be less clear about what problems were appropriate for discrete event simulation, and which problems were not.

Perhaps nowhere has this problem been more evident than in the area of supply chain planning. Supply chain planning problems encompass industrial production process design and improvement, inventory control policy, transportation management, supply procurement, and demand planning—in short, all of the major activities that a large industrial company could be involved with. Increasingly throughout this decade, corporate planners and operations managers have come to realize that it is the very fact of the complexity of the enterprise that results in planning and decision making problems. Although the first step of enterprise analysis and improvement efforts to reduce the scope of the problem to a manageable size by examining only one aspect (link) in the supply chain, it is now common knowledge that slicing up the problem can likely cause the underlying root causes of problem's symptoms to vanish.

In other words, simplifying the supply chain planning problem, or reducing it to parts, often renders the analysis itself moot. It is the complexity and interdependence of the operational links that result in the areas of interest for the typical industrial decision-maker. Hence, it has become a requirement of supply chain analysis projects to deal with not only complexity and interdependence, but randomness too; to model problems accurately, but to solve them as well; to describe and determine, only to then to predict and prescribe.

In short, supply chain planning and analysis places requirements upon its would-be participants to use multiple techniques and technologies, as needed, to arrive at different facets of a complex solution. Of course, this is exactly what sharp analytical approach domain definition facilitates, and hence exacerbates by its absence.

This is a problem with large financial implications for practitioners, and it demands attention. Over the last two years, a team of experts from different decision support technology niches has been collaborating on projects and sharing information about their products. The goal of this collaboration was to produce a common approach, or methodology, for utilizing different modeling techniques to help analyze and solve supply chain strategic planning problems. The team focused on strategic decisions because they are the most ambiguous and the most dependent on advanced modeling and simulation techniques. The remainder of this paper will attempt to outline the approach, called the Four Step Methodology.

It should be noted that new data and fresh perspectives have already resulted in modification to the Four Step Methodology. The Methodology is only a first, tentative step down a long path which, hopefully, will lead towards an improved environment for users and better supply chain planning decisions.

3 TERMS AND DEFINITIONS

Before we review the steps in the Four Step Methodology, we must define a few terms. The words simulation, optimization, modeling, and systems, are used by many people to describe many different things. The same is true for the term "supply chain," and clearly "strategic" is in the eye of the beholder.

As far as this paper is concerned, modeling is a generic term which refers to the process of creating an abstract representation of a system. The abstraction, or model, is used to gain insight into the working of the system that it represents, or to predict the system's future performance, or to test out the results of changing some aspect of the system. Modeling approaches vary greatly, from graphical and physical, to logical and data oriented. For the analysis of supply chain systems, modeling techniques are generally mathematical in nature, and are used to calculate some aspect of the real world system's performance.

Optimization means finding the specific certain set of inputs to a function, such that any change to any of the inputs will result in a less desirable function output. Optimization approaches are generally thought of as either analytical/mathematical or direct/empirical. Regardless of the specifics, in an optimization routine in the most general sense is a procedure that, when applied to a model, will result in the determination of the best model as defined by the fitness of an objective function.

Most problems are solved by matching a modeling approach with an optimization, or solving approach. Different matches have different strengths and weaknesses, but they operate on the same general concept. Simulation is a specific computer based modeling approach which uses a chain of cause and effect relationships to help the user build complex models from the ground up, one link at a time. On the other hand, optimization often requires a simplistic modeling approach in order to have a model that can be completely optimized.

Finally, while there are many published definitions of the term "supply chain," the most general and broadest definition is that the supply is the series of steps and operations that take raw materials and resources at one end of the process, and produce consumable products at the other end of the process. Supply chain operations include procurement, production, inventory, transportation, and demand planning.

While some consultants hold that a supply chain must necessarily be an "intra-enterprise" operation, this paper assumes that a company could be looking only at its own internal operations and processes. In this case, the term "business logistics" is just as appropriate, but as many projects are examining one slice of the supply chain with an eye towards expanding up and down the chain, the term "supply chain" seems to better capture the current spirit of these projects.

4 FOUR STEP METHODOLOGY OVERVIEW AND PURPOSE

Supply chain strategic planning problems involve decisions about how a company's internal supply chain and external linkages (both with suppliers and customers) are fundamentally organized. From a systems perspective, one can think of an entire supply chain as a series of objects that interact to perform a given function—in this case, the meeting of end customer demand in the most efficient way possible. The elements, or objects, that make up the system, can be considered a supply chain's *structure*. Some examples of structural elements include: products, sites, shipments, transportation assets, machines, and workers.

These objects all interact with each other, and how they do so is governed by the rules, or *policies*, that the objects follow. Policies can be rules that govern how much inventory is stocked at a given site, or how a site reacts when an order is received, or how that site deals with product shipments when they arrive. By combining a supply chain structure with a set of supply chain policies, one can arrive at a very precise description of a corporate supply chain. Most strategic decisions and planning activities involve either proposed changes to the supply chain's structure, or else modifications the supply chain's policies (behavior.) The point of the Four Step Methodology is to help guide users to decide what techniques are appropriate for each type of decision.

The Four Step Methodology starts from the assumption that you are beginning the strategic supply chain design process with a "clean sheet of paper." In other words, if all you have is a list of customer demand points, the methodology will take you completely through the entire strategic design with no presupposed objects. However, except for a few cases, such as planning to penetrate a new market, or in evaluating the potential of a green-field structure, a user usally has an existijg supply chain, and is looking to modify it. Since most companies already have a supply chain structure they wish to modify or change incrementally, users will not usually go through all the steps sequentially; most of the time they focus on one step or another, which will often force them to go back or forward to answer other new questions.

Special consideration must be given to the formulation of demand data to drive the analysis, regardless of which step or steps are included. For strategic level analyses, historical demand data is usually rolled up, or aggregated, into a higher level. However, since most strategic planning exercises are performed to make a decision in the future, in most analyses, some level of demand forecasting is required. Commonly used curve fitting tools just do not have the sophistication to deal with repeating patterns, trends, and seasonality. Yet, despite its importance to strategic modeling projects, demand forecasting has tended to receive scant attention by modelers.

With that caution, once we assume that we have a good future demand estimate for strategic level projects, we can proceed on to the first step.

4.1 Step One: Network Optimization

The objective of Step One is to arrive at an overall network structure that is efficient, meets all current demands, minimizes structurally based cost issues, and supports any other management constraints. To do this, a linear- mixed integer (LP-MIP) programming model is formulated, then solved. In LP-MIP models, the supply chain structure is built up as a generic network of nodes and arcs. By changing or removing the flow between different nodes, different costs result. The model is a mathematical model that takes only a split second to evaluate total cost. Powerful optimization solvers are applied to cycle through millions of alternative structures, turning candidate warehouses and factories off and on, and trying many different supply assignments. The resulting flows (dictated by the structure and the constraints) yield different cost outputs.

The power of network optimization modeling lies in two main strengths. First, it can be proven to provide the mathematically global optimal solution to the problem. The solver will, with near certainty (depending on the specific algorithm), locate the least cost feasible network structure. Second, network optimization models can handle millions and millions of possible alternative designs in a very short time. Large, global, multi-modal distribution networks can be optimized effectively.

Of course, the weaknesses of the approach stem from the same source of its strengths. In order to provide a model that can be evaluated quickly and solved, many simplifications are made. Most notably, this analysis normally is performed for a single time bucket, for aggregate data. In other words, the supply chain is simplified to be a distant abstraction from reality so it can be solved in a short amount of time.

A summary of some of the data requirements for Step One include:

- List of candidate sites, candidate site locations
- List of demand sites, demand locations
- Total demand quantities per location
- Cost per unit of flow and out of each site
- Cost of transporting units in and out
- Constraints, such as requiring that every demand point is within 500 miles of a warehouse

The output results of Step One include a number of summary statistics, such as total cost, total flow in and out of each node, the breakdown of transportation mode usage by lane, the manufacturing capacity utilized by the design, and which nodes supply which other nodes. By examining the final node to node flow totals, you can determine which warehouses should supply which customers, which factories should supply which warehouses, and so forth.

The technology for network optimization has been successfully deployed and used byt thousands of practitioners. Some of the more advanced tools for performing network optimization also have some capabilities to do multi-time period optimizations, incorporate production and throughput constraints, and handle complicated tax and tariff calculations.

4.2 Step Two: Network Simulation

While Step One will produce an "optimal" supply chain structure, it really ignores the issues of how the network will actually behave over time. As a result, it tells you what supply chain network design to select, but it cannot tell you exactly what will happen when that design is actually implemented.

In order to predict exactly how a proposed supply chain design will operate, the design must be simulated in Step Two of the Methodology. In this Network Simulation step, a discrete event simulation model is built to replicate the design that was produced in Step One. However, this design is simply a structure, or "shell," of a proposed network design. In order to predict the system's performance, more data is required by the simulation, while some of the data required by Step One is not needed in Step Two.

Most notably, in Step One, demand data was aggregated and process logic was not needed. In Step Two, the user must define the rules, or policies, which govern how inventory is managed and when it is replaced. Sourcing and transportation policies must also be defined.

To perform Network Simulation, time related demand data must be incorporated into the model. While aggregate quantities were sufficient for flow optimization, in order to simulate the demand properly, the model must know how the demand arrives over time.

A summary of some of the data requirements for Step Two include:

- It is formulated based on data such as:
- List of demand sites, demand locations
- Total demand quantities per location
- Cost per unit of flow and out of each site
- Cost of transporting units in and out
- Constraints, such as requiring that every demand point is within 500 miles of a warehouse

Network Simulation's greatest strength is its ability to predict very accurately how well a design will perform, in a variety of metric categories, such as inventory level, cycle time measurement, warehouse fill rate, and detailed costing. However, simulation as a technique generally requires long model building times, and long run times, limiting its usefulness as a "selection" tool. In Step Two, this not a major drawback, as the objective of Step Two is to predict a design's performance. For companies that already have an existing supply chain network design, Step One is not necessary, and they begin at Step Two.

Table 1 reviews the major differences between Step One and Step Two.

Table 1: Summary of Differences Between Network Optimization and Network Simulation

Network Optimization	Network Simulation
Evaluate larger number of alternatives (>100,000)	**Evaluate few alternatives (<10)**
Models structure only	**Models structure and behavior**
Aggregate network stats	**Detailed performance stats**
No complexity or variance	**Complexity and randomness**
Optimal problem solutions	**No optimization**
Use to determine candidate supply chain structures	**Use to make final supply chain decision**

It should be obvious that Step One and Step Two, Network Optimization and Network Simulation, are complementary modeling approaches which offer two different, useful ways to analyze and determine a supply chain design.

4.3 Step Three: Policy Optimization

While discrete event simulation is an extremely accurate modeling approach, capable of predicting system performance, it does not in itself help to improve system design. The net result of Step One and Step Two is a supply chain network design, including the structure and a proposed policy scheme. Network optimization provided a powerful means of selecting an optimal supply chain structure. However, the design can still be improved through attempting to optimize the policy choices used to govern the network's behavior.

Since DES must be used to predict the performance of various policy approaches, Step Three involves the running of multiple simulations in order to observe the effects of different policies and select the best set. This step can be performed by the analyst in a manual approach, but this is a tedious and difficult method. Instead, a better method is to use simulation-optimization as a modeling and problem solving approach which will result in an "optimized" simulation model that prescribes the inventory, sourcing, and transportation policies which should be adopted from a strategic level in the network design.

Simulation-optimization applies is a direct optimization method which applies an intelligent algorithm to a discrete event simulation model. Only in the last few years has this technique been commercialized and studied enough to render it a feasible method for practitioners.

The data requirements for Step Three are the same as for Step Two, with the additional requirement that candidate policies and policy parameters must be explicitly identified. For inventory policy for example, the upper and lower bounds of the reorder point and the reorder quantity must be defined. For transportation policy, all of the potential transportation modes must be identified (full truckload, less than truckload, combined truckload, etc.).

An additional requirement is that the data set for the simulation being optimized must be complete and accurate. While Step Two can be performed reasonably well with an incomplete data set, in Step Three any missing data or incomplete costs will result in the algorithm being "tricked" into recommending the wrong solution.

Policy Optimization is a cutting edge technology that can produce extremely valuable recommendations for policy improvement and better supply chain designs. However, along with this power, it has several weaknesses that must be watched with care. First, as mentioned, simulaiton-optimization requires a complete model with consistent and accurate input data and costs. Second, because each simulation run can take several minutes to complete, a full simulation optimization will take a lot of time (real world). This combines with the third problem, that realistic policy optimizations can result in hundreds or even thousands of decision variables, which must be manipulated and optimized.

4.4 Step Four: Design for Robustness

The final step in the Four Step Methodology is Design for Robustness. The objective of this step is to ensure that the final selection of the supply chain's network structure and policies will operate well under a wide variety of situations. During the first three steps of the Methodology, the user assumes that the design is being improved to operate as efficiently and effectively as possible

Perhaps more importantly, performed properly, Step Four will ensure that the selected supply chain design will, under less than expected or unusual circumstances will not perform unacceptably poor. This should not be confused with simple variance. In Steps Two and Three, random variance may have been introduced to produce more realistic approaches. So, Step Four is not centered around randomness and its effects; rather, it is the evaluation of the results of changing some of the external "given" data assumptions.

Step Four uses all of the techniques discussed in this paper as needed. There are no guidelines that would predict which technique to use for which answer. Instead, Step Four relies heavily on the knowledge and expertise of its users.

Table 2 outlines and summarizes all of the most important differences between each of the Four Steps.

Table 2: Strengths and Weaknesses of the Four Step Methodology

	Step One	Step Two	Step Three	Step Four
Name	**Network Optimization**	**Network Simulation**	**Policy Optimization**	**Design for Robustness**
Objective	**Optimze network structure**	**Predict network behavior**	**Optimize network behavior**	**Minimize risk of undesirable outcomes**
Technique Used	**Linear/Mixed Integer Programming**	**Discrete Event Simulation**	**Simulation-Optimization**	**All Techniques; Statistical Analysis**

5 CONCLUSIONS

Supply chain strategic analysis and planning places enormous difficulties in front of the intrepid user who would look to use the latest technologies. Each question that must be asked of a model, if it is truly strategic in nature, may require one or several different technological approaches. It is the complexity of the problem that necessitates advanced and multi faceted approaches to finding the solution. By combining the techniques discussed in this paper, within the context of the Four Step Methodology, the user can bring unprecedented power to solving existing problems, as well as problems that may occur in the future too.

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