



# Supply chain modeling: past, present and future

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## Abstract

Over the years, most of the firms have focused their attention to the effectiveness and efficiency of separate business functions. As a new way of doing business, however, a growing number of firms have begun to realize the strategic importance of planning, controlling, and designing a supply chain as a whole. In an effort to help firms capture the synergy of inter-functional and inter-organizational integration and coordination across the supply chain and to subsequently make better supply chain decisions, this paper synthesizes past supply chain modeling efforts and identifies key challenges and opportunities associated with supply chain modeling. We also provide various guidelines for the successful development and implementation of supply chain models. © 2002 Elsevier Science Ltd. All rights reserved.

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## 1. Background

In today's global marketplace, individual firms no longer compete as independent entities with unique brand names, but rather as integral part of supply chain links. As such, the ultimate success of a firm will depend on its managerial ability to integrate and coordinate the intricate network of business relationships among supply chain members (Drucker, 1998; Lambert & Cooper, 2000). A supply chain is referred to as an *integrated system* which synchronizes a series of inter-related business processes in order to: (1) acquire raw materials and parts; (2) transform these raw materials and parts into finished products; (3) add value to these products; (4) distribute and promote these products to either retailers or customers; (5) facilitate information exchange among various business entities (e.g. suppliers,

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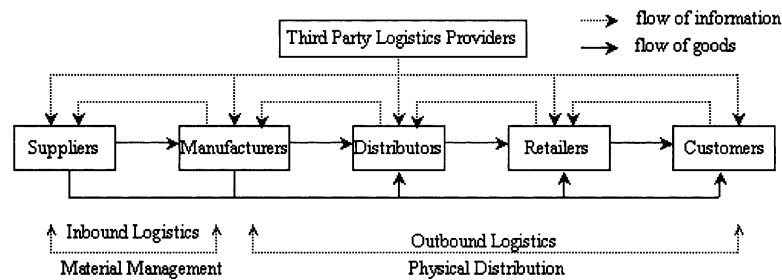


Fig. 1. The supply chain process.

manufacturers, distributors, third-party logistics providers, and retailers). Its main objective is to enhance the operational efficiency, profitability and competitive position of a firm and its supply chain partners. More concisely, supply chain management is defined as ‘the integration of key business processes from end-users through original suppliers that provide products, services, and information and add value for customers and other stakeholders’ (Cooper, Lambert, & Pagh, 1997b, p. 2). A supply chain is characterized by a forward flow of goods and a backward flow of information as shown by Fig. 1.

Typically, a supply chain is comprised of two main business processes:

- material management (inbound logistics);
- physical distribution (outbound logistics).

Material management is concerned with the acquisition and storage of raw materials, parts, and supplies. To elaborate, material management supports the complete cycle of material flow from the purchase and internal control of production materials to the planning and control of work-in-process, to the warehousing, shipping, and distribution of finished products (Johnson & Malucci, 1999). On the other hand, physical distribution encompasses all outbound logistics activities related to providing customer service. These activities include order receipt and processing, inventory deployment, storage and handling, outbound transportation, consolidation, pricing, promotional support, returned product handling, and life-cycle support (Bowersox & Closs, 1996). Combining the activities of material management and physical distribution, a supply chain does not merely represent a linear chain of one-on-one business relationships, but a web of multiple business networks and relationships. Along a supply chain, there may be multiple stakeholders comprised of various suppliers, manufacturers, distributors, third-party logistics providers, retailers, and customers.

In a nutshell, a concept of supply chain management is evolved around a customer-focused corporate vision, which drives changes throughout a firm’s internal and external linkages and then captures the synergy of inter-functional, inter-organizational integration and coordination. Herein, integration does not entail merger/acquisition or equity of the ownership of other organizations. The successful integration of the entire supply chain process, however, depends heavily on the availability of accurate and timely information that can be shared by all members of the supply chain. Considering that supply chain models enable management to access such information, the main purposes of this paper are threefold: (1) to identify key issues that should be addressed by supply chain models; (2) to determine key elements that should be included in supply chain models; (3) to provide perspectives on future efforts of supply chain modeling.

## 2. The main scope of supply chain modeling

Considering the broad spectrum of a supply chain, no model can capture all aspects of supply chain processes. To compromise the dilemma between model complexity and reality, a model builder should define the scope of the supply chain model in such a way that it is reflective of key real-world dimensions, yet not too complicated to solve. Although there is no systematic way of defining the scope of a ‘firm-specific’ supply chain problem, we may follow a simple guideline proposed by Chopra and Meindl (2001) and Stevens (1989). This guideline is based on the three levels of decision hierarchy: (1) competitive strategy; (2) tactical plans; (3) operational routines. The classes of supply chain problems encountered in competitive strategic analysis include location-allocation decisions, demand planning, distribution channel planning, strategic alliances, new product development, outsourcing, supplier selection, information technology (IT) selection, pricing, and network restructuring. Although most supply chain issues are strategic by nature, there are also some tactical problems. These include inventory control, production/distribution coordination, order/freight consolidation, material handling, equipment selection, and layout design. The problems encountered when dealing with operational routines include vehicle routing/scheduling, workforce scheduling, record keeping, and packaging. It should be noted that the aforementioned distinctions are not always clear, because some supply chain problems may involve hierarchical, multi-echelon planning that overlap different decision levels.

Regardless, such a guideline would help a model builder determine the breadth of the problem scope and the length of supply chain planning horizons.

Another guideline to follow is the three structures of a supply chain network suggested by Cooper et al. (1997b). These structures are: (1) the type of a supply chain partnership; (2) the structural dimensions of a supply chain network; (3) the characteristics of process links among supply chain partners.

### 2.1. The type of a supply chain partnership

When structuring a supply chain network, it is necessary to identify who the partners of the supply chain are. Yet, an inclusion of all potential partners may complicate the total network, since it may explode the number of partners added from one tier level to another (Cooper, Ellram, Gardner, & Hank, 1997a). The key is to identify the type of the partners who are critical to the value-added activities and determine a manageable number of the supply chain partners given resources.

Lambert, Cooper, and Pagh (1998) classified supply chain partners into two distinctive types: primary and secondary partners. In general, the primary partners are those autonomous channel captains or strategic business units which actually perform operational and/or managerial activities designed to create a specific product or service for a particular customer or market. These primary partners can be manufacturers such as *Dell* or mass-merchants such as *Wal-Mart*. In contrast, supporting partners are companies that simply provide resources (e.g. assets, application software, real-estate property), knowledge, and utility for the supply chain. These supporting partners can be transportation carriers, consulting firms, third-party logistics providers, IT service providers, on-line brokers, and educational institutions. The categories are not exclusive, however, as a firm can be both a primary and a supportive partner of the supply chain, performing primary activities related to one process and supportive activities related to another process.

Although the distinction between primary and supporting supply chain partners is not obvious in all cases, it allows the firm to define who the furthest upstream and downstream members of the supply

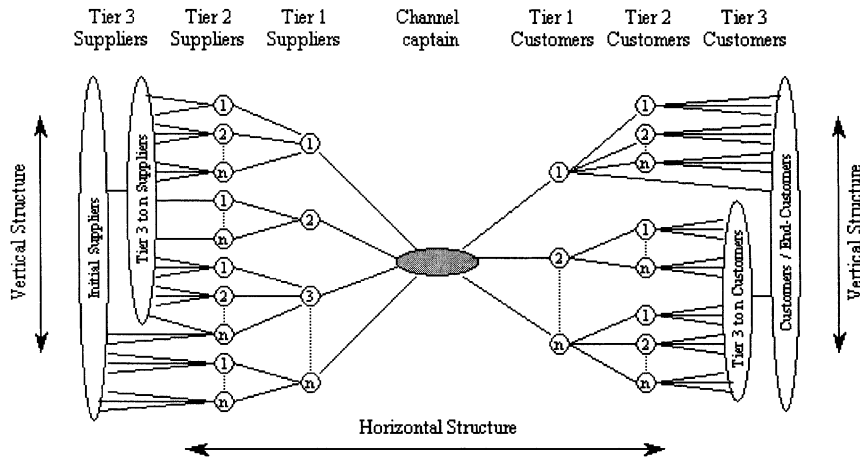


Fig. 2. Supply chain network structure [Source: Adapted from Lambert et al. (1998)].

chain are and identify where customer demand actually starts. The furthest upstream members of the supply chain typically represent supporting partners, while the furthest downstream represents the end of the supply chain where no further value is added, and the product and/or service is consumed. The furthest downstream (or point of consumption) may coincide with a 'value offering point' (VOP) where a customer allocates demand to his/her upstream supply chain partner (e.g. retailer, distributor, manufacturer). According to Holmstrom, Hoover, Eloranta, and Vasara (1999), VOP determines how and when customer demand is triggered to upstream supply chain partners and defines the economics of the customer (i.e. the tradeoff between value creation and transaction costs). Such a clarification of the supply chain network eventually helps a model builder understand whose decisions the model should aid and what scope of the supply chain problem should be addressed. For greater detail of the types of supply chain partnerships, the interested reader should refer to Lambert, Emmelhainz, and Gardner (1996).

## 2.2. Structural dimensions of the supply chain network

Understanding the structural dimensions of a supply chain is a pre-requisite for analyzing and modeling the supply chain link. In general, there are two structural dimensions: horizontal and vertical structure. The horizontal structure refers to the number of tiers across the supply chain. The supply chain may be lengthy, with numerous tiers, or short, with a few tiers. The vertical structure refers to the number of suppliers and customers represented within each tier as shown in Fig. 2 (Lambert et al., 1998).

As such, an increase or reduction in the number of suppliers and/or customers will alter the dimension of the supply chain. For example, as some companies make strategic moves toward either supply base reduction or customer selectivity, the supply chain becomes narrower. Outsourcing (inclusion of third-party logistics providers) or functional spin-offs will also alter the supply chain dimension by lengthening and widening the supply chain. Although the supply chain dimension is somewhat arbitrary and ambiguous, it is still important for a model builder to understand the key boundaries of a supply chain network and then determine which aspects (or ranges) of the supply chain network should be modeled.

### 2.3. Characteristics of supply chain links

Porter (1985) stressed the strategic importance of linkages among supply chain activities, since the linkages could lead to competitive advantages. To fully exploit the benefits of such linkages, a firm should understand specific characteristics of linkages (or links) that it is connected to. Lambert et al. (1998) identified four distinctive characteristics of supply chain links: (1) managed business process links, (2) monitored business process links, (3) not managed business process links, and (4) non-member business links.

*Managed process links* are the ones where the firm (typically a primary supply chain partner or a channel captain) integrates a supply chain process with one or more customers/suppliers. These links may connect multi-tier supply chain partners as the firm is actively involved in the management of tier one and a number of other links beyond tier one. Due to its direct involvement, the firm may allocate resources (e.g. manpower, equipment, technology, know-how) to its partners and share information with them. *Monitored process links* are not fully controlled by a firm (typically a primary supply chain partner), but the firm is involved in monitoring or auditing how the link is integrated and managed. *Not-managed process links* are the ones that the firm neither actively manages, nor monitors. In these links, the firm fully trusts its partners' ability to manage the process links appropriately and consequently leaves the management responsibility up to them. *Non-member process links* are the ones between both partners and non-members of the company's supply chain. Such links are not integral parts of the firm's supply chain structure, but can dictate the performance of the firm. Additionally, different characteristics of supply chain links affect the firm's allocation of resources and the subsequent supply chain planning and modeling. Therefore, those characteristics should be factored into supply chain modeling process.

## 3. Key components of supply chain modeling

Without knowing which essential components of a supply chain must be managed, one cannot establish specific supply chain goals (or visions). Absence of specific goals, in turn, means difficulty in developing appropriate performance measures that can be targeted or benchmarked by a supply chain partner. Since a performance measure dictates the desired outcome of the supply chain model, it is very important for a model builder to identify key components of a supply chain. Although those components may differ from one company to another, we offer some examples of those.

### 3.1. Supply chain drivers

Goal setting will be the first step of supply chain modeling. To set the supply chain goals, a model builder first needs to figure out what will be the major driving forces (drivers) behind the supply chain linkages. These drivers include customer service initiatives, monetary value, information/knowledge transactions, and risk elements.

#### 3.1.1. Customer service initiatives

Though difficult to quantify, the ultimate goal of a supply chain is customer satisfaction. Put simply, customer satisfaction is the degree to which customers are satisfied with the product and/or service received. The following list represents typical service elements in a supply chain.

- *Product availability.* Due to random fluctuations in the demand pattern, downstream supply chain members often fail to meet the real-time needs of customers. Thus, a supply chain model should reflect service performance measures such as inventory days of supply, an order fill rate (a percentage of customer orders that were filled on time), and an ‘order-accuracy’ rate (a percentage of items delivered in the right quantities, complete documentation, and correct configurations required by customers).
- *Response time.* Response time represents an important indicator of the supply chain flexibility. Examples of response time include time-to-market, on-time delivery (a percentage of a match between the promised product delivery date and the actual product delivery date), order processing time (the amount of time required from the time an order is placed until the time the order is received by the customer), transit time (duration between the time of shipment and the time of receipt), cash-to-cash cycle time (the amount of time required from the time a product has begun its manufacturing until the time it is completely sold and this metric is an indicator of how quickly customers pay their bills), and downtime (a percentage of time resources that are not operational due to maintenance and repair).

### 3.1.2. Monetary value

The monetary value is generally defined as a ratio of revenue to total cost. A supply chain can enhance its monetary value through increasing sales revenue, market share, and labor productivity, while reducing expenditures, defects, and duplication. Since such value directly reflects the cost efficiency and profitability of supply chain activities, this is the most widely used objective function of a supply chain model. More specifically, the monetary value is categorized as:

- *Asset utilization.* Asset utilization can be estimated by several different metrics such as net asset turns (a ratio of total gross revenue to working capital), inventory turns (a ratio of annual cost of goods sold to average inventory investment), and cube utilization (a ratio of space occupied to space available).
- *Return-on-investment (ROI).* This is a typical financial measure determining the true value of an investment. Its measure includes the ratio of net profit to capital that was employed to produce that profit, or the ratio of earnings in direct proportion to an investment.
- *Cost behavior.* In the supply chain framework, cost management requires a broad focus, external to the firm. Thus, cost may be viewed as a function of strategic choices of the firm’s competitive position, rather than a function of output volume (Shank & Govindarajan, 1993). In other words, a traditional cost classification (fixed versus variable cost), which works at the single firm level, may not make sense for the supply chain network affected by multiple cost drivers (e.g. scope, scale). An alternative cost management principle for a supply chain framework includes activity-based costing (ABC), target costing, and cost of quality (COQ). Since the application of the aforementioned cost management principles to the supply chain is still at the evolutionary stage, most of the model development efforts to date have been based on traditional cost measures such as inventory carrying cost, inventory ordering cost, transportation cost, and product return cost.

### 3.1.3. Information/knowledge transactions

Information serves as the connection between the various phases of a supply chain, allowing supply chain partners to coordinate their actions and increase inventory visibility (Chopra & Meindl, 2001).

Therefore, successful supply chain integration depends on the supply chain partners' ability to synchronize and share 'real-time' information. Such information encompasses data, technology, know-how, designs, specifications, samples, client lists, prices, customer profiles, sales forecasts, and order history.

- *Real-time communication.* The establishment of collaborative relationships among supply chain partners is a pre-requisite to information sharing. Collaborative relationships cannot be built without mutual trust among supply chain partners and technical platforms (e.g. the Internet, electronic data interchange (EDI), extensible markup language, enterprise resource planning (ERP), warehouse management systems (WMS)) for information transactions. The effectiveness of real-time communication hinges on the supply chain partners' organizational compatibility, which facilitates mutual trust, and technical compatibility, which solidifies electronic links among supply chain partners. Since organizational and technical compatibilities are hard to measure, some surrogate metrics such as the rate of EDI transactions (a percentage of orders received via EDI) and the percent of suppliers accepting electronic orders/payment can be used.
- *Technology transfers.* The collaboration fostered by supply chain partners can be a catalyst for the research and development (R&D) process throughout the supply chain. The rationale is that a firm, which initiated technology development, can pass its technology or innovative know-how to its supply chain partners thereby saving R&D cost and time. Therefore, a successful transfer of technology can help supply chain partners enhance their overall profitability.

#### 3.1.4. Risk elements

The important leverage gained from the supply chain integration is the mitigation of risk. In the supply chain framework, a single supply chain member does not have to stretch beyond its core competency, since it can pool the resources shared with other supply chain partners. On the other hand, a supply chain can pose greater risk of failure due to its inherent complexity and volatility. Braithwaite and Hall (1999) noted that a supply chain would be a veritable hive of risks, unless information is synchronized, time is compressed, and tensions among supply chain members are recognized. They also observed that supply chain risks (emanating from sources external to the firm) would be always greater than risks which arose internally, as less was known about them. Thus, a model builder needs to profile the potential risks involved in supply chain activities. The following list summarizes such profiles.

- *Risk of quality failure.* As illustrated by the recent recall of 6.5 million *Firestone* tires that are susceptible to tread separation in harsh driving conditions, the consequences of failing to assure quality failure at the upstream supply chain can be enormous. This is due to the inter-dependence of supply chain partners. Similarly, order picking errors and failures to schedule adherence should be prevented at the furthest upstream supply chain (if possible, at the initial source of supply).
- *Risk of information failure.* One of the well-known consequences of information failure in the supply chain is a bullwhip effect where orders at the upstream supply chain members tend to exaggerate the true consumption of end-customers (Lee, Padmanabhan, & Whang, 1997; Min, 2000). Since the bullwhip effect will create phantom demand and the subsequent overproduction and overstock, its risks should be factored into the supply chain models. One way of reducing such risks is to postpone the final assembly, branding, purchasing, packaging and shipment of products until they are needed.

### 3.2. Supply chain constraints

Supply chain constraints represent restrictions (or limitations) placed on a range of decision alternatives that the firm can choose. Thus, they determine the feasibility of some decision alternatives. These constraints include:

- *Capacity.* The supply chain member's financial, production, supply, and technical (EDI or bar coding) capability determines its desired outcome in terms of the level of inventory, production, workforce, capital investment, outsourcing, and IT adoption. This capacity also includes the available space for inventory stocking and manufacturing.
- *Service compliance.* Since the ultimate goal of a supply chain is to meet or exceed customer service requirements, this may be one of the most important constraints to satisfy. Typical examples are delivery time windows, manufacturing due dates, maximum holding time for backorders, and the number of driving hours for truck drivers.
- *The extent of demand.* The vertical integration of a supply chain is intended to balance the capacity of supply at the preceding stage against the extent of consumption (i.e. demand) of the downstream supply chain members at the succeeding stage. Thus, this constraint can be added to the supply chain model.

### 3.3. Supply chain decision variables

Since decision variables generally set the limits on the range of decision outcomes, they are functionally related to supply chain performances. Thus, the performance measures (or objectives) of a supply chain are generally expressed as functions of one or more decision variables. Though not exhaustive, the following illustrates these decision variables:

- *Location.* This type of variable involves determining where plants, warehouses (or distribution centers (DCs)), consolidation points, and sources of supply should be located.
- *Allocation.* This type of variable determines which warehouses (or DCs), plants, and consolidation points should serve which customers, market segments, and suppliers.
- *Network structuring.* This type of variable involves centralization or decentralization of a distribution network and determines which combination of suppliers, plants, warehouses, and consolidation points should be utilized or phased-out. This type of variable may also involve the exact timing of expansion or elimination of manufacturing or distribution facilities.
- *Number of facilities and equipment.* This type of variable determines how many plants, warehouses, and consolidation points are needed to meet the needs of customers and market segments. This type of variable may also determine how many lift trucks are required for material handling.
- *Number of stages (echelons).* This variable determines the number of stages that will comprise a supply chain. This variable may involve either increasing or decreasing the level of horizontal supply chain integration by combining or separating stages.
- *Service sequence.* This variable determines delivery or pickup routes and schedules of vehicles serving customers or suppliers.
- *Volume.* This variable includes the optimal purchasing volume, production, and shipping volume at each node (e.g. a supplier, a manufacturer, a distributor) of a supply chain.



- *Inventory level*. This variable determines the optimal amount of every raw material, part, work-in-process, finished product and stock-keeping unit (SKU) to be stored at each supply chain stage.
- *Size of workforce*. This variable determines the number of truck drivers or order pickers needed for the system.
- *The extent of outsourcing*. This type of variable determines which suppliers, IT service providers, and third-party logistics providers should be used for long-term outsourcing contacts and how many (e.g. single versus multiple sourcing) of those should be utilized.

#### 4. Taxonomies of supply chain modeling

Considering a broad spectrum of the supply chain concept, there may be various classification schemes to categorize supply chain models. To minimize confusion, we first developed a taxonomy based on classical textbook guidelines to dichotomize the mathematical models: deterministic and stochastic (Beamon, 1998; Bradley, Hax, & Magnanti, 1977; Budnick, McLeavey, & Mojena, 1988; Hillier & Lieberman, 2001; Mentzer & Schuster, 1983). As noted by Budnick et al. (1988), Silver (1981) and Zipkin (2000), some supply chain models based on inventory theory and simulation contain both deterministic and stochastic elements and consequently should be treated as hybrids. Therefore, we added a hybrid model to the category. Another category called 'IT-driven models' was added to the taxonomy to reflect the current advances in IT for improving supply chain efficiency. These categories are somewhat different from the taxonomy developed by Beamon (1998) who did not report the evolution of IT-driven models. To elaborate, we classified supply chain models into four major categories: (1) deterministic (non-probabilistic); (2) stochastic (probabilistic); (3) hybrid; (4) IT-driven. Deterministic models assume that all the model parameters are known and fixed with certainty, whereas stochastic models take into account the uncertain and random parameters. Deterministic models are dichotomized as single objective and multiple objective models. This category was developed to reflect the increasing need to harmonize conflicting objectives of different supply chain partners. Stochastic models are sub-classified into optimal control theoretic and dynamic programming models. Notice that we excluded the categories of decision analysis and queuing models from stochastic models, because the literature indicates that supply chain models rarely used such techniques. Hybrid models have elements of both deterministic and stochastic models. These models include inventory-theoretic and simulation models that are capable of dealing with both certainty and uncertainty involving model parameters.

Shapiro (2001) recently observed that IT development was the major driving force for supply chain innovations and the subsequent re-engineering of the business process. Considering the proliferation of IT applications for supply chain modeling, we decided to add the category of IT-driven models to the taxonomy. IT-driven models aim to integrate and coordinate various phases of supply chain planning on a real-time basis using application software so that they can enhance visibility throughout the supply chain. These models include WMS, transportation management systems (TMS), integrated transportation tracking, collaborative planning and forecasting replenishment (CPFR), material requirement planning (MRP), distribution resource planning (DRP), ERP, and geographic information systems (GIS). Some of these models, such as WMS, CPFR, ERP and GIS, are gaining popularity due to their significant roles in facilitating information flow across the supply chain.

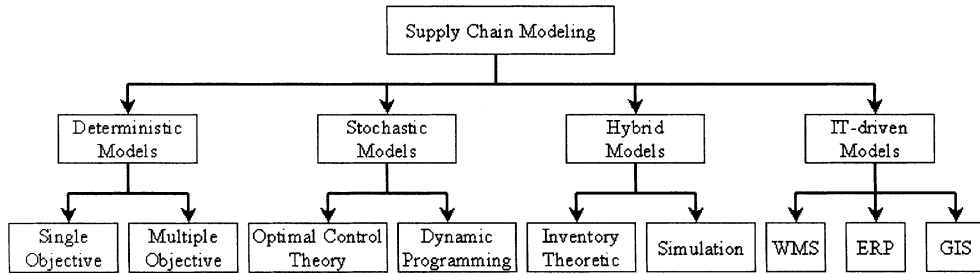


Fig. 3. Taxonomy of supply chain models.

A WMS generally refers to a series of computer software and hardware that integrate bar coding, radio frequency communication, cycle counting, and other warehouse-related operations to accelerate the flow of material and utilize space throughout the warehouse. WMS ultimately aims at reducing the stock in the supply chain, ensuring shorter lead times, and improving customer satisfaction. WMS can track and control the movement of inventory through the warehouse from receiving to shipping. WMS also gives users a current and accurate picture of the quantity, location, and age of inventory. Hence, without an effective WMS, the optimization of warehousing operations within the supply chain is nearly impossible. This optimization can be achieved by utilizing a WMS that enables the user to conduct any number of varying physical operations such as putaways, cross-docking, and cycle counting on a real-time basis (Alex, 2000).

CPFR is designed to link consumer demand with supply chain planning and execution by promoting a single, jointly owned demand plan and forecast throughout the entire supply chain (Ireland & Bruce, 2000). ERP employs a multi-module software for managing and controlling a broad set of supply chain activities including product planning, parts purchasing, inventory control, order tracking, and human resource planning (Swamidass, 2000). In other words, ERP acts as the central nervous system of an organization that manages every transaction involving the acquisition, movement, and storage of goods throughout the organization. The main intent of ERP is to increase the velocity of inventory throughout the supply chain. Along with WMS and CPFR, ERP is an important pre-requisite for successful collaboration among supply chain partners.

GIS simplifies the data display mechanism by separating data presentation from data storage and then allowing the model builder to visualize how distinctive one geographic site is from another by superimposing geographic information, such as population density, racial makeup, and temperature on a map. Combined with some database management system (DBMS), GIS may provide a friendly platform for the enhancement of dialogue among supply chain partners. Fig. 3 shows the taxonomies of supply chain modeling.

In addition to the taxonomy developed earlier based on the mathematical structure, supply chain models can also be classified into various frameworks with respect to their problem scope or application areas. We viewed the problem scope as a criterion for measuring the realistic dimensions of the model. Considering the inherent nature of supply chain problems that cut across functional boundaries, supply chain models involve making tradeoffs between more than one business process (function) within the supply chain. Therefore, only the models that attempt to integrate different functions of the supply chain are regarded as supply chain models. Such models deal with the multi-functional problems of location/routing, production/distribution, location/inventory control, inventory control/transportation, and

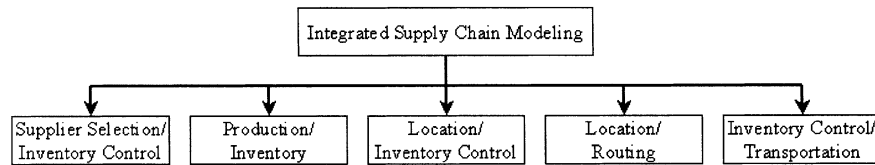


Fig. 4. Types of integrated supply chain models.

supplier selection/inventory control (Fig. 4). Interested readers may refer to Weber, Current, and Benton (1990) for a review of supplier selection problems, Min, Jayaraman, and Srisvastava (1998) for a review of location/routing models, and Erengüç, Simpson, and Vakharia (1999) for a review of production/distribution planning. Some of these models are also hierarchical in that they consider various phases (echelons) of supply chain planning. Within these frameworks, Section 4.1 seeks to summarize the evolution of supply chain models over the past several decades. Given the great availability of past studies on integrated modeling efforts, our review will focus primarily on studies that have been published since 1998 and can be viewed as important theoretical foundations for the evolution of analytical supply chain models. These theoretical foundations include new algorithmic developments and/or new mathematical formulations for supply chain problems. Also, we included past supply chain modeling efforts that are omitted by Beamon (1998), Ganeshan, Jack, Magazine, and Stephens (1999), Slats, Bhola, Evers, and Dijkhuizen (1995) and Thomas and Griffin (1996).

#### 4.1. Deterministic models

One of the earliest efforts to create an integrated supply chain model dates back to Glover, Jones, Karney, Klingman, and Mote (1979). They developed a computer-based production, distribution, and inventory (PDI) planning system that integrated three supply chain segments comprised of supply, storage/location, and customer demand planning. The core of the PDI system was a network model and diagram that increased the decision maker's insights into supply chain connectivity. The model, however, was confined to a single-period and single-objective problem.

Cohen and Lee (1989) developed a mixed-integer, non-linear, value-added chain model that coordinated the supply chain process comprised of sourcing, centralized production planning, and inter-plant transshipment. The model incorporated capacity, demand, and production constraints, but failed to capture risk factors inherent in a global setting.

Arntzen, Brown, Harrison, and Trafton (1995) presented a mixed-integer programming model, called global supply chain model (GSCM) which evaluated global supply chain alternatives involving multiple products and multiple stages (echelons). More specifically, GSCM took into account the interdependence of production, inventory and delivery processes to minimize activity days and costs associated with production, inventory, material handling, and transportation.

Ashayeri and Rongen (1997) refined a grid model and the multi-criteria solution method called *ELECTRE* to formulate the DC repositioning strategy based upon the analyses of material flows, DC locations, and throughput times. Although the proposed model and solution method were simple to use, they were confined to single-period and un-capacitated problems. Another multiple objective approach was proposed by Min and Melachrinoudis (1999) to configure multi-echelon supply chain networks connecting material flows among suppliers, manufacturers, break-bulk terminals, and customers. Their

analytic hierarchy process-based model also considers contingency planning associated with supply chain reconfiguration. It, however, did not consider multiple periods, capacity constraints and risk factors.

More recently, Melachrinoudis and Min (2000) extended their previous work (1999) by designing a multi-objective, multi-period mixed integer programming model that determined the optimal relocation site and phase-out schedule of a combined manufacturing and distribution facility from supply chain perspectives. A similar problem was solved by Melachrinoudis, Min, and Messac (2000) using a novel methodology called *physical programming* which allows a decision maker to express multi-criteria preferences not in the traditional form of weights but in terms of range for different degrees of desirability. In addition to the selection of the new site, the model determines the optimal schedule for relocating capacity from the existing site to the new site, the production levels in the two sites during the transitional period, and the shipments to the customers in each period of the multi-period planning horizon.

In an effort to integrate inventory, transportation and location functions of a supply chain, Nozick and Turnquist (2001) proposed an approximate inventory cost function and then embedded it into a fixed-charge facility location model. The fixed-charge facility location model was designed to consider a tradeoff between demand coverage and cost associated with the location of automobile DCs. Although the model deals with multiple objective (service-cost tradeoff) issues, it is confined to a single period, single echelon problem with no capacity constraint.

#### 4.2. Stochastic models

In an increasingly competitive environment, there are many uncertain or random elements in the supply chain such as customer demands, lead times, and production fluctuation. The stochastic models take into account these uncertain and random elements. One of the pioneering works dealing with the stochastic nature of the integrated supply chain is credited to Midler (1969), who developed a dynamic programming model based on optimal control theory for selecting an optimal combination of transportation modes, commodity flows, and re-routing of carriers from customers to suppliers over a multi-period planning horizon.

Tapiero and Soliman (1972) utilized optimal control theory to solve multi-commodity transportation, multi-regional production and inventory planning problems over time with uncertain demand. Despite its merit, the model combining linear and parametric programs created severe computational difficulty.

Lee and Billington (1993) attempted to integrate the material flows of marketing, manufacturing, and distribution processes by developing a stochastic program. Their model was designed to determine the material ordering policy, the customer service level for each product, and postponement strategies. Similarly, Lee and Feitzinger (1995) and Swaminathan and Tayur (1999) presented stochastic models to formulate postponement (delayed product differentiation) strategies. In particular, Swaminathan and Tayur (1999) solved a so-called *vanilla box* problem where the inventories of semi-finished products were stored in vanilla boxes and then were assembled into final products after a customer actually ordered them further into the supply chain. Their model considered random customer orders.

In the meantime, several attempts have been made to quantify the effects of imbalance between supply and demand in the supply chain. These attempts include Fisher, Hammond, Obermeyer, and Raman (1997) who developed a stochastic program that aimed to minimize underproduction and overproduction costs as a result of imbalance between supply and uncertain demand in the supply chain. Similarly, Lee

et al. (1997) investigated the bullwhip effect that might arise when order variances distorted customer demand and consequently created imbalance between supply and demand in the supply chain. Metters (1997) followed up on Lee et al. (1997) by developing a dynamic programming model that aimed to minimize the expected costs of production, inventory holding, and excess demand penalty, subject to production obeying capacity constraints.

#### 4.3. Hybrid models

The single highest cost in a supply chain is inventory which accounts for nearly half of the total logistics costs (Lancioni, 2000). Due to the heavy influence of inventory on the supply chain cost, the literature dealing with inventory theoretic models is relatively rich. Baumol and Vinod (1970) are credited with the introduction of one of the most classic inventory theoretic models. Although they did not differentiate between truckload (TL) and less-than-truckload (LTL) freight rates, their model allowed a decision maker to make tradeoffs among direct shipping cost, in-transit carrying cost, ordering cost, and a consignee's inventory carrying cost. Since in-transit carrying cost is a surrogate measure of transit time (speed of delivery), their model can be used for analyzing tradeoffs between cost (inventory level) and time (transit time).

Das (1974) modified the inventory theoretic model proposed by Baumol and Vinod (1970) by considering a more general estimate of the demand variability. His model can also be applied to inter-modal situations. Karmarkar and Patel (1977) used a decomposition approach to solve a single product, single period, multiple location inventory problem with stochastic demands and transshipment between locations. To consider interactions between inventory management and transportation modal choice, Constable and Whybark (1978) further extended the inventory theoretic model. They added expected backorder cost to the original inventory theoretic model suggested by Baumol and Vinod (1970).

Herron (1983) employed the inventory theoretic model to not only relate the level of customer service to the inventory level, but to also determine the frequency of expedite shipment in case of stock-outs. Blumenfeld, Hall, and Jordan (1985) developed a model similar to Herron (1983) to make a tradeoff between freight expedition and safety stock holding cost. Some variants of the inventory theoretic model were used on a location-inventory problem where demand is uncertain and re-distribution of inventories is permissible between order cycles (Das, 1975). Schwarz (1981) developed an inventory theoretic model based on Clark and Scarf (1960) to determine the size of the total inventory investment and the location of inventory stocking points simultaneously. Their model, however, is limited to a single commodity problem. Another shortcoming of the model is severe computational complexity that may prohibit its application to a real-world problem. Singh and Vrat (1984) developed a more practical model that was designed to determine the optimal location of repair part stocking points and the allocation of repair part inventory to that location.

Despite the popularity of the inventory theoretic models in the supply chain modeling literature, some alternative models were proposed by Bookbinder, McAuley, and Schulte (1989), Cachon (1999), Karabakal, Gunal, and Ritchie (2000) and Newhart, Stott, and Vasko (1993). To elaborate, Bookbinder et al. (1989) employed both spreadsheet-based simulation and linear programming models to evaluate inventory/production alternatives and then select the best alternative, while making a tradeoff between transportation cost and inventory investment. However, like past studies reviewed earlier, Bookbinder et al. (1989) did not estimate the impact of backhauls on transportation cost. Newhart et al. (1993) used

both spreadsheet-based inventory and mathematical programming models to determine the most cost-efficient methods of production and inventory with consolidation options.

More recently, Cachon (1999) utilized a game theory to take into account an infinite horizon, stochastic demand inventory problem between one supplier and one retailer. In his game theory, Cachon (1999) considered the possibility of ‘double marginalization’ (profit sharing between the supplier and the retailer), buy-back contracts, and quantity discounts to develop the optimal joint inventory policy. Karabakal et al. (2000) used a combination of simulation and mixed-integer programming models to determine the number and location of automobile distribution and processing centers as well as the set of market areas covered by each distribution and processing center, while evaluating customer performance measures such as the ability of supply chains to deliver a customer’s preferred vehicle within short time windows.

Given that a simulation model is well-suited for evaluating dynamic decision rules under ‘what-if’ scenarios, a few attempts have been made to develop simulation models to improve supply chain dynamics involving demand amplification with the presence of many supply chain players. These include Towill, Naim, and Wikner (1992) and Wikner, Towill, and Naim (1991). The main purpose of both studies is to create a best decision rule that will allow the decision maker to reduce lead times, compress the distribution channel and coordinate information flow throughout the supply chain. One of the most intriguing features of their models is the use of influence diagrams that visualize the cause-and-effect relationship between the decision rule and the improvement of supply chain performances.

Petrovic, Roy, and Petrovic (1998) developed a fuzzy generative supply chain model to determine target order-up-to levels of inventories along a supply chain under uncertain demand and external supply of raw material. The results of the fuzzy model were then used as input data for an evaluative simulation model that aimed to calculate replenishment quantities during a finite planning horizon. The simulation model also provides the user with the assessment of supply chain performance (e.g. end-product delivery performance). These fuzzy and simulation models, however, were confined to a single product problem with no capacity constraint. Petrovic (2001) extended these models by incorporating the element of uncertain lead times during the replenishment process into the fuzzy model framework. Both of these simulation studies are useful for understanding supply chain dynamics under uncertainty, but are still limited to periodic review inventory systems.

#### *4.4. IT-driven models*

One of the most critical drivers of supply chain success is enhanced visibility through an information sharing mechanism linking supply chain partners. Considering the significant role of IT in supply chain success, IT-driven models are in high demand. Nevertheless, IT-driven modeling efforts are still in their infancy. IT-driven models that are worth noting include Al-Mashari and Zairi (2000), Camm et al. (1997), Johnston, Taylor, and Visweswaramurthy (1999), Min and Melachrinoudis (2001), Richmond and Peters (1998) and Talluri (2000).

More specifically, Camm et al. (1997) combined an integer programming model involving the location of DCs and sourcing of multiple products with a GIS to develop a flexible decision support system (DSS). However, their model-based DSS did not include capacity constraints. Johnston et al. (1999) developed a stand-alone GIS model for managing and integrating multi-facility warehousing and production systems. The model aimed to find near-optimal storage locations for stock items in a

multi-facility warehousing environment. Min and Melachrinoudis (2001) blended GIS into a mixed integer programming model-based DSS which was designed to develop warehouse restructuring strategy. Their DSS was intended to determine which warehouses to retain and which warehouses to phase-out in such a way that the restructured supply chain network minimized total logistics costs, while meeting capacity, demand and delivery requirements.

Though descriptive rather than normative (analytical), Richmond and Peters (1998) presented a conceptual WMS model comprised of three phases: (1) WMS investment strategy, (2) WMS implementation planning, and (3) WMS execution. Phase one focused on operations strategy and software selection. Phase two was concerned with the detailed design and conference room pilot (the modeling of WMS software against re-engineering process) as well as the detailed specifications of material handling equipment solutions. Phase three got involved in the construction of material handling solutions, organizational structure, worker training, system testing, conversion and support.

Al-Mashari and Zairi (2000) developed a SAP R/3-based ERP architecture and a conceptual diagram in an effort to create value-oriented supply chains that enable a high level of integration and communication among all supply chain processes. Their ERP architecture consisted of three layers: presentation based on graphical user interface (GUI), application, and database. Talluri (2000) proposed a goal programming model for an effective acquisition and justification of IT for a supply chain. The model could be useful in selecting the right ERP system that can consider system acquisition and maintenance costs, flexibility, execution accuracy, and compatibility.

## 5. Concluding remarks and future research directions

Although the numerous benefits of integrated supply chain concepts are evident, analytical tools that can exploit those benefits are scarce. The scarcity of such tools may be attributed to confusion emanating from the supply chain concept and complexity inherent in integrated modeling. As discussed earlier, the supply chain concept represents new management thinking with heavy emphasis on customer service. Such a paradigm shift necessitates a new mindset that defies the pre-conceived importance of functional excellence. In other words, reinventing traditional analytical tools will not be the answer for many managerial issues involving real-world supply chain problems. Those issues may include organizational resistance to change, inter-functional or inter-organizational conflicts, joint production planning, dynamic demand forecasting, profit sharing, team-oriented performance measures, channel power shift, customer relationship management, information sharing, real-time communication, inventory ownership and technical compatibility. Since many of these issues are perceived 'soft' (e.g. ill-structured, strategic, behavioral), these are not necessarily 'hard' (e.g. structured, operational, technical) issues commonly addressed by analytical tools such as mathematical programming techniques.

Therefore, the mere extension of a traditional analytical tool to the broader context of supply chains is likely to neglect those critical supply chain issues. Indeed, most of the prior supply chain modeling efforts that we reviewed earlier still focused on well-defined hard issues such as location/allocation, inventory control, production planning, transportation mode selection, and supplier selection with the commonly accepted value propositions such as cost minimization and profit maximization. These limitations, however, do not signal the demise of some traditional models such as mathematical programming techniques, but necessitate the diversification of analytical techniques for supply chain

modeling. Based on these observations, we foresee the growing needs of the following lines of research for future supply chain-modeling efforts:

- The application of traditional mathematical programming techniques (e.g. mixed integer programming) to inter-functional integration (e.g. production/distribution, production/sourcing, location/inventory, inventory/transportation) should continue by exploring multi-echelon, multi-period issues.
- The future models should look into new problems associated with soft issues such as relationship management and conflict resolution between potential supply chain partners (e.g. buyers and suppliers). Such new problems may call for the use of game theory or a negotiation model. A good example is the work of Christy and Grout (1994) who employed game theory to investigate inter-related behaviors of a buyer and a supplier. Similarly, Min and Emam (1999) proposed a data-mining-based negotiation model to capture purchasing negotiation dynamics between suppliers and buyers.
- The supply chain is a complex network of organizations with conflicting objectives (Simchi-Levi, Kaminsky, & Simchi-Levi, 2000). This implies that the future supply chain research needs to include multi-objective treatments of joint procurement, production, and inventory planning decisions that can explicitly consider tradeoffs among total cost, customer service, and lead time.
- As is the case with large-scale logistics process modeling, the resurgence of the simulation model is needed to evaluate dynamic decision rules for managing an inter-related series of supply chain processes. The simulation model has already been proven to be useful for measuring the bullwhip effect.
- To simplify the complexity of a supply chain, future research endeavors may explore new methodology such as the Theory of Constraints (TOC). TOC is well-suited for a supply chain environment where there are an overwhelming number of interactions and inter-dependencies that exist among supply chain members, processes and resources. In particular, *TOC Logic-Trees* can be a useful tool for identifying high-leverage supply chain processes that heavily influence supply chain performances (see e.g. McMullen (1998) for a fundamental concept of TOC).
- Since the validity of the model depends on quality of input data, stand-alone mathematical models are losing ground in the supply chain research. Rather than developing a huge stand-alone mathematical model for a broad scope of the supply chain problem, future research efforts should be geared toward the design of model-based DSS that utilizes communication techniques (e.g. the Internet), knowledge discovery techniques (e.g. data mining) and visual aids (e.g. GIS). This implies that the development of IT-driven models will be the wave of the future.

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## References

- Alex, M. (2000). Where's the warehouse? *Manufacturing Engineer*, 79 (5), 214–215.
- Al-Mashari, M., & Zairi, M. (2000). Supply chain re-engineering using enterprise resource planning (ERP) software of a SAP R/3 implementation case. *International Journal of Physical Distribution and Logistics Management*, 30 (3/4), 296–313.



- Arntzen, B. C., Brown, G. G., Harrison, T. P., & Trafton, L. L. (1995). Global supply chain management at digital equipment corporation. *Interfaces*, 25, 69–93.
- Ashayeri, J., & Rongen, J. M. J. (1997). Central distribution in Europe: A multi-criteria approach to location selection. *The International Journal of Logistics Management*, 9 (1), 97–106.
- Baumol, W. J., & Vinod, H. D. (1970). An inventory theoretic model of freight transport demand. *Management Science*, 16 (7), 413–421.
- Beamon, B. M. (1998). Supply chain design and analysis: Models and methods. *International Journal of Production Economics*, 55, 281–294.
- Blumenfeld, D. E., Hall, R. W., & Jordan, W. C. (1985). Trade-off between freight expediting and safety stock inventory costs. *Journal of Business Logistics*, 6 (1), 79–100.
- Bookbinder, J. H., McAuley, P. T., & Schulte, J. (1989). Inventory and transportation planning in the distribution of fine papers. *Journal of the Operational Research Society*, 40 (2), 155–166.
- Bowersox, D. J., & Closs, D. J. (1996). *Logistical management: The integrated supply chain process*, New York, NY: McGraw-Hill.
- Bradley, S. P., Hax, A. C., & Magnanti, T. L. (1977). *Applied mathematical programming*, Reading, MA: Addison-Wesley.
- Braithwaite, A., & Hall, D. (1999). *Risky business: Critical decisions in supply chain management*, Logistics consulting partners. Hertfordshire, UK: LCP Ltd.
- Budnick, F. S., McLeavey, D., & Mojena, R. (1988). *Principles of operations research for management*, Homewood, IL: Irwin.
- Cachon, G. P. (1999). Competitive supply chain inventory management. In S. Tayur, R. Ganeshan & M. Magazine, *Quantitative models for supply chain management* (pp. 111–146). Boston, MA: Kluwer Academic Publishers.
- Camm, J. D., Chorman, T. E., Dill, F. A., Evans, J. R., Sweeney, D. J., & Wegryn, G. W. (1997). Blending OR/MS judgment, and GIS: Restructuring P&G's supply chain. *Interfaces*, 27 (1), 128–142.
- Chopra, S., & Meindl, P. (2001). *Supply chain management: Strategy, planning and operation*, Upper Saddle River, NJ: Prentice-Hall.
- Christy, D. P., & Grout, J. R. (1994). Safeguarding supply chain relationships. *International Journal of Production Economics*, 36, 233–242.
- Clark, A. J., & Scarf, H. (1960). Optimal policies for a multi-echelon inventory problem. *Management Science*, 6 (4), 475–490.
- Cohen, M. A., & Lee, H. L. (1989). Resource deployment analysis of global manufacturing and distribution networks. *Journal of Manufacturing and Operations Management*, 2, 81–104.
- Constable, G. K., & Whybark, D. C. (1978). The interaction of transportation and inventory decisions. *Decision Sciences*, 9, 688–699.
- Cooper, M. C., Ellram, L. M., Gardner, J. T., & Hank, A. M. (1997). Meshing multiple alliances. *Journal of Business Logistics*, 18 (1), 67–89.
- Cooper, M. C., Lambert, D. M., & Pagh, J. D. (1997). Supply chain management: More than a new name for logistics. *The International Journal of Logistics Management*, 8 (1), 1–13.
- Das, C. (1974). Choice of transport service: An inventory theoretic approach. *The Logistics and Transportation Review*, 10 (2), 181–187.
- Das, C. (1975). Supply and redistribution rules for two-location inventory systems: One-period analysis. *Management Science*, 21 (7), 765–776.
- Drucker, P. F. (1998). Management's new paradigms. *Forbes*, October, 152–177.
- Erengüç, S. S., Simpson, N. C., & Vakharia, A. J. (1999). Integrated production/distribution planning in supply chains: An invited review. *European Journal of Operational Research*, 115, 219–236.
- Fisher, M., Hammond, J., Obermeyer, W., & Raman, A. (1997). Configuring a supply chain to reduce the cost of demand uncertainty. *Production and Operations Management*, 6 (3), 211–225.
- Ganeshan, R., Jack, E., Magazine, M. J., & Stephens, P. (1999). A taxonomic review of supply chain management research. In S. Tayur, R. Ganeshan & M. Magazine, *Quantitative models for supply chain management* (pp. 840–879). Boston, MA: Kluwer Academic Publishers.
- Glover, F., Jones, G., Karney, D., Klingman, D., & Mote, J. (1979). An integrated production, distribution, and inventory planning system. *Interfaces*, 9 (5), 21–35.
- Herron, D. P. (1983). Management science in industrial logistics. *Applications of Management Science*, 3, 49–85.
- Hillier, F. S., & Lieberman, G. J. (2001). *Introduction to operations research*, (7th ed). New York, NY: McGraw-Hill.
- Holmstrom, J., Hoover Jr., W. E., Eloranta, E., & Vasara, A. (1999). Using value engineering to implement breakthrough solutions for customers. *The International Journal of Logistics Management*, 10 (2), 1–12.

- Ireland, R., & Bruce, R. (2000). CPFR: Only the beginning of collaboration. *Supply Chain Management Review*, 4 (4), 80–88.
- Johnson, G. A., & Malucci, L. (1999). Shift to supply chain reflects more strategic approach. *APICS—The Performance Advantage*, October (pp. 28–31).
- Johnston, D. A., Taylor, G. D., & Visweswaramurthy, G. (1999). Highly constrained multi-facility warehouse management system using a GIS system. *Integrated Manufacturing Systems*, 10 (4), 221–232.
- Karabakal, N., Gunal, A., & Ritchie, W. (2000). Supply chain analysis of Volkswagen of America. *Interfaces*, 30 (4), 46–55.
- Karmarkar, U. S., & Patel, N. R. (1977). The one-period,  $n$ -location distribution problem. *Naval Research Logistics Quarterly*, 24 (4), 559–575.
- Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management. *Industrial Marketing Management*, 29, 65–83.
- Lambert, D. M., Emmelhainz, M. A., & Gardner, J. T. (1996). Developing and implementing supply chain partnerships. *The International Journal of Logistics Management*, 7 (2), 1–17.
- Lambert, D. M., Cooper, M. C., & Pagh, J. D. (1998). Supply chain management: Implementation issues and research opportunities. *The International Journal of Logistics Management*, 9 (2), 1–19.
- Lancioni, R. A. (2000). New developments in supply chain management for the millennium. *Industrial Marketing Management*, 29, 1–6.
- Lee, H. L., & Billington, C. (1993). Material management in decentralized supply chains. *Operations Research*, 41 (5), 835–847.
- Lee, H. L., & Feitzinger, E. (1995). Product configuration and postponement for supply chain efficiency. *Fourth Industrial Engineering Research Conference Proceedings* (pp. 43–48). Institute of Industrial Engineers.
- Lee, H. L., Padmanabhan, V., & Whang, S. (1997). Information distortion in a supply chain: The bullwhip effect. *Management Science*, 43 (4), 546–558.
- McMullen Jr., T. B. (1998). *Introduction to the theory of constraints management system*, Boca Raton, FL: The St. Lucie Press.
- Melachrinoudis, E., & Min, H. (2000). The dynamic relocation and phase-out of a hybrid, two-echelon plant/warehousing facility: A multiple objective approach. *European Journal of Operational Research*, 123 (1), 1–15.
- Melachrinoudis, E., Min, H., & Messac, A. (2000). The relocation of a manufacturing/distribution facility from supply chain perspectives: A physical programming approach. *Multi-Criteria Applications*, 10, 15–39.
- Mentzer, J. T., & Schuster, A. D. (1983). Computer modeling in logistics: Existing models and future outlook. *Journal of Business Logistics*, 3 (2), 1–55.
- Metters, R. (1997). Quantifying the bullwhip effect in supply chains. *Journal of Operations Management*, 15, 89–100.
- Midler, J. L. (1969). A stochastic multiperiod multimode transportation model. *Transportation Science*, 3, 8–29.
- Min, H. (2000). The bullwhip effect in supply chain management. In P. Swamidass, *Encyclopedia of production and manufacturing management* (pp. 66–70). Boston, MA: Kluwer Academic Publishers.
- Min, H., & Emam, A. (1999). *A data mining approach to understanding the effects of expertise and experiential learning on purchasing negotiations*, Working paper series 1999-5. Louisville, KY: Logistics and Distribution Institute.
- Min, H., & Melachrinoudis, E. (1999). The relocation of a hybrid manufacturing/distribution facility from supply chain perspectives: A case study. *Omega*, 27 (1), 75–85.
- Min, H., & Melachrinoudis, E. (2001). Restructuring a warehouse network: Strategies and models. In G. Salvendy, *Handbook of industrial engineering* (pp. 2070–2082).
- Min, H., Jayaraman, V., & Srisvastava, R. (1998). Combined location-routing problems: A synthesis and future research directions. *European Journal of Operational Research*, 108 (1), 1–15.
- Newhart, D. D., Stott, K. L., & Vasko, F. J. (1993). Consolidating product sizes to minimize inventory levels for a multi-stage production and distribution systems. *Journal of the Operational Research Society*, 44 (7), 637–644.
- Nozick, L. K., & Turnquist, M. A. (2001). Inventory, transportation, service quality and the location of distribution centers. *European Journal of Operational Research*, 129, 362–371.
- Petrovic, D. (2001). Simulation of supply chain behavior and performance in an uncertain environment. *International Journal of Production Economics*, 71, 429–438.
- Petrovic, D., Roy, R., & Petrovic, R. (1998). Modeling and simulation of a supply chain in an uncertain environment. *European Journal of Operational Research*, 109, 299–309.
- Porter, M. E. (1985). *Competitive advantage: Creating and sustaining superior performance*, New York, NY: The Free Press.
- Richmond, B., & Peters, E. (1998). Warehouse management systems technologies: Technology-enabled warehouse excellence. In J. Gattorna, *Strategic supply chain alignment: Best practice in supply chain management* (pp. 393–406). Hampshire, England: Gower Publishing Limited.

- Schwarz, L. B. (1981). Physical distribution: The analysis of inventory and location. *AIIE Transactions*, 13 (2), 138–150.
- Shank, J. K., & Govindarajan, V. (1993). *Strategic cost management: The new tool for competitive advantage*, New York, NY: The Free Press.
- Shapiro, J. F. (2001). *Modeling the supply chain*, Pacific Grove, CA: Wadsworth Group.
- Silver, E. D. (1981). Operations research in inventory management: A review and critique. *Operations Research*, 29, 628–645.
- Simchi-Levi, D., Kaminsky, P., & Simchi-Levi, E. (2000). *Designing and managing the supply chain: Concepts, strategies, and case studies*, New York, NY: Irwin McGraw-Hill.
- Singh, N., & Vrat, P. (1984). A location-allocation model for a two-echelon repair-inventory system. *IIE Transactions*, 16 (3), 222–228.
- Slats, P. A., Bhola, B., Evers, J. J. M., & Dijkuizen, G. (1995). Logistics modeling. *European Journal of Operational Research*, 87, 1–20.
- Stevens, G. C. (1989). Integrating the supply chain. *International Journal of Physical Distribution and Materials Management*, 19, 3–8.
- Swamidass, P. M. (2000). *Encyclopedia of production and manufacturing management*, Boston, MA: Kluwer Academic Publishers.
- Swaminathan, J. M., & Tayur, S. R. (1999). Stochastic programming models for managing product variety. In S. Tayur, R. Ganeshan & M. Magazine, *Quantitative models for supply chain management* (pp. 585–622). Boston, MA: Kluwer Academic Publishers.
- Talluri, S. (2000). An IT/IS acquisition and justification model for supply chain management. *International Journal of Physical Distribution and Logistics Management*, 30 (3/4), 221–237.
- Tapiero, C. S., & Soliman, M. A. (1972). Multi-commodities transportation schedules over time. *Networks*, 2, 311–327.
- Thomas, D. J., & Griffin, P. M. (1996). Coordinated supply chain management. *European Journal of Operational Research*, 94, 1–15.
- Towill, D. R., Naim, M. M., & Wikner, J. (1992). Industrial dynamics simulation models in the design of supply chains. *International Journal of Physical Distribution and Logistics Management*, 22 (5), 3–13.
- Weber, C. A., Current, J. R., & Benton, W. C. (1990). Vendor selection criteria and methods. *European Journal of Operational Research*, 50, 2–18.
- Wikner, J., Towill, D. R., & Naim, M. (1991). Smoothing supply chain dynamics. *International Journal of Production Economics*, 22 (3), 231–248.
- Zipkin, P. H. (2000). *Foundations of inventory management*, New York, NY: McGraw-Hill.