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Coordinated supply chain management

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Abstract

Historically, the three fundamental stages of the supply chain, procurement, production and distribution, have been managed independently, buffered by large inventories. Increasing competitive pressures, and market globalization are forcing firms to develop supply chains that can quickly respond to customer needs. To remain competitive, these firms must reduce operating costs while continuously improving customer service. With recent advances in communications and information technology, as well as a rapidly growing array of logistics options, firms have an opportunity to reduce operating costs by coordinating the planning of these stages. In this paper, we review the literature addressing coordinated planning between two or more stages of the supply chain, placing particular emphasis on models that would lend themselves to a total supply chain model. Finally, we suggest directions for future research.

Keywords: Distribution; Supply chain; Logistics

1. Introduction

In the past, organizations have focused their efforts on making effective decisions *within* a facility. In this case, the various functions of an organization, including assembly, storage, and distribution are generally decoupled into their functional and geographic components through buffers of large inventories. In this way, the complexity of the decisions is reduced since each component is treated independently of the others. Ignoring these component dependencies, however, can have costly consequences. This becomes increasingly apparent with market globalization. As a result, firms are moving from decoupled decision making processes toward more coordinated and integrated design and control of all of their components in order to provide

goods and services to the customer at low cost and high service levels.

Supply Chain Management (SCM) is the management of material and information flows both in and between facilities, such as vendors, manufacturing and assembly plants and distribution centers (DC). SCM is an area that has recently received a great deal of attention in the business community. In the United States, annual expenditures on non-military logistics are estimated at \$670 million; over 11% of the Gross National Product. With logistics costs of 30% of cost of goods sold, not uncommon for U.S. manufacturing firms [5], potential savings in coordination cannot be ignored. Competitive pressures drive profit margins down, forcing firms to reduce costs while maintaining excellent customer service.

There are three traditional stages in the supply chain: procurement, production and distribution. Each one of these stages may be composed of several fa-

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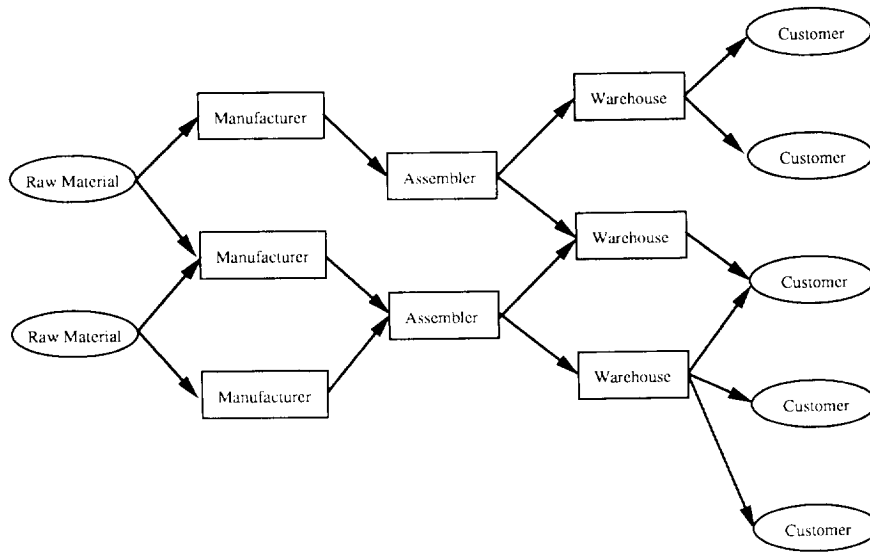


Fig. 1. Schematic of a generic supply chain.

ilities in different locations around the world. Fig. 1 shows the general structure of a supply chain network. Note that frequently, the supply chain for a particular product will cross functional or corporate boundaries. This presents an organizational obstacle to coordinated supply chain modeling. Fawcett [30] points out functional boundaries can distribute knowledge of all value-added activities such that no one, including top management, has complete knowledge of the process.

While SCM is relatively new, the idea of coordinated planning is not. The study of multi-echelon inventory/distribution systems began as early as 1960 by Clark and Scarf [19]. Since that time, many researchers have investigated multi-echelon inventory and distribution systems. Less research has been aimed at coordinating production and distribution scheduling, although there have been some notable efforts recently.

In addition to this organizational issue, the quality of data and the complexity of the supply chain make global formulation of the supply chain problem very difficult. Not surprisingly, the research community has spent more energy modeling smaller sections of the supply chain.

In this paper, we offer a review of research done in the area of coordinated SCM, including models addressing specific sections of the supply chain. In Section 2, we review the operational models addressing

various kinds of coordinated planning and scheduling. In particular, we focus on models that we believe would fit well in a coordinated SCM framework. In Section 3, we examine models that address strategic issues. For the most part, the strategic models are mixed integer programming based. In Section 4, we discuss the emerging research area of environmentally conscious supply chain management, and finally, in Section 5, we present some concluding remarks.

2. Operational planning

We define three categories of operational coordination. Buyer–Vendor coordination, Production–Distribution coordination and Inventory–Distribution coordination. The models we review in this section are targeted at such issues as: selection of batch size, choice of transportation mode and choice of production quantity. Table 1 shows the breakdown of the models reviewed.

2.1. Buyer–vendor coordination

The supply chain begins with the procurement of raw materials or subassemblies. It is not uncommon for raw material and subassembly purchase to account for over 50% or more of the cost of sales. Many tradi-

Table 1
Operational models

Buyer–vendor coordination	Production–distribution coordination	Inventory–distribution coordination
Monahan (1984)	Williams (1981)	Clark and Scarf (1960)
Lee and Rosenblatt (1986)	Ishii, Takahashi and Muramatsu (1988)	Muckstadt and Thomas (1980)
Banerjee (1986)	Haq, Vrat and Kanda (1991)	Erkip, Hausman and Nahmias (1990)
Benjamin (1990)	Pyke and Cohen (1993, 1994)	Svoronos and Zipkin (1991)
Goyal (1988)	Chien (1993)	Rogers and Tsubakitani (1991)
Anupindi and Akella (1993)	Chandra and Fisher (1994)	Ernst and Pyke (1993)
Kohli and Park (1994)		Muckstadt and Roundy (1993)
Lau and Lau (1994)		Van Eijs (1994)

tional inventory models have focused on determining optimal order quantities for the purchaser. Such models neglect two opportunities. First, it may be possible to reduce costs without changing the ordering policy. This could be done by investment in material handling equipment or data exchange technology, such as electronic data interchange (EDI). Second, the firms can find an order quantity that is *jointly* optimal for the buyer and vendor. The two sides must then negotiate to determine how to divide the savings. Since investments in material handling and data technology are strategic decisions, we will focus on the second savings opportunity in the section. Please note, however, that we can view the results of such strategic investments as changes in the parameters used in the operational models we discuss. This provides a framework for evaluating strategic investments quantitatively, using the models discussed in this section.

Lee and Rosenblatt [45] develop an algorithm to determine a profit maximizing quantity discount pricing schedule for a single product, single buyer model. Their model is based on the observation that when a buyer employs an EOQ policy, and the ordering and holding costs are known, a certain order quantity can be achieved by an appropriate quantity discount pricing schedule.

They extend the earlier work of Monahan [47] by requiring a minimum profit margin, and allowing the vendor to purchase in any quantity rather than lot-for-lot. Without these additions, Monahan shows that the factor by which the optimal order quantity should be increased is

$$K^* = \sqrt{(S_2/S_1) + 1}, \quad (1)$$

where S_1 and S_2 are the ordering costs for the buyer

and vendor respectively. Note that this expression is independent of the holding costs of both the buyer and vendor.

Lee and Rosenblatt develop a more realistic model, and an algorithm for simultaneously finding the optimal order quantity increase factor K , and the optimal order quantity for the vendor. They show that the optimal order quantity for the vendor will be an integer multiple k of the buyer's order quantity. Using this fact, they present an algorithm for finding optimal values for k and K .

Banerjee [6] develops a joint economic lot size model for a single buyer, single vendor system where the vendor has a finite production rate. Under the assumption that a production setup is incurred every time an order is placed, he shows that the optimal joint production or order quantity is

$$Q^* = \sqrt{\frac{2D(S_1 + S_2)}{r(C_r(D/P) + C_Q)}}, \quad (2)$$

where D is the buyers annual demand, P is the producers annual production rate, r is the unit carrying charge, and C_r and C_Q are the unit production cost and unit purchase cost respectively.

Goyal [34] extends Banerjee's model by relaxing the lot-for-lot production assumption. He argues that the economic production quantity will be an integer multiple of the buyer's purchase quantity. For a given integer multiple n , the buyers economic order quantity is shown to be:

$$Q(n) = \sqrt{\frac{2D(S_1 + S_2/n)}{r(C_Q - C_r + nC_r(1 + D/P))}}. \quad (3)$$

The optimal value of n satisfies the inequality:

$$n^*(n^* + 1) \geq \frac{S_2(C_Q - C_c)}{S_1 C_c (1 + D/P)} \geq n^*(n^* - 1). \quad (4)$$

Anupindi and Akella [2] develop optimal ordering policies for a single buyer with multiple vendors. Three models are presented. In the first model, all goods ordered from vendor i arrive in the current period with probability β_i , and in the next period with probability $1 - \beta_i$. In the second model, a random fraction of demand is delivered in the current period, and the remainder is canceled. The third model is similar to the second, except that the remainder is delivered in the next period. For each model they present an optimal ordering policy that orders nothing when the inventory level is above an upper bound, orders from one vendor when the inventory level is between bounds, and orders from both vendors when the inventory level is below the lower bound.

Kohli and Park [40] investigate joint ordering policies as a method to reduce transaction costs between a single vendor and a homogeneous group of buyers. They present expressions for optimal joint order quantities assuming all products are ordered in each joint order.

Their model calculates the savings in fixed order costs, but does not explicitly model transportation costs. In fact, splitting orders across multiple vendors will lead to smaller transportation quantities. Smaller transportation quantities will most likely imply larger per unit transportation costs. Furthermore, the requirement that every product is included in each order is limiting. The authors admit this weakness and point out that relaxing this assumption results in a set-partitioning problem, which is *NP*-complete.

Lau and Lau [42] determine the optimal ordering policy for a buyer using a (Q, R) continuous review system with two vendors. One vendor has a lower price but poorer lead time performance. Complete back-ordering is assumed. Demand is deterministic and lead times are stochastic, with known distributions. The authors develop a total cost expression as a function of Q^* , the optimal order quantity, R^* , the optimal reorder point, and r_2 , the optimal fraction of the order quantity obtained from vendor 2, ($r_1 = 1 - r_2$). The average inventory for the two vendor case is shown to be

$$R - \mu_1 d + \frac{1}{2}Q - r_2 d(\mu_1 - \mu_2), \quad (5)$$

where μ_1 and μ_2 are the mean lead times (it is as-

sumed $\mu_1 > \mu_2$), and d is the demand. In the one vendor case, the average inventory is

$$R - \mu_1 d + \frac{1}{2}Q, \quad (6)$$

implying a reduction in inventory of $r_2 d(\mu_1 - \mu_2)$, when both vendors are used. Numerical examples are presented, where the cost equations are minimized using the IMSL numerical subroutine BCPOL.

2.2. Production–distribution coordination

The production–distribution link in the supply chain can take on many forms. Products can be manufactured and sent to distribution centers, retailers or plants. The literature addressing both production planning, and distribution planning is rich. However, there are few models that attempt to address these problems simultaneously. There are several reasons why this may be true. First, many problems in these areas are tremendously hard to solve by themselves. Both vehicle routing and machine scheduling fall into this category. Second, in practice, these problems are often separated, by inventory buffers. Finally, different departments are often responsible for these two planning activities.

Williams [63] studies dynamic programming based heuristics that minimize production and distribution costs in an assembly production network and an arborescent distribution network with constant demand over an infinite horizon. The algorithm connects the production and distribution networks at a “dummy” node. Dynamic programming algorithms are applied to both the production and distribution sides of the network, proceeding in opposite directions, both moving toward the dummy node. The final step combines the two results by minimizing system cost over all possible batch sizes for the dummy node.

The algorithm presented can be computationally expensive since it relies on dynamic programming. The problem addressed is basically the same as that addressed by Muckstadt and Roundy [48], which is discussed below. The main advantages of the dynamic programming formulation are twofold. First, optimal solutions are found rather than *near* optimal solutions. Second, the DP formulation permits general cost functions for each stage in the network. These cost functions can even be non-algebraic, represented in tabular form.

Ishii et al. [37] address the issue of finite product life in a paper that develops a model for determining base stock levels and production lead times to minimize obsolete stock for products with explicitly defined life-cycles. The authors examine a three-stage “pull” system with a manufacturer, wholesaler and retailer. The time a product spends in the entire supply chain may be very long. In industries where product life-cycles are short, such as electronic component manufacture, dead stock is a serious concern.

Benjamin [8] considers choice of transportation mode in a production–distribution network with multiple supply and demand points and a single product class. Setup, order, and inventory costs are considered, as well as both linear and concave transportation costs. The problem is formulated as a nonlinear program, and a heuristic solution procedure is presented along with a procedure for computing a lower bound on the global minimum. The solution procedure uses a form of Benders’ decomposition by fixing order quantities for origin, destination and mode, and then solving the resulting LP subproblem to determine shipping quantities.

This model makes an important contribution in its attempt to explicitly model transportation costs for multiple mode choices. Although nonlinear transportation costs make the model much more difficult, models with linear transport costs have very limited application in practice.

Haq et al. [36] develop a mixed integer program to determine production and distribution batch sizes that minimize system costs in a multi-stage production–inventory–distribution system. System costs include unit production cost, setup cost, carrying cost and transport cost. All costs are either fixed or linear. The assumption of linear transportation costs greatly limits the applicability of this model.

Pyke and Cohen [54] present a Markov chain model of a single product three-level supply chain, consisting of a factory, a finished goods stockpile and a retailer. The performance of this system is evaluated, focusing on the finished goods replenishment cycle. Near-optimal algorithms are presented to determine the expedite batch size, the normal replenishment batch size, the normal reorder point, the expedite reorder point and the order-up-to level at the retailer.

A multiple-product simulation model is used to test the accuracy of the single product approximation.

The authors find that the single product approximation works well when utilization is not very high, and the number of cycles containing an expedite order is relatively small. This is because the single product approximation does not account for extra setup times and queue delays that may result under the circumstances described.

In a follow-up paper, Pyke and Cohen [55] present multi-product extensions to their previous work. An algorithm is presented to determine the approximate steady state distribution of certain random variables, such as number of periods between replenishment batches, number of periods between expedite batches and inventory position at the beginning of a cycle. This algorithm is shown to converge. Several test cases are run, and the authors provide insights into the supply chain interactions caused by certain decisions. In particular, they note that small replenishment batch sizes effectively reduce production capacity (due to more setups), thus increasing production lead times. This increase forces greater downstream inventories.

Chien [18] addresses the problem of trying to find profit maximizing production and shipping quantities for a single product. Weekly demands are assumed to be independent and stationary, and follow a known probability distribution. Transportation costs are modeled with a fixed charge per truck and no variable cost. Expressions for production cost, transportation cost, shortage penalty cost, inventory carrying cost, regular revenue and salvage revenue (unsold units) are developed as functions of the demand density. An iterative procedure is presented and used to find nearly optimal solutions to test cases assuming a uniform demand distribution. The optimality gap of solutions obtained was experimentally determined to be between 0.2% to 3.8%.

Chandra and Fisher [17] present a single plant, multi-customer multi-period model that seeks to combine a production planning problem with a vehicle routing problem. Two solution procedures are presented: “uncoordinated” and “coordinated.” In the uncoordinated approach, the production planning problem is solved to optimality, and the vehicle routing problem for each period is solved heuristically. The procedure then looks to improve the solution by combining the shipment for a particular customer with a shipment to that customer in an earlier period, while observing inventory balance and truck capacity con-

straints. The coordinated procedure takes the solution from the uncoordinated approach and looks for consolidating shifts that can be made when the production schedule can be altered.

Both procedures were extensively tested on hypothetical data. The results indicate that the value of coordinating production and distribution increases as: production capacity becomes less constrained, the time horizon is increased, holding costs decrease, and setup costs decrease.

2.3. Inventory–distribution coordination

The first area of research to address supply chain coordination was multi-echelon inventory systems. With customer service requirements constantly increasing, effective management of this part of the supply chain is crucial.

Clark and Scarf [19] provide one of the earliest efforts in this area. They present a recursive decomposition approach to determine optimal policies for serial multi-echelon structures. Silver and Peterson [57] provide a formulation and discussion of simple two-echelon inventory systems.

Muckstadt and Thomas [49] investigate the applicability of multi-echelon methods in low demand systems. Two approaches are presented for determining stock levels in a two-echelon system, item decomposition and level decomposition. Level decomposition sets an aggregate service level goal for each echelon. Item decomposition determines stock levels for each item at each echelon. Both approaches use a Lagrangian relaxation technique that results in a separable problem that can be solved easily. Real data from a large industrial spare parts distribution system are presented. Item decomposition outperforms level decomposition in this case, and the conclusion is that the role of higher level echelons is to support low level echelons, and evaluating the performance of higher level echelons based on fill rate can lead to poor performance.

Erkip et al. [27] present an approach to determine optimal ordering policies at a depot that distributes to multiple warehouses with correlated demand. An optimal order-up-to level for the depot is determined when there is high correlation between demand in successive periods as well as high correlation between demand for the same item at different locations. Effective stan-

dard deviation is computed as a function of the correlation coefficient. Correlation coefficients observed by the authors in a consumer products manufacturer and distributor increased effective standard deviations significantly, resulting in substantially higher optimal safety stock levels.

Svoronos and Zipkin [58] evaluate the performance of arborescent inventory/distribution systems with independent Poisson demand at the lowest echelon, assuming stochastic transit times and a one-for-one replenishment policy. The authors develop an approach for using two moments of the transit time to approximate density functions for inventory and back-orders at a single stage, given a base stock level. The approach can be applied recursively to develop densities for each stage in a multi-echelon system. The approximate densities developed can be used to formulate an overall cost optimization model to determine base stock levels.

Rogers and Tsubakitani [56] develop necessary conditions for optimal inventory levels of a component that is used in multiple end products (at multiple sites), subject to an overall investment constraint. The optimality conditions take the form of a critical ratio similar to the classic newsboy critical ratio policy $F(Z^*) = p_u / (p_u + p_o)$, where $F(\cdot)$ is the cumulative distribution function of demand, Z^* is the optimal inventory quantity, and p_u and p_o are the under-stocking and over-stocking costs.

The critical ratio for the inventory levels of the finished goods takes precisely the form of the newsboy ratio, namely, the expected cost of under-stocking in the numerator and the expected cost of under-stocking plus the expected cost of over-stocking in the denominator. The only difference is that the expected cost of over-stocking is a function of the optimal Lagrange multiplier. The ratio for the component inventory is not as simple, since the cost of under-stocking is a complicated function of the finished goods inventory levels.

These results provide only necessary conditions, since the critical ratios are functions of a Lagrange multiplier representing the dualized budget constraint. Some numerical optimization technique is required to find the optimal multiplier.

Ernst and Pyke [28] study a two-echelon system composed of a warehouse and retailer, with random demand occurring at the retailer only. Both the retail-

ers and the warehouse operate under a base stock policy. It is assumed that the warehouse has a fleet of trucks, or equivalently a long term agreement for a certain amount of truck capacity. Common carrier shipments are used when the regular fleet is not adequate. Optimal truck capacity, review periods and base stock policies are developed for several test cases, assuming normally distributed demand.

With linear costs, optimal truck capacity is zero in many cases, greater than mean demand in some cases, and less than mean demand in others. In general, as variability of demand increases, truck capacity relative to mean demand increases. Results with concave costs are similar, although optimal truck capacity tends to be higher since the incremental cost of capacity is less than in the linear case. Holding costs have no effect on the results since it is assumed throughout that regular shipments and common carrier shipments arrive at the retailer at the same time (they have the same lead time).

Muckstadt and Roundy [48] present efficient algorithms for finding near optimal solutions to multi-echelon production or distribution networks. The authors consider nested *powers-of-two* policies where each stage must produce a multiple of two (i.e. $1, 2, \dots, 2^k$) times as often as any predecessor stage. It is shown that for serial systems and arborescent assembly systems that nested policies are optimal, and *powers-of-two* nested policies can deviate from the optimal nested policy by at most 6% with a fixed base planning period, and 2% if the base planning period is considered a variable. Very fast ($O(n \log n)$, where n is the number of stages) algorithms are presented. These algorithms are based on sorting the stages based on the ratio of setup cost to holding cost and clustering stages that will use the same reorder interval. The algorithm is extended to arborescent distribution networks, where again the optimal nested *powers-of-two* policy deviates from the optimal policy by 6% and 2% as above. In this case, however, a nested policy is not guaranteed to be optimal, and in fact can be arbitrarily bad.

An $O(n^4)$ algorithm for solving general, acyclic production–distribution networks is presented. The algorithm solves several max-flow problems to find an optimal clustering of stages (stages that will use the same reorder interval). Again, this algorithm produces solutions that are within 6% and 2% of an optimal

nested policy.

An algorithm to solve a resource-constrained version of the problem is also presented. A Lagrangian relaxation approach is used, which is not guaranteed to converge, although it did work well in a practical application (see Jackson et al. [38]).

A fast ($O(NI \log NI)$, N stages, I products) algorithm for computing non-nested *powers-of-two* policies for one-warehouse, multi-retailer, multi-product systems is presented. The results are shown to be within 6% and 2% of optimal, as above.

Van Eijs [60] presents a heuristic procedure for reducing transportation costs for a buyer of N items, employing a coordinated (R, S) periodic review system. Demand for each item is assumed to be independent and identically distributed for each period. Transportation costs are assumed to be a linear function of the order size up to a certain break point, with zero additional cost for some finite quantity of product beyond the break point. Lead time is assumed to be constant. This cost structure is consistent with less-than-truckload (LTL) versus full-truckload (TL) freight rates, however, lead time is often greater for LTL shipping, and this is not taken into account.

At each review period, the heuristic calculates the expected reduction in transportation costs and the expected increase in inventory costs associated with increasing the size of an order. Numerical examples are presented, showing a significant savings (up to 20%) when the heuristic is employed.

3. Strategic planning

In this section we review supply chain models used to support strategic decision making. Strategic supply chain decisions may include: plant or DC openings and closings, allocation of equipment to manufacturing facilities, selection of a location or locations for manufacture of a new product, or evaluation of changes in the flow of a particular product through the supply chain.

While we focus on analytic models that appear in the research literature, it should be noted that many of the principles behind such models are discussed in the business literature. Authors such as Hammer and Champy [35], and Porter [53] have facilitated the popularity of Business Process Re-engineering (BPR)

and the application of BPR to the value-chain concept. It is easy to see that, as management philosophies, BPR and SCM have a great deal in common. Specifically, both approaches analyze the value-added implications of all business related activities. Evans et al. [29] present the similarities between BPR and SCM more rigorously. In Berry et al. [10], some of the same authors describe an application of BPR to an electronic products supply chain.

O'Sullivan and Geringer [51] present an important concept in the SCM or re-engineering framework, the notion of a *natural* vs. a *contrived* value chain. The *natural* value chain is a conceptual ideal of the necessary value chain activities, while a *contrived* value chain is "an imperfect implementation of the natural value chain." The authors outline an approach for defining the natural value chain and stress the importance of keeping this natural chain in mind when re-engineering the actual, *contrived* chain.

A large number of the models reviewed are mixed integer programming models, these are discussed in Section 3.1. The remaining strategic planning models are presented in Section 3.2. Table 2 classifies the strategic models as predominantly a methodological work, a case study or a discussion of strategic issues.

3.1. Mixed integer programming models

The majority of strategic planning models are mixed integer programming based. In one of the earliest papers to address distribution system design, Geoffrion and Graves [32] present a mixed integer programming formulation of multi-commodity distribution system design. A subset of DCs are selected from a list of potential sites. Customer zones with known demand must be uniquely assigned to a DC. For each DC that is opened, there is a minimum and maximum throughput. This allows nonlinearities in DC cost as a function of throughput to be modeled. Supply constraints are formulated for each plant-product combination, effectively fixing the production mix at each plant. A solution procedure based on Benders' decomposition is presented. This decomposition separates the problem at each iteration into several easily solved LPs (one for each commodity). Computational results show that Benders' decomposition performs remarkably well on this class of problems.

More recently, Geoffrion and Powers [33] discuss the evolution of strategic distribution system design in the twenty years since the Geoffrion and Graves [32] paper. They note some significant changes in algorithms, including the development of specialized network flow solvers. However, the authors argue that technological changes and changes in corporate culture have had a much greater impact on distribution system design. In particular, they claim that the rise of logistics as a corporate function and the evolution of powerful desktop computers and client-server architecture has affected distribution design in ways unanticipated by the research community. Desktop computers and logistics software allow logistics professionals to evaluate different strategies and scenarios.

Cohen and Lee [22] present an integer programming model designed to support strategic resource deployment decision making in a global manufacturing and distribution network. The authors describe different resource deployment strategies for each of the primary supply chain stages. An example of such a decision would be choosing between a regionalized plant strategy, where each plant in a network would produce a full product line and completely serves a customer region, and a consolidated strategy, where production is centralized. Clearly, the plant deployment decision has major implications on the requirements of the distribution system.

The objective of the integer programming model is to maximize after-tax profit, however, the large number of 0–1 variables require that the model be solved in a hierarchical manner. That is, the model is used to determine resource deployment, given a logistics structure. In practice, such a tool is useful for evaluating and supporting strategic decision making. Furthermore, firms using such a model would most likely have an existing logistics structure, making variable-fixing an appropriate action.

Brown et al. [14] present a mixed integer formulation for a multi-commodity production-distribution system. The formulation addresses the opening and closing of plants, the assignment of equipment to plants, and the delivery of multiple products directly from plants to customer zones. A primal goal decomposition method is presented, based on the observation that fixing the opened plants, the assignment of equipment to those plants, and the production at each plant results in pure network subproblems, one

Table 2
Strategic models

Methodology	Case study	Discussion
Geoffrion and Graves (1974)	Kleutghen and McGee (1985)	Lee and Billington (1992)
Burns, Hall, Blumenfeld and Daganzo (1985)	Larson (1988)	Novack, Rinehart and Fawcett (1993)
Brown, Graves and Honczarenko (1987)	Van Roy (1989)	Gelders, Mannaerts and Maes (1994)
Cohen and Lee (1988, 1989)	Martin, Dent and Eckhart (1993)	Fawcett (1995)
Wikner, Towill and Naim (1991)	Davis (1993)	Benjamin and Wigand (1995)
Lee and Billington (1993)	Pooley (1994)	Geoffrion and Powers (1995)
Bitran and Sarkar (1994)	Ashayeri, Westerhof and Van Alst (1994)	O'Sullivan and Geringer (1993)
	Arntzen, Brown, Harrison and Trafton (1995)	
	Cohen and Lee (1989)	
	Berry, Naim and Towill (1995)	

for each commodity. The master problem includes a set of production *goals* that may be violated at a linear penalty cost. Penalty costs are determined by a heuristic that examines shortages and excesses in production in successive master problems. A decision support system was developed for use at Nabisco Foods, Inc. Computational results are reported for large, practical problems addressing strategic decisions such as new product roll-out and plant closings. The authors suggest that this sort of decomposition provides a significant improvement over traditional decomposition methods.

Van Roy [61] develops an optimization model for the production and distribution network for a petrochemical company, with several levels of distribution (2 commodities, 2 refineries, 10 bottling plants, 40 potential depot locations, 40 breakpoints and 200 customer locations). The model is used to find an optimal balance between transportation, bottling and holding costs. Bottling costs can be reduced by centralizing bottling facilities (at the refineries), but this results in increased transportation costs since bulk transport is cheaper than bottle transport. A branch-and-cut approach was employed, using MPSARX, a mathematical programming system. The model was used for strategic planning, addressing issues such as change of fleet size and type, and consolidation or decentralization of bottling.

Arntzen et al. [3] describe the development of a large mixed integer programming formulation for modeling supply chain decisions at Digital Equipment Corporation. The model is used to evaluate several global supply chain decisions at Digital. An

important contribution of this formulation is its modeling of opportunities to avoid import taxes or *duty drawback*. Duty drawback can be claimed if a product is re-exported in the same condition, re-exported in a different condition (i.e. incorporated into a sub-assembly), or re-imported in a different condition. Reasonably large problems (2000 rows by 14000 columns) are solved to an integrality gap of 0.0005 percent, using X-System from Insight, Inc.

Martin et al. [46] develop a linear programming model for the flat glass product subdivision of Libbey-Owens-Ford. Flat glass production is subject to very large, sequence dependent setup times, due to different tints. Furthermore, glass can be "cut" to customer specifications on-line, or flat glass can be stored, and cut later. Yields for off-line cutting are significantly lower, but this form of cutting is necessary due to the long cycle lengths for glass tints. The LP model was originally designed to be used as a tactical or operational model, but has been used to address strategic issues such as new plant/facility location and new product introduction.

Ashayeri et al. [4] describe the development and use of a large mixed integer program at Netherlands Car BV (formerly known as Volvo Car BV). Netherlands Car BV produces cars for third parties, such as Volvo and Mitsubishi. Subassembly purchase costs comprise 80% of the total cost, making inventory and logistics management vitally important. The authors simplify the model by using some approximations. In particular, they use an approximation developed by Daganzo [23,24], for estimating local delivery distance based on customer density. They also make some

packaging decisions exogenously, to reduce the number of decision variables. The simplified program is solved using traditional branch and bound methods.

Pooley [52] describes facility planning at a division of Ault Foods. The investigation led to a much better understanding of cost structure (what was fixed, and what was variable). A mixed integer program was developed and solved several times, evaluating different scenarios.

3.2. Strategic planning models

A number of researchers have addressed issues of strategic planning without modeling the problem as a mixed integer program. In this section we review such models.

Cohen and Lee [21] develop a stochastic supply chain model for discrete parts manufacture with an arborescent distribution network. The supply chain is decomposed into four sub-models, material control, production, stockpile inventory and distribution. The relationship between local control policies in these sub-models and overall system performance is investigated. Some simplifying assumptions are made in order to achieve tractability. Material requests are modeled as a compound Poisson process, based on the overall arrival rate and the average mix of materials based on demand. A serial multi-stage, multi-line process is used in the production sub-model. Each workstation is viewed as an M/G/1 queue even though the output process of such a queue is not necessarily Poisson.

Under these assumptions, each sub-model can be optimized for cost given a required service level. The service level of each sub-model will have an effect on downstream sub-models. Since, the overall optimization model is a constrained nonlinear problem that is not tractable, the approach used is to select service levels for the sub-models that provide good customer service and low cost. Software was developed that determines system performance and cost based on selected service levels. In a hypothetical example, trade-offs between investment in different stages are developed, demonstrating the type of strategic analysis for which the authors developed this model.

Burns et al. [15] develop analytic methods for minimizing total inventory and distribution cost under known demand. The authors compare two strategies,

shipping directly to each customer, and *peddling*, sending one truck to multiple customers. Transportation costs are calculated based on a fixed dispatching cost, a fixed cost per stop, and a per mile cost. Using an algorithm presented by Daganzo [23,24], the delivery distance to randomly located customers is approximated, thus permitting the development of closed form analytic results. These results allow easy cost estimation of the two strategies based on estimates of a few parameters. In general, peddling is the method of choice when customers density is high, holding costs are high or customers are far away.

Wikner et al. [62] consider several techniques for reducing demand amplification in a three echelon production–distribution system. They claim that poor information flow between echelons will lead to alternating periods of stockouts and surpluses due to over-reactions at individual stages of the supply chain. The behavior is similar to MRP “nervousness.” The effectiveness of several strategies is evaluated using a simulation model. They conclude that of the strategies tested, improved information flow between echelons is the most effective way to damp demand amplification.

Lee and Billington [43] provide an excellent discussion of the dangers of poorly managing supply chain inventories. In particular, they point out that the cost of reworking stored components due to engineering changes, and the risk of obsolescence can inflate holding cost rates upwards of 40%. Not considering such factors could lead to inappropriate mode choices. That is, a faster, more expensive shipping mode may save enough in inventory investment to justify the increase in shipping cost, but only if inventory cost rates are appropriately chosen.

The same authors describe their experience in analyzing material flow for the HP DeskJet in a decentralized global supply chain [44]. In particular, they consider a global supply chain model that permits decentralized control, that is, each part of the supply chain makes decisions based on local information. Note that the development of a global supply chain model is not necessarily inconsistent with decentralized control. Their global model considers the relocation of value-added activities, provided decentralized control can occur after the re-deployment of such activities.

They analyze a scenario where generic printers are distributed to DCs, and localization, including instruc-

tions in the appropriate language and an appropriate power supply, occurs at the DCs. The postponement of product differentiation permits lower system inventories as well as decreased investment in manufacturing flexibility.

Kleutghen and McGee [39] describe the motivation and subsequent development of an integrated inventory management system at Pfizer Pharmaceuticals. Pfizer created a centralized inventory management function and developed quantitative models to manage inventory. Many of these models were implemented on a spreadsheet. Accounting was updated to track different categories of inventory more accurately, and better inventory forecasting was emphasized. The program resulted in a reduction of \$23.9 million in inventory investment, and annual savings of nearly \$8 million. In a manner similar to Lee and Billington [43], this paper demonstrates the important role accounting systems and cost structures can play in supply chain management.

Larson [41] describes the development of a decision support system for municipal sewage disposal transport in New York City. A new model needed to be developed since the EPA designated a new dumping site 106 miles offshore replacing the previous site which was only 12 miles offshore. Waste is directed to fourteen processing plants which are located on the water. These plants fill storage tanks which are drained into inner-harbor vessels which then take the sludge to a transshipment point where the sludge is transferred to ocean-going vessels. Waste production at the plants is considered to be independent and normally distributed. The objective is to minimize costs while providing good service to the plants. Good service is defined as not allowing the tanks at a plant to fill up. A heuristic is presented to develop vessel routes. The heuristic starts with the feasible solution of one stop tours for all plants and then looks for the best pairwise combinations, using the well known 2-opt exchange of Lin and Kernighan. Software was developed to evaluate different strategies, allowing management to test different scenarios, such as multiple transshipment points and different ship sizes.

Davis [26] describes the development and application of a total supply chain model at Hewlett-Packard. He describes a case study where the manufacture and distribution of the HP Desk Jet printer is evaluated. HP was able to greatly reduce their inventory invest-

ment in Europe by equipping DCs to prepare generic printers for their final market. This final preparation consisted of including the appropriate power cord and transformer, as well as documentation in the appropriate language.

Bitran and Sarkar [12] present mathematical models that permit the impact of variance reduction and capacity improvements to be measured efficiently. Modeling a generic manufacturing network with a Markovian routing matrix and a series of GI/G/1 queues, the authors develop a model that evaluates the expected work-in-process (WIP) inventory levels in the system given different levels of investment. The costs of variability reduction and capacity improvement are modeled with convex functions, representative of the increasing marginal cost of improvement which is likely to occur in practice.

Estimating the impact of process and variability investment on WIP is very important from a supply chain modeling standpoint. Reduction in WIP translates to shorter manufacturing lead times, facilitating the ability to rapidly respond to customer requirements.

4. Environmentally conscious SCM

Recent legal and political trends seem to indicate that the importance of environmentally conscious manufacturing and distribution will continue to grow. The International Organization for Standards (ISO) will adopt ISO 14001 in 1996, providing an international standard for environmental management systems [1,59]. The adoption of ISO 14001 may force companies to pay more attention to environmental issues in supply chain modeling, in order to avoid exclusion from markets requiring compliance.

Despite the impending adoption of ISO 14001, as well as various other legislative environmental initiatives, the body of research that specifically addresses environmentally conscious supply chain management is quite sparse. Research on environmental manufacturing has focused primarily on product and process design, including such concepts as Design for the Environment (DFE) and Life Cycle Analysis (LCA) [16].

Bloemhof-Ruwaard et al. [13] discuss the application of operations research models to environmental management issues. Their work was motivated by re-

cent developments in environmental policy. In particular, they argue that the shift in focus from *end-of-pipe* control to waste prevention at the source suggests an integrated modeling approach, similar to supply chain management. The authors review early research efforts that attempt to combine environmental management and operations research, citing references from both environmental and operations research journals. They conclude that in the near future, the operations research community must integrate with related sciences to adequately address environmental issues.

Beckman et al. [7] present a qualitative discussion of environmentally conscious supply chain management. They draw parallels with Total Quality Management (TQM) concepts, particularly those addressing supplier relations and product design. The authors observe that assessing the environmental impact of the physical characteristics of a new product is by itself a formidable task. Assessing the impact of the flow of a new product through the supply chain requires the modification or development of a supply chain model.

Clegg et al. [20] develop a linear programming model to determine profit-maximizing material flows for both new and reclaimed or recycled parts in a re-manufacturing operation. Reclaimed parts can be totally or partially disassembled. The parts and part components may then be reused in manufacturing or discarded (perhaps sold). The authors point out that the contribution of their model is not that it can determine appropriate material flows for actual operation, but rather that the model can be used to examine the sensitivity of the model parameters, such as limits on disposal, disassembly capacity and availability of reclaimed parts.

5. Conclusions

Independently managing facilities in a supply chain can result in very poor overall behavior. Further, as global markets continue to open, more firms are becoming multi-national which adds complexity to the supply chain. For these reasons, supply chain management will continue to be an important area of research for many years.

This review shows that strategic models based on case studies are popular. The majority of these models are based on complicated integer programs. For-

tunately, these integer programs have an underlying network structure that can often be exploited using a decomposition method. The computational efficiency of these decomposition methods, along with advances in computational resources, suggest that IP-based coordinated planning models can yield useful results to real problems.

Though several useful models have been developed, there are several important elements which have not yet been adequately addressed. These include:

(1) Knowledge of all value-added activities in the supply chain is critical to coordinated modeling. Restructuring of these activities can provide excellent opportunities for improvement. Lee and Billington [44] present an excellent example of how reorganizing and relocating value-added activities can provide significant improvements in cost and service.

Furthermore, performance measures that are consistent with the goals of the supply chain modeler must be established. Gelders et al. [31] report that in a recent survey of Belgian manufacturers, although many manufacturers felt that rapid and reliable delivery was a very important competitive element, very few manufacturers had performance measures related to delivery time. Muckstadt and Thomas [49] and Lee and Billington [44] both point out that poorly selected local performance measures can lead to poor system performance.

(2) The single largest component of logistics cost is transportation cost, often comprising over half of total logistics cost. In the research literature, we see many models using linear transportation cost functions. While linear functions often yield nice analytic results, such costs are typically not realistic. Many transportation modes are available to logistics managers, and most of these modes are best described with nonlinear (often concave) cost functions. Daganzo [25] offers an excellent discussion of these costs.

(3) In a recent article appearing in the *Wall Street Journal* [11], it was estimated that the contract logistics industry will triple in size over the next five years to \$50 billion in annual revenue. Since the use of third-party logistics providers is just beginning to grow, it is not surprising that the research community has yet to adequately address these opportunities.

Logistics providers offer a wide range of services, extending far beyond traditional transportation activities. Value added logistics (VAL) services provided

by third parties are now widely available. Such services may including storing or distributing goods requiring special handling. These services may be necessary for perishable or fragile goods.

(4) Long supply chains inhibit a firm's ability to respond quickly to consumer requirements. Furthermore, in many industries, product life cycles are very short, and long supply chains expose the producer to a high risk of inventory obsolescence. For this reason, life cycle constraints and costs need to be considered in supply chain models.

Benjamin and Wigand [9] offer a discussion of the potential implications that the development of the information superhighway will have on supply chain management. In particular, they suggest that the creation of electronic markets may eliminate many wholesalers and retailers as customers are provided with direct access to manufacturers.

(5) The determination and design of interface points between stages of the supply chain is another important issue. Novack et al. [50] describe some of the interface issues facing firms attempting to coordinate the management of stages of their supply chain.

(6) International trade barriers continue to erode, however, large import taxes still exist between many countries. Import duties can be as high as 200% of product value, although 5–10% is typical. These import taxes, as well as the location of tax havens need to be incorporated into global supply chain models. Models that can incorporate forecasted currency fluctuations and changes in international tax laws would also be very valuable.

(7) Due to the network structure of many of these problems, efficient decomposition methods can often be used. Despite the efficiency of such procedures, many models will still be too large or too complicated to reasonably solve. Typically, these models will be working with approximate data, so some carefully selected approximations will not sacrifice the integrity of the solutions, and in some cases may allow the study of logistics problems that would otherwise be too complex. Exogenous variable fixing or elimination can simplify models greatly. The Netherlands Car BV case [4] and the resource deployment model of Cohen and Lee [22] demonstrate the usefulness of these approaches.

(8) There is clearly a sparsity in the literature addressing supply chain coordination at an operational

level. Most of the recent research has focused on stochastic models, which require strong assumptions regarding demand distribution and stationarity.

(9) As environmental laws become more and more stringent, the environmental impact of supply chain activities will have to be considered and carefully modeled. In particular, supply chain models that can be used to evaluate how 'green' the manufacture and distribution of a new product will be important. Furthermore, many of the models and principles discussed here can be applied to reverse logistics and recycling systems.

In summary, with recent advances in communications and information technology, firms have an opportunity for significant savings in logistics costs by coordinating the planning of the various stages of SCM. However, there still remain several important issues yet to be adequately addressed by the research community.

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