A REVIEW OF THE STATE-OF-THE-ART AND FUTURE RESEARCH DIRECTIONS FOR THE STRATEGIC DESIGN OF GLOBAL SUPPLY CHAINS

Marc Goetschalckx(1), Usha Nair-Reichert (2), Shabbir Ahmed (1), and Tjendera Santoso (1)
(1) School of Industrial and Systems Engineering
(2) School of Economics
Georgia Institute of Technology, Atlanta, GA 30332.

Abstract

To remain competitive in today's competitive global economy corporations must constantly adjust their global logistics strategy, their supply chain configuration, and update their tactical production and distribution planning. The corporations must make these adjustments in the framework of the global trade environment with its taxation, tariffs, and environmental regulations. The relevant logistics data are often derived based on imprecise and fast changing forecasts. Corporations desire a supply chain configuration that is both efficient in the short term and robust with respect to changes in the long term and that can be implemented in stages. Neither the scientific methodology nor the design algorithms to support these global, integrated, dynamic and stochastic decisions exist at this time. As a result decisions are made in an ad hoc or hierarchical-and-sequential manner, which may lead to significant smaller profits when compared to robust and integrated strategic-tactical decisions. Potential savings from integrated supply chain decisions in the 5 % to 30 % range have been observed in preliminary case studies.

We will first review the current state-of-the-art in the modeling of these strategic supply chain design problems. This includes identifying the various factors that differentiate global supply chains from domestic supply chains such as exchange rates, tariff barriers, non-tariff barriers, transfer prices, duties, global transportation, taxes, and local content regulations. For each factor we will identify the advantages and disadvantages of various modeling approaches.

We will next review the various optimization algorithms and techniques for solving the formulations developed above. This includes mixed-integer programming based on linear relaxation, primal Benders decomposition, dual decomposition, and statistical sampling methods for stochastic mixed-integer programming formulations.

We will conclude the presentation with a review of some the case studies published in the literature, focusing on their formulations and solution methodologies. Finally, future research directions and challenges in the modeling and the solution algorithms will be identified.

1 Introduction

2.1 Definitions

Logistics, supply chains, and value chains have become very popular topics in the current research and business literature. Advertising by providers of third party logistics services, transportation services, and enterprise resource planning software has popularized the notion that a corporation is required to have efficient logistics practices to remain competitive in today's global economy. Given the large of variety of users, it should come as no surprise that many different definitions of logistics and supply chain exists.

Logistics is concerned with the organization, movement, and storage of material and people. The term logistics was first used by the military to describe the activities associated with maintaining a fighting force in the field and, in its most narrow sense, describes the housing of troops. The term gradually spread to cover business and service activities. There exist a multitude of formal definitions. The Council of Logistics Management (CLM) is a large trade association in the United States that promotes the practice and education of logistics. Their definition is probably the most widely used.

"Logistics is the combination of transport, storage, and control of material all the way from the supplier, through the various facilities, to the customer, and the collection of all recyclable materials at each step."

Logistics focuses on three types of flows: material flows, information flows, and monetary flows. The most traditional flow is the physical "material flow", where the material can range from traditional products, through services, to livestock, and people. The "flows" can refer to material in motion, indicating the space utility typically associated with transportation, or to material at rest, indicating the time utility typically associated with storage and inventory. The second important flow in logistic activities is the flow of information. The sharing of information on the status of the physical flows across the various organizations executing the logistics functions can dramatically decrease the magnitude of the physical material flows. This has led to the implementation of massive software packages for Enterprise Resource Planning (ERP) that provides such information first within a single organization and now among all the organizations in a supply chain. Finally, the increasingly global nature of trade and logistics has sharpened the focus on monetary flows in logistics. Currency fluctuations and fiscal regulations of trade associations such as the Economic Union (EU) and North American Free Trade Association (NAFTA) can dramatically change the feasibility and efficiency of the physical flows.

Very closely related to the logistics is the concept of a supply chain. A supply chain is a network of functional organizations that through their activities perform the logistics functions. Again many alternative definitions exist.

"A supply chain is a network of organizations that are involved through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer," Christopher (1998).

The linkages consist of material, information, and financial flows. The supply chain is usually not a single or simple chain but a complex network with many divergent and convergent flows.

Because of the current focus of companies on their core competencies, there are typically many different organizations in a supply chain. If all these organizations belong to the same (multinational) corporation, information flows usually are more complete and powerful and decision-making is easier, but the fundamental nature of the supply chain remains unchanged. In other words, there is no difference in the definition of a supply chain depending on the fact if one or more corporations are involved.

A company's supply chain is comprised of a number geographically dispersed facilities, at which commodities are acquired, transformed, stored, or sold, and that are connected by a set of transportation channels. The commodities can be raw materials, intermediate components, and final products. The combination of the facilities and transportation links is typically called the supply chain network. The facilities that are sources of materials are called vendors or suppliers. The facilities that transform or store materials are called manufacturing plants and distribution centers (or warehouses). The facilities that are the sinks for materials are called customers or markets. The facilities can be located in a single country for a domestic supply chain or in multiple countries for a global or international supply chain. A schematic illustration of a global supply chain is shown next, which appeared in Vidal and Goetschalckx (2001).

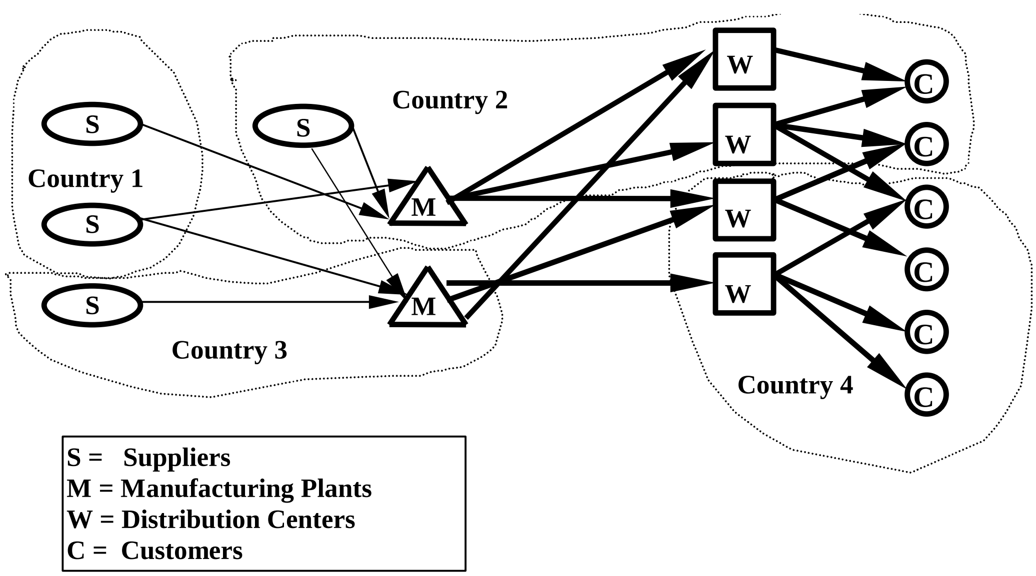

Figure 1. Global Supply Chain Schematic

On of the goals of the corporation is to increase the value of the commodities while they traverse the supply chain. In general, the manufacturing plants provide the form and functional value to the commodities, while the warehouse and transportation channels provide the temporal and location value (or time and place value) to the commodities. While there exist many different manifestations and configurations, the underlying structure of any supply chain remains a network of capacitated production, storage, and transportation assets to provide customer service by the timely delivery of goods and services to the customers at the lowest possible cost.

Stadtler and Kilger (2000) define supply chain management (SCM) as *"the task of integrating organizational units along a supply chain and coordinating materials, information, and financial flows in order to fulfill the demands of the ultimate customer with the aim of improving competitiveness of a supply chain as a whole."*

2.2 Research Publications

There exists a vast literature in archival research journals on topics related to logistics and supply chains. The following table summarizes the number of research publications reported by Scirus for various key words in April 2002. For comparison purposes the number of research publications related to topics in material handling are also shown.

Table 1 Count of Research Publications by Topic

Topic	# Research Articles
supply chain	14638
supply chain design	1215
supply chain modeling	326
global supply chain	972
global supply chain design	698
global supply chain modeling	188
supply chain management	692
logistics	6045
global logistics	35
global logistics modeling	12
material handling (excl. ergonomics, injury)	1239
material handling design	852
material handling modeling	208
facilities design	162
facilities layout	62
facilities design modeling	15
warehousing (excl. data warehousing)	191
warehousing design	91
warehousing modeling	15

Several observations can be made based on these frequency data. For all of the topic areas, there is significant decrease in the number of articles when narrowing the search from the general description of the system, to design of the system, and then to modeling of the system. A qualitative, general treatment or analysis are much more popular with researchers than design of the system. Second, design of the system based on mathematical modeling techniques is described even less often. A third observation is that global (or international) supply chains are much less researched than single-country or domestic supply chains.

2 Global Supply Chain Models

2.1 Use of Models in Supply Chain Design

Models are primarily used for assistance in making decisions regarding complex systems. Models can be classified as being either descriptive or normative. The prime example of descriptive models for material handling systems and supply chains is digital simulation. Ballou and Masters (1993) surveyed developers and practitioners in the logistics and supply chain industry to determine the most important characteristics of and the state of the art in decision support systems for supply chain design. They found that model features and user friendliness were the most important characteristics of the models and design packages. Ballou and Masters (1999) repeated the survey six years later and observed that advances in computer hardware and software had allowed real-world strategic supply chain systems design projects to be completed using mathematical models that were incorporated in commercial software packages. They reported that specialized and efficient algorithms had been developed to solve the spatial or geographical location aspect of supply chain systems, but that specialized or general-purpose simulation models are used for the temporal aspects such as tactical inventory and production planning. Few models combine or integrate the spatial and temporal aspects of the supply chain. Based on a survey of active models and software packages, they found that the models are becoming more comprehensive and are beginning to include some tactical aspects. Global characteristics such as taxes, duties and tariffs, and exchange rates are included in only a few models. They reported that linear programming (LP), mixed-integer programming (MIP), and heuristics are the most commonly used techniques to find solutions. In the survey the practitioners responded with a large majority that modeling was used to configure their supply chain. In contrast with the 1993 result, in 1999 the practitioners ranked the optimality of the solution as the most important characteristic of the software. According to the practitioners, the best features of the models were their ability to represent the real-world system and to find an effective configuration. The worst features were the difficulty in obtaining the necessary data, the complexity of using the model, and the poor treatment of inventory costs, especially in connection to customer service levels. Finally, the authors observed that a consolidation trend is reducing the number of models and software applications.

The remainder of this paper will focus on normative models, whose results specify what the corporation should do in order to optimize a certain objective and are often called optimization models.

2.1 Model Taxonomy

The difficulty of developing an accurate normative model of the supply chain or a solution algorithm depends on many factors, but the following four factors appear to dominate.

1. The level of decisions made by the model. Decisions are typically divided into strategic, tactical, and operational depending on what are the decision variables and constraints, the permanence of the decisions, and the frequency and importance of the decisions. The level of difficulty increases from operational to strategic.

2. The scope and scale of the model. The scope is based on the number and interactions of commodities, the number of echelons or stages in the supply chain, and the number of periods in the planning horizon. The scale is based on the number of supplier, transformation, and customer facilities and transportation channels. Obviously a larger scope or larger number of logistics objects increases the level of difficulty in collecting the data and finding an "optimized" solution.
3. The number of different countries or trading associations included in the model. While this factor could be included in the previous scope factor, the significant increase in complexity when more than one sovereign government, taxing authority, and currency are involved warrants a separate factor.
4. The degree of uncertainty explicitly incorporated into the model. Any planning model will involve the forecasting of future values of parameters, such as demand, yield, costs, and exchange rates. Deterministic models are then based on a single value for each parameter, most often the mean value. Stochastic models explicitly incorporate multiple values each with their own probability or probability distributions. A common subclass of stochastic models employs scenario analysis. One can think of deterministic models as stochastic models with a single scenario. The level of difficulty increases significantly with the number of scenarios.

2.2 Model Characteristics

A summary of the various objectives, logistics components, and constraints present in models for the strategic configuration of global supply chains is shown in the next table. This table has changed and continues to evolve with the inclusion of new factors and publications. Previous or alternative versions have appeared among others in Vidal and Goetschalckx (1997) and Goetschalckx (2001).

Several observations can be made based on the characteristics of the models as presented in the next two tables. For domestic models, there is a trend for the models to become more comprehensive by including more costs, constraints, or logistics objects. The models are also fairly consistent in the factors, components, and costs that are incorporated. Those two observations do not hold for international or global models. Features included in an earlier model may not be repeated in later models. For both types of models, deterministic cost minimization and profit maximization are mostly used. Objectives such as supply chain flexibility or robustness are not used. The sole exception is the paper by Arntzen et al. (1995), which includes an inventory minimization objective as a surrogate for supply chain responsiveness.

Table 2. Domestic Characteristics of Supply Chain Models

Factors	Cohen, JMOM, 1989	Cohen, EJOR, 1991	Arntzen, Interfac., 1995	Canel, IJPR, 1997	Dogan, IIE TR, 1999	Vidal, EJOR, 2000	Philpott. Appita J., 2001
Single-Country (Domestic) Characteristics							
Objective							
Cost minimization		x	x	-	x	-	-
Profit maximization	x	-		x	-	x	x
Inventory minimization		-	x	-	-	-	-
Cost Variance Minimization		-		-	-	-	-
Costs							
Materials	x	x	x	x	x	x	x
Production	x	x	x	x	x	x	x
Distribution	x	x		-	x	x	x
Internal Transportation	x	x		x	x	x	-
External Transportation (Suppliers and Customers)		x	x	x	x	x	x
Inventory		-	x	-	x	-	-
Sales Revenue (Negative Cost)	x	-		x	-	x	x
Fixed Transformation Facility	x	-	x	x	x	x	-
Fixed Distribution Facility	x	-			x	x	
Fixed Machine		-		x	x	-	x
Fixed Product-Mix		x		-	-	-	x
Fixed Vendor-Use	x	-		-	-	-	-
	Cohen, JMOM, 1989	Cohen, EJOR, 1991	Arntzen, Interfac., 1995	Canel, IJPR, 1997	Dogan, IIE TR, 1999	Vidal, EJOR, 2000	Philpott. Appita J., 2001
Decisions							
Supplier-Facility (Purchasing)	x	x	x	x	x	x	x
Product-Transformer (Production)	x	x	x	x	x	x	-
Product-Machine (Production)		-	x	-	x	-	x
Product-Mix-Machine (Production)		-		-	-	-	x
Transformer-Customers (Distribution)	x	x	x	x	x	x	x
Machine-Customers (Distribution)		-		-	x	x	x
Tactical Inventory Levels		-	x	-	x	-	-
Dynamic Facility Status (more than one change)		-		-	-	-	-
Components							
Countries	M	1	M	M	1	M	1
Products	M	M	M	1	M	M	M
Bill of Material Levels	3	2		1	1	2	2
Suppliers	M	M	M	M	M	M	M
Machines & Technologies		-		-	M	-	M
Transformation Facilities	M	M	M	M	M	M	M
Distribution Facilities	M	M	M		M	M	-
Customers	M	-	M	M	M	M	M
Transportation Modes		1		1	M	M	2
Echelons		1		1	M	M	1
Constraints							
Production Capacities	x	x	x	-	x	x	x
Supply Capacities	x	x		-	x	x	x
Sales Upper Bound by Demand	x	-		-	-	x	x
Demand Satisfaction		x	x	x	x	-	-
Transportation Capacities		-		-	-	-	-
Planning Horizon							
Strategic Periods	1	1	M	M	1	1	1
Inflation Rate		-		-	-	-	-
Monetary Discount Rate		-		-	-	-	-
Tactical Periods		-		-	3	-	-
Response time		-	x	-	-	-	-
Order Fill Rate		-		-	-	-	-
Chain Flexibility		-		-	-	-	-

The number of echelons is defined as the number of transformation facilities between the suppliers and customers without distinguishing between manufacturing and distribution transformation facilities, i.e., a supplier-manufacturer-distributor-customer supply chain is said to have two echelons. Cohen and Moon (1991) include economies of scale and scope for production costs, which yields concave production costs.

Table 3. Global Characteristics of Supply Chain Models

	Cohen, JMOM, 1989	Cohen, EJOR, 1991	Arntzen, Interfac., 1995	Canel, IJPR, 1997	Dogan, IIE TR, 1999	Vidal, EJOR, 2000	Philpott. Appita J., 2001
Multiple-Country (Global) Characteristics							
Objectives							
Global After-Tax Profit Maximization	x			x		x	
International Costs							
Country-Specific Tax Rates	x		x	x		x	
Tariffs			x	x		x	
Duties			x	-		x	
Export Incentives (Negative Cost)			x	x		-	
Transfer Prices or Markups				x		x	
Decisions							
Transfer Prices or Markups	x			-		x	
Transportation Cost Allocation	x			-		x	
International Constraints							
Local Content / Manufacturing Offset	x		x	-		-	
Minimum Taxes per Country	x			-		x	
International Factors							
Exchange Rates	x			x		x	

2.3 Stochastic Formulation of the Global Supply Chain Design Problem

While there is considerable variation in the models published in the literature, there is much more agreement on what the desired global supply chain design model should contain. The model has to be comprehensive, able to deal with uncertainty, and include flexibility, robustness, and responsiveness in addition to the traditional economic objectives in the objective function. A verbal specification of such a model is given next.

Maximize The expected value of the sum of the global after-tax time-discounted yearly profits in the reference currency of the corporation

Subject to: For every planning period:

Expressions for the net income before taxes of the activities of the corporation
Expressions for the after tax profit in each country
Suppliers' capacity
Production capacity at manufacturing plants and distribution centers
Transportation capacity of the transportation channels and modes
Customer demand constraints
Bill of materials and flow balance constraints at the facilities, for manufacturing lines, and in the transportation channels
Minimum profit for subsidiaries on a country basis
Linkage constraints between manufacturing lines and facilities and between material flows and facilities and transportation channels
Bounds on transfer prices and general bounds on decision variables

The net income before taxes consists of the difference between the sales price to either the final customer or a downstream subsidiary minus the total cost, which includes operating and acquisition costs. The total cost on a country and planning period basis is defined as:

Total Cost = Supply cost + Fixed manufacturing cost + Variable manufacturing cost + Fixed facility operating cost + Variable facility operating cost + Warehousing cost + Cycle inventory cost at the facilities + Pipeline inventory cost + Safety inventory cost + Inventory carry-over cost between periods + Transportation cost + Duties and Tariffs

Several major challenges are associated with the above model. The first one is the large size of the formulation. The second is the presence of binary variables associated with configuration of the supply chain and with economies of scale and scope, which yield concave production costs. The third challenge is caused by requirement to model the complete production history of a product in order to capture the effects of duties, duty drawbacks, and local content laws. This typically leads to path-based optimization formulations, which are much larger than the corresponding arc-bases optimization models. The fourth challenge is related to the explicit treatment of uncertainty, which yields a stochastic optimization problem. The fifth challenge is caused by a lack of generally agreed upon definition and mathematical objective for flexibility of the supply chain.

2.4 Solution Algorithms

Geoffrion and Graves (1974) reported on the successful application of Benders decomposition to solve the classical multicommodity distribution system design problem with concave throughput costs at the distribution centers and customer single sourcing. A more recent application of Benders decomposition to distribution system design is given in Moon (1989), where the production cost are concave due to economies of scale and scope. He observes that Benders decomposition does not generate good solutions efficiently unless the dual prices in the Benders cuts are adjusted based on the problem structure. This observation is consistent with the findings in Dogan and Goetschalckx (1999) that a generic application of Benders decomposition does not yield high quality solutions efficiently, but that a careful enhancement of the dual variables based on problem structure is required. Such strengthening of the dual variables requires advanced expertise in mathematical programming that is not available to the casual user of optimization software. Similarly, Geoffrion and Powers (1995) report that Benders decomposition is being removed from strategic supply chain design software because of the difficulty of implementation and usage.

The common thread among these and other successful applications of model-based strategic supply chain design is the sustained effort of a group of highly specialized designers, who exploited the structure of the problem to generate a formulation of acceptable size and degree of realism and a solution algorithm that had an acceptable computation time.

2.5 Commercial Models and Algorithms

In the last two decades, several companies have developed Enterprise Resource Planning (ERP) systems in response to the need of global corporations to plan their entire supply chain. Two major examples of such software vendors are Baan and SAP. ERP systems integrate the data of one or more principal business functions such as accounting, human resources, production planning, and sales. In their initial implementations, the ERP systems were primarily used for the recording of transactions rather than for the planning of resources on an enterprise-wide scale. Their main advantage was to provide consistent, up-to-date, and accessible data to the enterprise.

In recent years, the original ERP systems have been extended with Advanced Planning Systems (APS). The main function of APS is for the first time the planning of enterprise-wide resources and actions. *"The goal of APS is to find feasible, near-optimal plans across the supply chain as whole, while potential bottlenecks are considered explicitly,"* Stadtler and Kilger (2000). This implies a coordination of the plans among several organizations and geographically dispersed locations. APS are responsible for planning, while an ERP system is still required as a transaction and execution system. APS use or extract data stored in the ERP to support algorithm-based decision-making and then store the plans back into the ERP. APS do not substitute for ERP but supplement existing ERP systems.

APS typically comprise several planning modules ranging from strategic network planning, through intermediate demand planning and master planning, to operational material requirements planning (MRP), production planning, distribution planning (DRP), and transportation planning. At the current time, the major emphasis in APS is on the operational planning and execution levels. The strategic planning modules are still in their infancy in current implementations. The organization of the various planning modules in supply chain planning and the relations between them are shown in Figure 2. More details on the hierarchy of planning tasks and on APS can be found in Stadtler and Kilger (2000). Software to plan the supply chain that has been created outside the ERP system many times is called Supply Chain Management (SCM) software.

Strategic	Stratetic Enterprise Planning			Strategic Demand Planning
Tactical	Master Production and Distribution Planning			Tactical Demand Planning
Operational	Material Requirem. Planning	Production Planning	Distribution Planning	Operational Demand Planning
Execution	Purchasing	Scheduling	Vehicle Dispatching	Demand Monitoring

Figure 2. Organization of Supply Chain Planning Modules

The individual planning tasks in an APS constitute in themselves very difficult planning problems. Sophisticated optimization algorithms, such as mixed integer programming (MIP), constraint programming techniques and heuristic algorithms may be used. Since decisions are made at different times, by different decision makers, and in different locations, no single integrated and comprehensive planning model and corresponding planning algorithm exist. Most often, the overall planning task is solved using hierarchical decomposition or hierarchical planning.

Examples of major software houses offering APS or SCM are Baan, I2, Manugistics, J.D. Edwards, and SAP. Several of these companies also provide the ERP system, while others rely on third-party ERP systems. The modules in these APS, their capabilities and functionalities change continuously and dramatically. Many times, the only available information is based on marketing and promotional materials provided by the software vendors. The detailed assumptions, constraints, and objectives of the strategic models and algorithms are particularly hard to determine.

Anderson Consulting, in cooperation with the Council of Logistics Management (CLM), annually compiles a database of software packages used for the planning and scheduling of logistics operations, see Haverly and Whelan (2000) for a recent edition.

Conclusions

There will always exist a tradeoff between model solvability and model realism used for strategic network design. The more realistic the model is, the more resources have to be allocated for model development and validation, data collection and validation, model maintenance, and model solving. Since all models involve some level of abstraction, approximations, and assumptions, the results of the models should always be interpreted carefully with common (engineering) sense. Different models with different levels of detail and realism are appropriate and useful at different stages of the design process. Systematically increasing the level of model complexity for the same problem and evaluating their solutions and their consistency provides a way to, at least partially, validate the models.

The more complex the real world system is, the more approximate any model will become. Models used to assist in strategic decision-making are infamous for not capturing many of the real world factors and subjective influences. Such strategic models should only be used as decision support tools for the design team. A healthy skepticism with respect to the results of any model is required. Just because a computer model specifies a particular decision, does not imply that this is the best decision for the real world system.

At the current time three factors continue to make models for the design of global supply chains complex, very large, and very difficult to solve to optimality. The first factor consists of the complications created by taxation, duties, tariffs, and local content rules and regulations that create a non-homogeneous domain for the supply chain. For example, a realized profit may not have the same value because of different tax rates, or the value of an otherwise identical product may be different depending on its country of origin. Corporations in the short run can only respond to these regulations by varying either the materials flows in the supply chain or by changing the transfer prices. Models for these global supply chains will require more variables to keep track of the products that are now differentiated by their complete production history. Incorporating transfer prices leads to non-linear models that are much harder to solve than the corresponding mixed-integer linear models. The second factor is the increasing velocity of the supply chain and the decreasing life cycle of the products, which have become even more constraining because of the inherent greater length in distance and time of global supply chains. A product may go from introduction, to demand exceeding capacity, to being phased out in a time span of six months. This implies that supply chain models have to incorporate more and more tactical and even operational features. The most important among them is the incorporation of pipeline, cycle, and safety inventory. The third factor is the requirement that global supply chains at the same time should be efficient for the current set of economic conditions but also flexible and robust enough so that the chain can resist sudden chocks and changes and can adapt to constantly changing products, customers, and suppliers.

Models that incorporate all these features will tend to be complex and most likely will no longer have the standard linear mixed-integer structure. Specialized solution algorithms and heuristics will have to be developed to solve these models in a reasonable amount of computing time. At the same time corporations have come to realize that small deviations from optimality can result in significant financial consequences and are demanding more and more optimal solutions.

The increasing complexity of the models, the demand for near-optimal solutions, and the complexity of the solution algorithms to achieve acceptable solution times, all require a high level of technical expertise in model development and solution algorithm execution. Even the ever increasing processing speeds and growing memory capacity of computers will not be sufficient to allow the use of standard non-specialized solution techniques. Very few organizations will have the technical expertise to build and solve their own models, but most will rely on third parties to provide them with this service.

To remain competitive global corporations need a methodology to evaluate and efficiently configure global logistics systems in a short amount of time. While at the current time, there exist several comprehensive models and solution algorithms for the design of single-country or domestic logistics systems, such methodology does not appear to exist for global logistics systems. The development of such a methodology poses a significant challenge to researchers both from the methodological as from the applied point of view.

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