Supply chain (re)design: Support for managerial and policy decisions

Wout Dullaert*, Olli Bräysy**, Marc Goetschalckx*** and Birger Raa****
* Institute of Transport and Maritime Management Antwerp (ITMMA)
University of Antwerp
Keizerstraat 64, B-2000
Antwerp
Belgium
tel: +32 3 275 5141
fax: +32 3 275 5150
e-mail: wout.dullaert@ua.ac.be

** Agora Innoroad Laboratory
Agora Center
University of Jyväskylä
P.O. Box 35, FI-40014
Jyväskylä
Finland
tel: +358 14 260 1211
fax: +358 14 260 1021
e-mail: olli.braysy@jyu.fi

*** School of Industrial and Systems Engineering
Georgia Institute of Technology
765 Ferst Drive, GA 30332-0205
Atlanta
USA
tel: +1 404 894 2317
fax: +1 404 894 2301
e-mail: marc.goetschalckx@isye.gatech.edu

**** Department of Industrial Management (TW18)
Ghent University
Technologiepark 903, 9052
Zwijnaarde
Belgium
tel: +32 9264 5497
fax: +32 9264 5847
e-mail: birger.raa@ugent.be

A well-structured supply chain is of key importance in achieving efficient operations amongst the suppliers, manufacturers, distribution facilities and distribution channels that constitute the supply chain. The changing economic and political environment challenges multinational corporations to redesign their existing production and distribution network and to develop new strategies to meet customer service levels at lowest cost. This paper reviews the literature on supply chain design since 1999 with the objective of supporting the development of richer supply chain models capable of taking all logistics costs into account thereby optimizing the full cost of ownership for multinational corporations and allowing for a consolidation of value adding activities in high-wage regions.

1. Introduction

A well-structured supply chain is of key importance in achieving efficient operations amongst the suppliers, manufacturers, distribution facilities and distribution channels that constitute the supply chain. The changing economic and political environment challenges multinational corporations to redesign their existing production and distribution network and to develop new strategies to meet customer service levels at lowest cost (Goetschalckx et al., 2002a). Labor costs and regulations, productivity, taxes and duties can change rapidly in an international context and can therefore alter the attractiveness of locations (Tong and Walter, 1980) and encourage companies to redesign their network to offer the highest value for the shareholder (Kirca and Koksalan, 1996).

At the strategic level, long-term decisions are taken, which involve (re)designing the network by selecting facility locations, production technologies and plant capacities. The mid-term decisions at the tactical level address material flow management issues, including production levels at plants, inventory levels, lot sizes etc. The day-to-day management of production and distribution activities, designing production schedules and distribution routes for JIT deliveries to customers, is situated at operational level (Schmidt and Wilhelm, 2000). The strategic configuration of the supply chain is thus a key factor influencing the efficiency at tactical and operational level. Its long term impact on the efficiency of the supply chain, combined with the commitment of substantial capital resources, render this level crucial.

Currently, production activities in Europe and the United States are often relocated based solely on differences in variable production costs. Sea transport from Asia is (still) cheap, but all other logistics costs are increasing. Lead times are being extended due to the increase in transportation times to customers. Further, longer production rates and the lower frequency and higher volume of deliveries result in higher levels of cyclic and safety stocks. Far too often, delocalization decisions are based on intuition or simple performance measures such as direct labor or marginal cost of production. At best, decisions are taken in a hierarchical or sequential manner. Further research is needed to redesign supply chains taking all logistics costs into account in order to optimize the full cost of ownership for multinational corporations and to allow for a consolidation of value adding activities in high-wage regions. During the last decade, significant progress has been made at including exchange rates, tariff barriers, non-tariff barriers, transfer prices, duties, global transportation, taxes and local content regulations in global supply chain planning models (see e.g. Goetschalckx et al., 2002a). Logistics costs and constraints are not common in global supply chain models, but

are explored in a number of domestic models (e.g. Arntzen et al., 1995). Redesigning supply chains on a strategic level (determining the optimal location and size of production facilities) and tactical level (assigning products to plants, warehouse and transportation modes) at the same time, taking into account complications created by taxation, duties, tariffs, and local rules and regulations, economies of scale in production and transportation and uncertainty (see e.g. Santoso et al., 2005), would lead to models that are too complex to be solved by standard linear mixed integer structures. Decomposition approaches, offering different models with different levels of detail and realism, are appropriate at different stages of the design process and the design of new heuristic approaches is needed to solve these models within a reasonable amount of computing time.

As the literature on supply chain planning has been reviewed in Goetschalckx et al. (2002a) and literature reviews on production-distribution (location) system design date back to Sarmiento and Nagi (1999) and Erengüç et al. (1999), this paper focuses on reviewing the literature on strategic supply chain system (re)design since 1999 with a view to supporting the design of richer supply chain (re)design models. The remainder of this paper is structured as follows. In section 2, network design problems involving the location and/or sizing of production and distribution facilities are considered. Although production facility or distribution facility location problems often do not combine production and distribution features, they include real-life extensions that still have to be implemented in joint production and distribution facility location problems. For the problems in section 3, the network structure is considered to be fixed. Instead of deciding upon the size, location and number of facilities, decisions on production and distribution planning are examined. Section 4 concludes with the current approach to production-distribution network design and planning and offers new approaches for further research.

2. Production and distribution system design

In the existing literature on location theory, in the main three types of objective functions have been used: the median objective, the center objective and the cent-dian objective. The p-median problem involves the location of p facilities or warehouses and assigns customers to the nearest facility to minimize the weighted sum of all customer-facilities. If the objective is to minimize the maximum distance from a customer to a facility, e.g. to ensure fast reaction in the case of emergency services such as hospitals or fire departments, the problem becomes a p-center problem. The cent-dian objective is a convex combination of sum and max objectives [see Nickel and Puerto (1999) for an integrated approach to the above objective functions]. In general the discrete versions of p-median and p-center problems are NP-hard, but can be solved in polynomial time on trees (see Burkard, 2000). On the design of problem instances for location problems, Schilling et al. (2000) highlight the impact of network distance characteristics in problem instances on the computational effort of p-median location problems and related problems such as the uncapacitated facility location problem.

The uncapacitated facility location problem (UFLP), an extension of the basic p-median problem, is perhaps the simplest version of a production-distribution system design problem (PDSDP) consisting of a network with two echelons (i.e. plants and customers), a single echelon of facilities to be located (i.e. plants) to minimize distribution costs for a single commodity. The concept consists of selecting a number of facilities from a set to minimize the sum of the fixed costs of opening plants and the variable cost of satisfying demand

(Efroymson and Ray, 1966). Generally speaking, the production-distribution system design problem (PDSDP) involves the determination of the best configuration of the supply chain regarding location, size, technology content and product range to achieve the firm's long-term goals (Dasci and Verter, 2001a).

Dasci and Verter (2001a) identify extensions of the UFLP to design a taxonomy of analytical approaches to production system design problems. Given that the taxonomy of Dasci and Verter (2001a) will be adapted to survey the post 1999 literature on production-distribution system design and planning, the classification criteria are briefly discussed below:

1. Objective function: minimizing costs, maximizing profits or a multiple objective function;
2. Number of echelons in the P&D system : 2, 3 or multiple echelons to model supply chain interactions in order to better support managerial decisions;
3. Number of echelons to be located;
4. Number of commodities: single versus multiple commodities;
5. Capacity limitations on facilities: to model the limited availability of production and distribution resources at alternative sites;
6. Nature of demand: deterministic or stochastic;
7. Number of time periods: single or multiple time periods;
8. Other side-constraints;
9. Capacity or technology acquisition: different facility configurations (e.g. size) are no longer modeled in at the input stage of the problem as 'different' facilities based on their predetermined configuration, but can be endogenously determined;
10. International features: impact of price and exchange rate uncertainties, tariffs and duties are taken into account for production-distribution decisions.

The majority of the analytical models to the PDSDP utilize discrete mixed integer programming models to represent facility design decisions, only a few papers taking into consideration continuous models (e.g. Dasci and Verter, 2001a; Verter and Dincer, 1995). Both types of models are discussed in this paper.

2.1 Single echelon facility location

The Uncapacitated Facility Location Problem (UFLP) consists of finding the optimal number of facilities (warehouses) of unrestricted size among *m* possible locations, with the objective of minimizing the sum of the fixed facility cost and transportations costs while meeting demand requirements at the *n* customer locations. In the more difficult, Capacitated Plant Location Problem (Sridharan, 1995) each facility has a capacity restriction on the demand it can serve. In the Modular Capacitated Location Problem, the capacity of each location must be chosen from a finite and discrete set of available capacities (Correia and Captivo, 2003). In this section production or warehouse facility location problems are discussed and summarized in table 1.

2.1.1 Production facility location

Lim and Kim (1999) classify general plant location problems into three categories: (1) static (single period); (2) dynamic (multi-period) uncapacitated plant location problems; and (3) dynamic capacitated plant location problems. In the dynamic capacitated plant location

problem, capacities of the plants are to be determined as opposed to the dynamic uncapacitated plant location problem.

Ignoring timing considerations offers the possibility to include more and more complex side constraints in location models. Static facility location problems therefore tend to be richer and/or involve larger networks than multi-period location models.

For solving larger real-life production-distribution systems, Dhaenens-Flipo (2000) proposes a four level decomposition approach for a static facility location in which the production, distribution and setup costs are to be minimized for the plants involved. At the central level, long-term production planning decisions on plant level are made. At regional level, demands are assigned to factories (a set of jobs that a factory has to perform). At plant level, factories are considered as machines to make the problem equivalent to scheduling jobs on independent parallel machines with sequence-dependent changeover times. This problem is modeled as an integer linear program based on a vehicle routing problem formulation. At production line level no decisions are taken as such. The sub-problems of the decomposition approach are solved using branch-and-bound. The approach is tested on a real-life case of a can producer with 10 plants, 16 production lines and 80 product orders.

Melkote and Daskin (2001) study the simultaneous optimization of facility location and transportation network design. This problem is solved effectively by reformulating it as a special case of the classical network design problem. Problems with up to 40 nodes and 160 links are solved in less than two minutes. Moreover, the trade-off between constructing facilities and links is investigated, i.e. as more facilities are built, fewer links are needed.

Dasci and Verter (2001b) present an analytical approach for the simultaneous optimization of the location, capacity and technology equipment of plant locations (single echelon) in a multi-commodity environment. In the so-called Uncapacitated Plant Location and Technology Acquisition Problem (UPL&TAP), production technology alternatives are dedicated, i.e. can only be used to produce a single product, and there are no limits to availability. For a single product and linear technology costs, the problem reduces to the uncapacitated facility location problem, which is known to be NP-complete (Krarup and Pruzan, 1983). As a result, the UPL&TAP is NP-complete by restriction. Because the technology acquisition and operation cost at each facility can be approximated by a piecewise linear concave function, the Progressive Piecewise Linear Underestimation technique (Verter and Dincer, 1995) is used as the backbone of the solution algorithm for the UPL&TAP which is tested on problem instances involving 8 alternative plant locations, 25 customer zones and 3 commodities and 2 technology alternatives.

In Verter and Dasci (2002) the authors extend their previous work (Dasci and Verter, 2001b) by simultaneously optimizing facility location, capacity acquisition and technology selection decisions for a multi-commodity single period problem in which a plant may contain a number of dedicated facilities each capable of producing a single commodity, and/or a flexible facility capable of producing a subset of products. The problem is formulated as a mixed integer nonlinear programming model and problem instances up to 50 sites, 50 customer zones and 5 products are solved by an exact decomposition approach and three heuristic approaches.

Wouda et al. (2002) determine the optimal number of plants, their locations and the allocation of the product portfolio to these plants, while minimizing the sum of production and transportation costs in the supply network of Nutricia Dairy & Drinks Group in Hungary. The mixed integer programming model of the application involving 400 farmers consolidated in 9 zones, 300 products in 13 product groups, 17 distribution centers, 17000 shops consolidated

in 20 geographical regions and per region a gravity point in sales volume, is solved using Xpress-MP.

Syam (2002) introduces logistical cost components such as holding, ordering and transportation costs in the multi-commodity production facility location problem. As the underlying *p*-median problem and multi-commodity distribution problems are both NP-complete (Garey and Johnson, 1979), the proposed model is solved heuristically by a simulated annealing and Lagrangean relaxation approach. Both approaches are tested on problems involving at most 100 possible plant locations, 20 plants, 20 candidate warehouse locations, and 8 warehouses. The Lagrangean approach outperforms simulated annealing for medium to large problems with respect to both solution quality and solution time.

Opening and closing facilities have budgetary implications and this is made explicit in Wang et al. (2003) by extending the *p*-median problem by minimizing the total weighted travel distance subject to a budget for opening and closing facilities. As the budget constrained facility location problem where facilities may be opened and closed simultaneously is NP-hard, a mathematical programming model is developed and three heuristic algorithms (greedy interchange, tabu search and Lagrangean relaxation approximation) are developed. Computational testing confirms the capability of solving medium and large-scale problems.

Gendron et al. (2003) impose balancing requirements on the multi-commodity capacitated location problem. The balancing requirements refer to the relocation of e.g. empty containers between depots used to service customer locations. The problem is thus to locate the depots that will service the customers and relocate empty containers between the depots, while minimizing the cost of opening and operating the depots and the cost generated by customer-to-depot and inter-depot movements. Initial solutions generated by a slope scaling approach are improved upon by a tabu search metaheuristic. This approach is capable of solving large-scale problem instances, involving up to 200 depot locations, 500 customers and 20 commodities, which could not be solved by existing commercial MIP solvers.

In dynamic location models timing considerations are considered to be too important to be simplified to single period decision problems. In a multi-period setting, deciding upon facility locations becomes difficult to solve for real-life problem instances. Therefore, Hormozi and Khumawala (1996) introduced procedures to reduce the number of single period solutions that need to be examined in a dynamic programming approach. Balakrishnan (2004) offers a new pruning rule to further reduce the number of candidate single period location configurations to be examined and increases the value of the multi-period facility location problem (MPFLP) for real-life applications.

Lim and Kim (1999) consider a dynamic capacitated plant location problem in which the capacities of opened plants are determined by acquisition and/or disposal of multiple types of facilities. The problem lies in deciding which plants to open in each period to minimize the sum of discounted fixed costs of opening plants, acquisition and operating costs of facilities within these plants and delivering products to customers. Production facilities can either be flexible (capable of performing multiple operations or producing multiple types of products) or dedicated (capable of performing a single operation or producing a single product). A mixed integer programming formulation is given and a solution approach is developed based on Lagrangean relaxation and a branch-and-cut algorithm using Gomory cuts. This approach is tested on problem instances up to 30 customers, 10 alternative locations and a planning horizon of 10 periods. The authors indicate that in a real-life setting a company will not open or close as often as their model allows for and that the model could be enriched by taking into account BOM relationships between plants.

Antunes and Peeters (2001) develop a simulated annealing metaheuristic for a dynamic modular capacitated facility location problem (DMCFLP). The objective is to find the minimum discounted cost solution for a set of facilities over a given planning horizon to meet customer demands by deciding upon opening new facilities and expanding, reducing or closing existing facilities. The SA approach was first tested on the uncapacitated facility location problem to compare its performance to existing local search procedures. Computational testing for the DMCFLP revealed the limitations of the SA implementation for large-scale problems. Augmenting the SA with penalty schemes, tabu lists and faster solution procedures for underlying transportation problems is suggested to improve the computational capabilities of the approach.

Canel et al. (2001) consider the multi-period, multi-commodity, capacitated facility location problem. An algorithm is proposed that first generates a list of candidate configurations for each period. These lists are effectively minimized using D&O rules. Next, dynamic programming is used to select the optimal configurations from these lists. The algorithm is used to solve an instance with 3 plants, 5 possible facility locations, 15 customers and 5 time periods.

Table 1. Production facility location

	Year	Objective function	Number of echelons in the P&D system	Number of echelons to be located	Number of plants	Number of warehouses/crossdocks	Number of customers	Number of commodities	Capacity restrictions	Stochastic or deterministic demand	Number of time-periods	Side-constraints	Capacity acquisition	International features	Industrial application
Lim and Kim	1999	C	2	1	10		30	10	Y		10	BC	Y		N
Dhaenens-Flipo	2000	C	3	0	10		80	1	Y	D	1				Y
Antunes and Peeters	2001	C	2	1	29		38		N	D			Y		Y
Melkote and Daskin	2001	C	2	1		21	21	1	N	D	1				N
Canel et al.	2001	C	2	1	4		5	2	Y	D	3				
Dasci and Verter	2001	C	3	1	16		50	5	N	D	1		Y		
Verter and Dasci	2002	C	2	1		50	50	5	N	D	1		Y		N
Wouda et al.	2002	C	3	1		9	20	13	N	D	1	BOM			
Wang et al.	2003	C	2	1		84	459	1	Y	D	1				Y
Gendron et al.	2003	C	2	1		200	500	20	Y	D	1				N
Balakrishnan	2004	C	2	1		12	NA	1	NA	D	NA				N

BOM = Bill of materials, BC = Budget constraint

2.1.2 Distribution facility location

The design of a distribution network involves many interdependent decisions on facilities, transportation, and inventory, the costs of which should be balanced in the optimal network design. Ideally the network model should also consider the effect of network design on demand through its effect on customer service (Ho and Perl, 1995). Because of the high complexity of such rich models, research has mainly focused on exploring some of these aspects in either discrete or continuous location models. Full integrating approaches remain limited to small to medium size problems.

In the multi-depot location-routing problem (Srivastava, 1993; Tuzun and Burke, 1999; Wu et al., 2002) decisions on the location of the depots and the construction of the routes, to service the customers on routes starting and ending at the depot, are to be optimized. Wu et al. (2002) consider a multi-depot location-routing problem with a heterogeneous vehicle fleet in which the number of available vehicles is limited. The problem is decomposed into a location-allocation problem and a vehicle routing problem, both to be solved using a simulated annealing metaheuristic in which a tabu list is used to prevent cycling. Tests on problem instances up to 150 nodes show that this approach outperforms previous approaches on traditional multi-depot location routing problems with a heterogeneous fleet and unlimited number of vehicles.

Liu and Lee (2003) integrate inventory control and routing decisions and propose a two-phase heuristic which is tested on problem instances up to 20 depots and 200 customers. In the first phase, a route-first, locate-second approach based on location, transportation and inventory costs is used. The solution is improved upon by an improvement heuristic in the second phase.

Wasner and Zäpfel (2004) consider the integrated problem of deciding on the number and location of hubs and depots and determining the routes. A heuristic approach consisting of a sequential procedure with feedback loops is presented. A case study for a mid-sized Austrian parcel delivery service with 40.000 parcels per day is presented. Inventory control decisions (e.g. order or shipment quantity, order frequency) are ignored although they also affect facility location and route design.

Because the required safety stock for a given service level depends on the number of warehouses used in the network, a number of papers have tried to embed this relationship in distribution facility models.

Erlebacher and Meller (2000) present a location-inventory model for designing a two-level distribution system with continuously-represented customer locations. A stylized analytical model is developed and applied to a real-life application of 42 plants, one regional DC and 325 local DCs.

Daskin et al. (2002) present a three-tier system consisting of one or more suppliers, distribution centers and retailers. As the location of the suppliers and retailers is known, the problem consists of determining and locating the optimal number of distribution centers, assigning retailers to the DCs and determining the optimal ordering policy at the DCs. To this end, a nonlinear integer programming formulation is developed for a DC location problem in which working inventory and safety stock inventory costs at the DCs are taken into account. Moreover, transportation costs between suppliers and DCs are no longer assumed to be linear and economies of scale are included by using a fixed term. Lagrangean relaxation heuristics are tested on problems up to 150 retailers.

In Nozick and Turnquist (2001) a conservative estimate of safety stock requirements based on the number of DCs and including the distance between DC and retail outlets as a measure of customer response is integrated in a fixed charge facility location model. An application of an automotive manufacturer serving continental USA, consisting of 698 demand areas/potential DC locations is solved using standard algorithms for the fixed-charge facility location problem.

Kalfakakou and Tsouros (2001) consider the effect of network design on customer demand by constraining service to customers that are located within a given time or distance limit. The location problem is subject to a specified installation budget that cannot be exceeded. A tree search implicit enumeration procedure is described but no detailed computational results are offered to evaluate its performance.

In Hwang (2002) DCs are selected from a discrete set of locations to minimize the fixed costs of the DCs and the variable transportation costs while making sure that the probability of each customer to be covered is not less than a pre-specified service level. The minimum number of warehouses is determined by solving a stochastic set-covering problem and vehicle routes are designed by a simple cluster-first, route-second approach using genetic algorithms that solve a traveling salesman problem for each route. The approach is evaluated on problem instances up to 99 nodes.

Table 2. Distribution facility location

	Year	Objective function	Number of echelons in the P&D system	Number of echelons to be located	Number of plants	Number of warehouses/crossdocks	Number of customers	Number of commodities	Capacity restrictions	Stochastic or deterministic demand	Number of time-periods	Side-constraints	Capacity acquisition	International features	Industrial application
Erlebacher and Meller	2000	C	2	1	42	368	cont	1	N	D	1				Y
Kalfakakou and Tsouros	2001	C	2	1								BU			
Nozick and Turnquist	2001	C	3	1			698	1	N	D	1	CD			Y
Daskin et al.	2002	C	2	1		150	150	1	N	D	1				N
Wu et al.	2002	C	2	1		150	150	1	Y	D	1				N
Hwang	2002	C	2	1		99	99	1	Y	D	1	SL			N
Liu and Lee	2003	C	2	1		20	200	1	Y	S	1				N
Hidaka and Okano	2003	C	2	1		1024	6000	1	N	D	1				Y
Eskigun et al.	2004	C	3	1		NA	NA	1	Y	D	1				Y
Wasner and Zäpfel	2004	C	2	1		2042	2042	1	Y	D	1				Y

cont = continuous; BC = budget constraint; CD = cover demand; SL = service level

In Eskigun et al. (2004) the service implications of network design are modeled through the impact on lead times. The proposed Lagrangean heuristic performs well on real-life problem instances.

Research on large scale distribution location models is limited. Hidako and Okano (2003), however, report on a new approximation algorithm for a large real-life instance of spare parts logistics for a manufacturing company in Japan involving 6000 customers and 380000 warehouse candidates. A greedy heuristic based on a subset of warehouse candidates was able to reduce total cost by 9-11% which could be reduced by an additional 0.5-1.5% by an interchange heuristic. Finally, a 'balloon search' heuristic taking into account all warehouse candidates reduced costs further by 0.5 to 1.5%.

2.2 Multiple echelon location problems

Designing or re-designing a production-distribution network can call for a simultaneous or sequential optimization of the locations and size of both production and various types of distribution facilities. Moreover, clients (either customer zones or individual large customers) have to be assigned to the distribution facilities (distribution or transshipment points) which then in turn have to be allocated to open production facilities for their supply. Finally, routes have to be designed to (re-)supply distribution facilities and service customers and customer zones. This section discusses the existing approaches dealing with such multiple echelon location problems and discusses their computational capabilities for solving real-life cases and the extent to which performance measures, other than facility, warehousing and transportation costs (e.g. inventory costs and service levels) can be incorporated. The features of the applications are summarized in table 3.

Hinojosa et al. (2000) deal with a multi-period two-echelon multi-commodity capacitated location problem. For each period, a decision is to be taken on which plants and warehouses to open or close and on the amounts of the different products to be shipped from the plants to the warehouses and on to the customers. A mixed integer programming formulation is given and a repair heuristic for obtaining feasible solutions from the lower bounds from a Lagrangean relaxation approach is developed. Computational experiments show that this approach is acceptable for small and medium-sized problem instances.

Jayaraman and Pirkul (2001) also consider a joint production and distribution facility location and a distribution planning problem in a multi-commodity environment. A mixed integer programming formulation is given and a heuristic procedure based on Lagrangean relaxation is evaluated on a problem involving 75 customer zones, 30 warehouse locations, 5 plant locations, 2 vendors and 2 types of raw materials.

Jayaraman and Ross (2003) describe the PLOT design system (Production, Logistics, Outbound, Transportation), characterized by one central manufacturing site, multiple distribution center and cross-docking sites and customer zones with demand for multiple items. The PLOT design system is a sequential approach using two different models. The first is a strategic model in which decisions on opening or closing warehouses and cross-docks, and on assigning customer zones to cross-docks and cross-docks to warehouses for each commodity are made. The second model in the PLOT design system is an operational model in which the optimal flow of goods is determined through the network proposed by the first model. A simulated annealing algorithm is presented that solves both models simultaneously. Computational experiments with up to 5 warehouses, 15 cross docks, 75 customer zones and 3 commodities are reported. Within one second, these problem instances can be solved to within 5% from optimality.

In their 1997 review on production-distribution models, Vidal and Goetschalckx (1997) pointed out that there was a lack of models taking the complex bill of materials (BOM)

constraints into account. Yan et al. (2003) are the first to fully integrate BOM considerations into a multi-commodity, multi-echelon location single period problem in which suppliers are selected from a candidate set of material (or component) suppliers, and a number of production and distribution facilities are located subject to production and distribution facility restrictions and demand requirements. In previous approaches (e.g. Cohen and Lee, 1988; Cohen et al., 1989; Cohen and Lee, 1989; Antzen et al., 1995) BOM requirements just act as a consistency check instead of steering or coordinating the behavior of suppliers with the production and distribution activities. LINDO is used to solve a small-scale problem instance involving four suppliers, three producers, three DCs, and four customer zones providing no insights on the applicability of the model for medium to large scale problem instances.

Table 3. Multiple echelon location problems

	Year	Objective function	Number of echelons in the P&D system	Number of echelons to be located	Number of plants	Number of warehouses/crossdocks	Number of customers	Number of commodities	Capacity restrictions	Stochastic or deterministic demand	Number of time-periods	Side-constraints	Capacity acquisition	International features	Industrial application
Hinojosa et al.	2000	C	3	2	40	40	75	2	Y	D	4	MNP/MND			
Jayaraman and Pirkul	2001	C	4	2	10	15	75	3	Y	D	1	MaxDC			
Goetschalckx et al.	2002	C	4	2	6	6	238	12	Y	D	3		MLL		
Jang et al.	2002	C	4	2	4	3	4	4/3	Y	D	1	BOM			
Syam	2002	C	3	2	10	6	NA	5	Y	D	1	SC			
Jayaraman and Ross	2003	C	4	2	1	5/15	75	3	Y	D	1				
Yan et al.	2003	C	4	3	3	3	4	6/2	Y	D	1	BOM			Y
Ambrosino and Scutellà	2004	C	3	2	3	25	135	1	Y	D	1				Y

MNP/MND = minimum number of plants/DCs; MaxDC= max number of warehouses; MLL = Manufacturing line location; SC = Shipment consolidation

Ambrosino and Scutellà (2005) offer a mathematical programming formulation for a number of static and dynamic scenarios based on the general multi-echelon location problem discussed above. To explore the computational complexity of the models, linear programming approaches are used to find the optimal solution or at least provide lower bounds for problem instances based on a real-life case. Computational testing is limited to locating distribution and transshipment points and assigning large customers and customer zones to these distribution facilities. As such, the multiple echelon approach and routing considerations discussed in the earlier sections are not explored in the computational

experiments. The optimal solution could only be found for the smallest problem instance, involving possible locations for 2 distribution centers, 5 transshipment points, 5 large customers and 25 customer zones. As the problem instances become larger, the gap between the best integer solution found, within a time limit of several days for the large instances, and the MIP lower bound provided by CPLEX increases rapidly up to more than 45%. As a result, heuristic approaches seem to be more appropriate, even for the scaled down problems used for the computational experiments.

3. Production-Distribution Planning

This section surveys models that redesign existing production distribution networks, after strategic decisions on the location of facilities have been taken, to assign customers to facilities, also taking into consideraton the location, timing and size of inventories, sometimes in the face of international features such as impact of price and exchange rate uncertainties, tariffs and duties. International characteristics in pre 1996 logistics models are surveyed in Goetschalckx et al. (2002a). The paper also presents two new mixed integer programming models: one on setting transfer prices and optimizing material flows to maximize profits for a multi-national corporation, and a second on multi-period production and distribution allocation and scheduling in a single country for a company facing seasonal demand. Both models are solved heuristically, the first by an iterative heuristic approach alternating between the optimizing of transfer prices and material flows, the second by a decomposition approach for production and transportation decisions.

In Mohamed (1999) an integrated production-distribution model is presented for a multi-national company (MNC) operating in an environment of changing exchange rates. Decisions variables in the model include capacity planning (opening, closing and retaining facilities), assigning products to the facilities, inventory levels and distribution of products to markets. The MIP formulation of the problem is solved for a number of small scale problems and managerial insights are formulated.

Dhaenens-Flipo and Finke (2001) formulate a multi-period model for production and distribution decisions for a multi-facility, multi-product industrial problem with seasonal demand. Relatively few additional 0-1 variables are used to describe the linking constraints between periods. An application involving 10 plants, 16 production lines, 16 products, 12 periods, 50 warehouses and 300 distribution points could be solved using CPLEX, but for large-scale applications the authors suggest the heuristic approach from Dhaenens-Flipo (2000).

Mallya et al. (2001) present a linear programming model with a rolling horizon for multi-facility, multi-product, multi-period production-distribution planning in continuous manufacturing. The implementation of the model in an anonymous continuous large process company using EXCEL, ACCESS and AMPL resulted in an increase of annual throughput of 15% and reduced inventory levels by about 22%.

Jang et al. (2002) decompose the entire network into three sub-networks, the inbound network, accommodating the BOM relationship between sub-plants and plants, the distribution network and the outbound network. The design problem is solved with Lagrangean relaxation heuristics. The subsequent integrated production and distribution planning problem is also split into three overlapping multi-stage, multi-product sub-models: the P-P-P model, the P-P-W model and the W-D-C model (where P = plant, W = warehouse,

D = distribution center, C = customer). A genetic algorithm solution approach is proposed for these sub-models, and illustrated on the P-P-P model. For problems with 5 periods, 4 components and 3 end-products in networks with up to 6 suppliers, 4 plants, 3 DCs and 4 customer zones, a gap between the GA solution and the optimal solution of 0.2% is reported.

Lee and Kim (2002) and Lee et al. (2002) combine an analytical and simulation method for addressing a multi-period, multi-product, multi-shop production and distribution problem. By regarding operation time, machine capacity or distribution capacity constraints in the analytical LP model as stochastic factors to be adjusted according to the results of the underlying simulation model, more realistic production-distribution plans are aspired to.

Table 4. Production-distribution planning

	Year	Objective function	Number of echelons in the P&D system	Number of echelons to be located	Number of plants	Number of warehouses/crossdocks	Number of customers	Number of commodities	Capacity restrictions	Stochastic or deterministic demand	Number of time-periods	Side-constraints	Capacity acquisition	International features	Industrial application
Mohamed	1999	P	2	0			3	1	Y	D	3			Y	N
Dhaenens-Flipo and Finke	2001	C	4	0	10	50	300	8	Y	D	12			Y	Y
Mallya et al.	2001	C	3	0					Y	D	22	BOM			Y
Goetschalckx et al.	2002	P	4		8	10	80	35/12	Y	D	1	BOM		TP	
Jang et al.	2002	C	4		4	3	4	4/3	Y	D	1	BOM			
Lee and Kim	2002	C	3	0	2	2	3	2	Y	D	3				
Lee et al.	2002	C	3	0	2	2	3	2	Y	D	3				
Romeijn and Morales	2003	C	2		5		300	1	Y	D	6				N
Bhutta et al.	2003	C	2		3		4	2	Y	D	NA		Y	Y	N
Santoso et al.	2005	P	3	1	87	17	17	29	Y	S	1		Y	N	Y

TP = transfer prices; BOM = Bill of Materials

International features are ignored in the multi-period single sourcing problem by Romeijn and Morales (2003). In their cyclic model, a fixed set of production and distribution facilities is considered, and customers are assigned to a single facility in each period. Facilities are assumed to have sufficient production capacity, unlimited physical storage capacity and throughput capacity. Production costs and inventory costs are assumed to be linear and transportation costs are carried out by a third-party logistics service provider so that each customer receives an individual shipment. Even determining whether there exists a feasible solution to the multi-period single sourcing problem is NP-complete (Martello and Toth 1990), and consequently the problem is reformulated as a generalized assignment problem with a nonlinear objective function. A new class of pseudo-cost functions is designed for the

greedy heuristic by Martello and Toth (1981) and proven to be asymptotically feasible and optimal in a probabilistic sense.

Bhutta et al. (2003) extend existing models on multi-national corporation facility location models by including exogenous variables such as exchange rates, tariffs in the decision on facility configurations, production levels and distribution strategies. The mixed integer linear formulation of the problem is solved for small problem instances, confirming accepted economic theories.

Santoso et al. (2005) propose a stochastic programming approach for addressing uncertainty in large scale supply chain networks. Whereas previous approaches (MirHassani et al. 2000; Alonso-Ayuso et al. 2003; Tsiakis et al. 2001) are limited to a small number of scenarios, the suggested sample average approximation scheme and accelerated Benders decomposition are able to account for a large number of scenarios for problem instances of a realistic scale. The approach is tested on a cost minimization domestic and a cash flow maximation global case involving international model features.

4. Conclusions and reseach directions

The existing literature on supply chain design and supply chain planning already addresses the key issues for optimizing global supply chains. The literature since 1999 has been directed at augmenting production-distribution models with real-life features and has addressed joint production-distribution issues. The majority of the research, however, still focuses on single echelon optimization. Papers that do address multi-echelon optimization problems often provide interaction through an iterative sequential approach instead of offering an integrated solution approach. The increased complexity of integrated solution approaches and hence the greater computational effort that is required to solve them can offset the potential advantages of an integrated optimization approach. A decomposition approach has the additional advantage of being more flexible in dealing with the different time grid (size of time buckets) at the different levels (strategic, tactical, operational) of supply chain decision. Decomposition of production distribution problems also allows distribution decisions to be modeled realistically by only a limited number of product groups (e.g. containers, full truckloads, reefers, etc.).

The potential of metaheuristics, possibly combined with exact solution techniques for sub-problems, remains largely unexplored. Comparing the computational power of various approaches to production-distribution problems clearly requires a standard set of challenging problem instances. Such test sets do exist for standard single echelon location problems (capacitated and uncapacitated facility location problems), but are unavailable for advanced multi-echelon production-distribution problems. As such the evaluation of proposed solution techniques and the development of high-quality exact and metaheuristic methods are hampered.

Acknowledgements

References

Alonso-Ayuso, A., Escudero, L.F., Garin, A., Ortuno, M.T. and Perez, G. (2003). An approach for strategic supply chain planning under uncertainty based on stochastic 0-1 programming. *Journal of Global Optimization*, vol. 26, pp. 97-124.

Ambrosino, D. and Scutellà, M.G. (2005). Distribution network design: New problems and related models. *European Journal of Operational Research*, vol. 165, no. 3, pp. 610-624.

Antunes, A. and Peeters, D. (2001). On solving complex multi-period location models using simulated annealing. *European Journal of Operational Research*, vol. 130, pp. 190-201.

Antzen, B.C., Brown, G.G., Harrison, T.P. and Trafton, L.L. (1995). Global supply chain management at Digital Equipment Corporation. *Interfaces*, vol. 25, pp. 69-93.

Balakrishnan, J. (2004). An improved algorithm for solving a multi-period facility location problem. *IIE Transactions*, vol. 36, pp. 19-22.

Benjamin, J. (1989). An analysis of inventory and transportation costs in a constrained network. *Transportation Science*, vol. 23, no. 3, pp. 177-183.

Bhutta, K.S., Huq, F., Frazier, G. and Mohamed, Z. (2003). An integrated location, production, distribution and investment model for a multinational corporation. *International Journal of Production Economics*, vol. 86, pp. 201-216.

Burkard, R.E.. (2000). Location problems: From classical geometry to managerial decisions. *Central European Journal of Operational Research*, vol. 8, pp. 3-11.

Canel, C., Khumawala, B.M., Law, J. and Loh, A. (2001). An algorithm for the capacitated, multi-commodity, multi-period facility location problem. *Computers & Operations Research*, vol. 28, pp. 411-427.

Chandra, P. and Fisher, M.L. (1994). Coordination of production and distribution planning. *European Journal of Operational Research*, vol. 72, pp. 503-517.

Cohen, M.A. and Lee, H.L. (1988). Strategic analysis of integrated production-distribution systems: models and methods. *Operations Research*, vol. 36, pp. 216-28.

Cohen, M.A., Fisher, M. and Jaikumar, R. (1989). International manufacturing and distribution networks: a normative model framework. In: Ferdows, K. (ed.), *Managing international manufacturing*, Amsterdam, The Netherlands, pp. 67-93.

Cohen, M.A., and Lee, H.L. (1989). Resource development analysis of global manufacturing and distribution networks. *Journal of Manufacturing and Operations Management*, vol. 2, pp. 81-104.

Correia, I. and Captivo, M.E. (2003). A Lagrangean heuristic for a modular capacitated location problem. *Annals of Operations Research*, vol. 122, pp. 141-161.

Crainic, T.G., Gendreau, M., Soriano, P. and Toulouse, M. (1993). A tabu search procedure for multicommodity location/allocation with balancing constraints. *Annals of Operations Research*, vol. 41, pp. 359-383.

Dasci, A. and Verter, V. (2001a). A continuous model for production-distribution system design. *European Journal of Operational Research*, vol. 129, pp. 287-298.

Dasci, A. and Verter, V. (2001b). The plant location and technology acquisition problem. *IIE Transactions*, vol. 33, pp. 963-973.

Daskin, M.S., Coullard, C.R. and Shen, Z-J.M. (2002). An inventory-location model: formulation, solution algorithm and computational results. *Annals of Operations Research*, vol. 110, pp. 83-106.

Dhaenens-Flipo, C. and Finke, G. (2001). An integrated model for an industrial production-distribution problem. *IIE Transactions*, vol. 33, pp. 705-715.

Dhaenens-Flipo, C. (2000). Spatial decomposition for a multi-facility production and distribution problem. *International Journal of Production Economics*, vol. 64, pp. 177-186.

Efroymson, M.A. and Ray, T.L. (1966). A branch and bound algorithm for plant location. *Operations Research*, vol. 26, pp. 361-368.

Erengüç, S.S., Simpson, N.C. and Vakharia, A.J. (1999). Integrated production/distribution planning in supply chains: An invited review. *European Journal of Operational Research*, vol. 115, pp. 219-236.

Erlebacher, S.J. and Meller, R.D. (2000). The interaction of location and inventory in designing distribution systems. *IIE Transactions*, vol. 32, pp. 155-166.

Eskigun, E., Uzsoy, R., Preckel, P.V., Beaujon, G., Krishnan, S. and Tew, J.D. (2004). Outbound supply chain design with mode selection, lead times and capacitated distribution centers. *European Journal of Operational Research*, vol. 165, no. 1, pp. 182-206.

Garey, M.R. and Johnson, D.S. (1979). *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W.H. Freeman and Co.

Gendron, B., Potvin, J.-Y. and Soriano, P. (2003). A tabu search with slope scaling for the multicommodity capacitated location problem with balancing requirements. *Annals of Operations Research*, vol. 122, pp. 193-217.

Goetschalckx, M., Vidal, C.J. and Dogan, K. (2002a). Modeling and design of global logistics systems: A review of integrated strategic and tactical models and design algorithms. *European Journal of Operational Research*, vol. 143, pp. 1-18.

Goetschalckx, M., Nair-Reichert, U., Ahmed, S. and Santoso, T. (2002b). *A review of state-of-the-art and future research directions for the strategic design of global supply chains*. MHRC 2002 Portland, Maine.

Hidaka, K., and Okano, H. (2003). An approximation algorithm for a large-scale facility location problem. *Algorithmica*, vol. 35, pp. 216-224.

Hinojosa, Y., Puerto, J. and Fernández, F.R. (2000). A multiperiod two-echelon multicommodity capacitated plant location problem. *European Journal of Operational Research*, vol. 123, pp. 271-291.

Ho, P.-K. and Perl, J. (1995). Warehouse location under service-sensitive demand. *Journal of Business Logistics*, vol. 16, no. 1, pp. 133-150.

Hormozi, A.M. and Khumawala, B.M. (1996). An improved algorithm for solving a multi-period facility location problem. *IIE Transactions*, vol. 28, pp. 105-114.

Hwang, H-S. (2002). Design of supply-chain logistics system considering service level. *Computers & Industrial Engineering*, vol. 43, pp. 283-297.

Jang, Y-J., Jang, S-Y., Chang, B-M. and Park, J. (2002). A combined model of network design and production/distribution planning for a supply network. *Computers and Industrial Engineering*, vol. 43, pp. 263-281.

Jayaraman, V. and Pirkul, H. (2001). Planning and coordination of production and distribution facilities for multiple commodities. *European Journal of Operational Research*, vol. 133, pp. 394-408.

Jayaraman, V. and Ross, A. (2003). Simulated annealing methodology to distribution network design and management. *European Journal of Operational Research*, vol. 144, pp. 629-645.

Kalfakakou, R. and Tsouros, C.C. (2001). Determining the size and location of suppliers for a minimum total distribution route problem. *International Journal of Production Economics*, vol. 71, pp. 401-405.

Khouja, M. (2003). Optimizing inventory decisions in a multi-stage multi-customer supply chain. *Transportation Research Part E*, vol. 39, pp. 193-208.

Kirca, O. and Koksalan, M.M. (1996). An Integrated Production and Financial Planning Model: An Application. *IIE Transactions*, vol. 28, pp. 677-686

Krarup, J. and Pruznan, P.M. (1983). The simple plant location problem: survey and synthesis. *European Journal of Operational Research*, vol. 12, pp. 36-81.

Lee, Y.H. and Kim, S.H. (2002). Production-distribution planning in supply chain considering capacity constraints. *Computers & Industrial Engineering*, vol. 43, pp. 169-190.

Lee, Y.H., Kim, S.H. and Moon, C. (2002). Production-distribution planning in supply chain using a hybrid approach. *Production Planning & Control*, vol. 13, pp. 35-46.

Lim, S.K. and Kim, Y-D. (1999). An integrated approach to dynamic plant location and capacity planning. *Journal of the Operational Research Society*, vol. 50, pp. 1205-1216.

Liu, S.C. and Lee, S.B. (2003). A two-phase heuristic method for the multiple-depot location routing problem taking inventory control decisions into consideration. *International Journal of Advanced Manufacturing Technology*, vol. 22, pp. 941-950.

Mallya, S., Banerjee, S. and Bistline, W.G. (2001). A decision support system for production/distribution planning in continuous manufacturing. *Decision Sciences*, vol. 32, no. 3, pp. 545-556.

Martello, S. and Toth, P. (1981). An algorithm for the generalized assignment problem. In: Brans, J.P. (ed.) *Operational Research '81*. IFORS, Amsterdam, The Netherlands, pp. 589-603.

Martello, S. and Toth, P. (1990). *Knapsack problems, algorithms and computer implementations*. Wiley, New York

Melkote, S. and Daskin, M.S. (2001). An integrated model of facility location and transportation network design. *Transportation Research Part A*, vol. 35, pp. 515-538.

MirHassani, S.A., Lucas, C., Mitra, G., Messina, E. and Poojari, C.A. (2000). Computational solution of capacity planning models under uncertainty. *Parallel Computing*, vol. 26, pp. 511-538.

Mohamed, Z.M. (1999). An integrated production-distribution model for a multi-national company operating under varying exchange rates. *International Journal of Production Economics*, vol. 58, pp. 81-92.

Nickel, S. and Puerto, J. (1999). A Unified Approach to Network Location Problems. *Networks*, vol. 34, pp. 283-290.

Nozick, L.K. and Turnquist, M.A. (2001). Inventory, transportation, service quality and the location of distribution centers. *European Journal of Operational Research*, vol. 129, pp. 362-371.

Romeijn, H.E. and Morales, D.R. (2003). An asymptotically optimal greedy heuristic for the multiperiod single-sourcing problem: the cyclic case. *Naval Research Logistics*, vol. 50, pp. 412-437.

Santoso, T., Ahmed, S., Goetschalckx, M. and Shapiro, A. (2005). A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research*, vol. 167, pp. 96-115.

Sarmiento, A.M. and Nagi, R. (1999). A review of integrated analysis of production-distribution systems. *IIE Transactions*, vol. 31, no. 11, pp. 1061-1074.

Schmidt, G. and Wilhelm, W.E. (2000). Strategic, tactical and operational decisions in multi-national logistics networks: a review and decision of modelling issues. *International Journal of Production Research*, vol. 38, no. 7, pp. 1501-1523.

Schilling, D.A., Rosing, K.E. and ReVelle, C.S. (2000). Network distance characteristics that affect computational effort in *p*-median location problems. *European Journal of Operational Research*, 127, pp. 525-536.

Sridharan, R. (1995). The capacitated plant location problem. *European Journal of Operational Research*, vol. 87, pp. 203-213.

Srivastava, R. (1993). Alternate solution procedures for the location-routing problem. *Omega*, vol. 21, pp. 497-506.

Syam, S.S. (2002). A model and methodologies for the location problem with logistical components. *Computers & Operations Research*, vol. 29, pp. 1173-1193.

Tong, H. and Walter, C.K. (1980). An empirical study of plant location decisions of foreign manufacturing investors in the United States. *Columbia Journal of World Business*, pp. 66-73.

Tsiakis, P., Shah, N. and Pantelides, C.C. (2001). Design of multi-echelon supply chain networks under demand uncertainty. *Industrial & Engineering Chemistry Research*, vol. 40, pp. 3585-3604.

Tuzun, D. and Burke, L.I. (1999). A two-phase tabu search approach to the location routing problem. *European Journal of Operational Research*, vol. 116, pp. 87-99.

Verter, V. and Dasci, A. (2002). The plant location and flexible technology acquisition problem. *European Journal of Operational Research*, vol. 136, pp. 366-382.

Verter, V. and Dincer, M.C. (1995). Facility location and capacity acquisition: an integrated approach. *Naval Research Logistics*, vol. 42, pp. 1141-1160

Vidal, C.J., and Goetschalckx, M. (1997). Strategic production-distribution models: a critical review with emphasis on global supply chain models. *European Journal of Operational Research*, vol. 98, pp. 1-18.

Wang, Q., Batta, R., Bhadury, J. and Rump, C.M. (2003). Budget constrained location problem with opening and closing of facilities. *Computers & Operations Research*, vol. 30, pp. 2047-2069.

Wasner, M. and Zäpfel, G. (2004). An integrated multi-depot hub location vehicle routing model for network planning of parcel service. *International Journal of Production Economics*, vol. 90, no. 3, pp. 403-419.

Wiles, P.G. and Van Brunt, B. (2001). Optimal location of transshipment depots. *Transportation Research Part A*, vol. 35, pp. 745-771.

Wouda, F.H.E., Van Beek, P., Van der Vorst, J.G.A.J. and Tacke, H. (2002). An application of mixed-integer linear programming models on the redesign of the supply network of Nutricia Dairy & Drinks Group in Hungary. *OR Spectrum*, vol. 24, pp. 449-465.

Wu, T-H., Low, C. and Bai, J-W. (2002). Heuristic solutions to multi-depot location-routing problems. *Computers & Operations Research*, vol. 29, pp. 1393-1415.

Yan, H., Yu, Z. and Cheng, T.C.E. (2003). A strategic model for supply chain design with logical constraints: formulation and solution. *Computers & Operations Research*, vol. 30, pp. 2135-2155.