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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Network Design Decisions in Supply Chain Planning

M.T. Melo, S. Nickel and F. Saldanha-da-Gama

Abstract Structuring global supply chain networks is a complex decision-making process. The typical inputs to such a process consist of a set of customer zones to serve, a set of products to be manufactured and distributed, demand projections for the different customer zones, and information about future conditions, costs (e.g. for production and transportation) and resources (e.g. capacities, available raw materials). Given the above inputs, companies have to decide where to locate new service facilities (e.g. plants, warehouses), how to allocate procurement and production activities to the various manufacturing facilities, and how to manage the transportation of products through the supply chain network in order to satisfy customer demands. We propose a mathematical modelling framework capturing many practical aspects of network design problems simultaneously. For problems of reasonable size we report on computational experience with standard mathematical programming software. The discussion is extended with other decisions required by many real-life applications in strategic supply chain planning. In particular, the multi-period nature of some decisions is addressed by a more comprehensive model, which is solved by a specially tailored heuristic approach. The numerical results suggest that the solution procedure can identify high quality solutions within reasonable computational time.

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1 Introduction

Supply Chain Management (SCM) is the process of planning, implementing and controlling the operations of the supply chain efficiently. SCM spans all movements and storage of raw materials, work-in-process inventory, and finished goods from the point-of-origin to the point-of-consumption (see [34]). Part of the planning processes in SCM aim at finding the best possible supply chain configuration so that all operations can be performed in an efficient way. This entails integrating facility location with other important functions of the supply chain such as procurement, production, inventory, distribution, and routing.

Typically, three planning levels are distinguished depending on the time horizon: strategic, tactical and operational (see [4]). As stated in [34], “the strategic level deals with decisions that have a long-lasting effect on the firm. These include decisions regarding the number, location and capacities of warehouses and manufacturing plants, or the flow of material through the logistics network”. This statement establishes a clear link between location models and strategic SCM.

The terms *network design* and *supply chain network design* (SCND) are often employed as synonyms of strategic supply chain planning (see [5, 21, 33]). Although typically no location decisions are made on the tactical or even operational level, a number of issues are strongly related to them such as inventory control policies, the choice of transportation modes and capacities, warehouse layout and management, and vehicle routing. According to [38], “in today’s competitive market, a company’s distribution network must meet service goals at the lowest possible cost. In some instances, a company may be able to save millions of dollars in logistics costs and simultaneously improve service levels by redesigning its distribution network. To achieve this, an ideal network must have the optimum number, size, and location of warehouses to support the inventory replenishment activities of its retailers”. This statement calls for sophisticated facility location models to determine the best supply chain configuration. Moreover, it underlines the interrelation between the strategic and the tactical/operational planning levels.

From the above reasoning it becomes clear that good location models are needed to support the SCND phase. Moreover, certain aspects should be taken explicitly into consideration to obtain a facility location model that is compatible with the planning needs of the supply chain environment. Naturally, facility location and supply chain aspects could be handled in an iterative manner. The approach followed in [37] is such an example of non-integrated decision-making in SCND: first, new facilities are selected from a candidate set and next, the corresponding transportation problem is solved. Since the two problems are solved separately, they do not fulfill the requirements of SCM to find a global optimal network configuration. The motivation for using an iterative methodology is due to the fact that location decisions may impose a strong simplification on the tactical/operational level (especially those directly related to the location of new facilities). However, optimality can only be guaranteed with full integration (see [12, 17]).

The remainder of this chapter is organized as follows. Section 2 describes the general settings and assumptions of classical facility location models and discusses the reasons why such models are not suitable to support strategic decisions in supply chain planning. Section 3 introduces a comprehensive model that captures important practical aspects of SCND. Section 4 is dedicated to a number of features specific to strategic SCM but which have not received adequate attention in the literature on facility location. One of the discussed aspects concerns an extended planning horizon which is further examined in Section 5 through the development of a multi-period facility relocation model. A novel heuristic approach based on tabu search is briefly described for solving this problem. Finally, Section 6 presents some conclusions and possible directions for future research.

2 Classical models

Historically, researchers have focused relatively early on the design of distribution systems (see [14]), but without considering the supply chain as a whole. Typically, a discrete facility location model was proposed which possibly included some additional features. As early as 1985, some important mixed-integer linear formulations for production-distribution systems were reviewed in [1]. However, these models had limited scope and could not deal with a realistic supply chain structure. Later in the 90's, [14] argued that the first steps towards embedding relevant features for SCM in facility location models were being gradually taken. These included: (i) customer-specific product subsets; (ii) lower as well as upper limits on the shipments of a given product at a given plant; (iii) product specific weighting factors for throughput measures at distribution centres (DCs); (iv) piecewise linear approximations to non-linear costs; (v) the ability to locate plants as well as DCs; (vi) joint capacity constraints across products at plants; (vii) raw material conversion activities at one or two layers; (viii) additional distribution and production layers. By the same time, [29] also suggested including additional features in facility location models, namely new objectives (e.g. maximum return on investment) and decisions related to the choice of equipment to be installed in new facilities.

In a discrete facility location problem, the selection of the sites where new facilities are to be established is restricted to a finite set of available candidate locations. The simplest setting of such a problem is the one in which p facilities are to be selected to minimize the total (weighted) distances or costs for supplying customer demands. This is the so-called p-median problem which has attracted much attention in the literature (see e.g. [7, 9, 30]). This setting assumes that all candidate sites are equivalent in terms of the setup cost for establishing a new facility. When this is not the case, the objective function is extended with a term for fixed facility location costs and as a result, the number of facilities to be open typically becomes an endogenous decision. This new setting is known in the literature as the uncapacitated facility location problem (UFLP). Extensive references to the UFLP can be found, for example, in [25] and [31]. In both the p-median problem and the UFLP, each customer is allocated to the open facility that minimizes his/her assignment cost. One of the most important extensions of the UFLP is the capacitated facility location problem (CFLP), in which exogenous values are considered for the maximum demand that can be supplied from each potential site. In this case, the closest-assignment property is no longer valid.

The above mentioned models have several common characteristics namely, a single-period planning horizon, deterministic parameters (i.e. demands and costs), a single product, one type of facility, and location-allocation decisions. Clearly, these models are insufficient to handle realistic facility location settings. Therefore, many extensions to the basic problems have been proposed and extensively studied.

A crucial aspect of many practical location problems regards the existence of different types of facilities, each one of which playing a specific role (e.g. production or warehousing), and a natural material flow (that is, a hierarchy) between them. Each set of facilities of the same type is usually denoted by a layer or an echelon, thus defining a level in the hierarchy of facilities. Starting with the pioneering article [19], new facility location models emerged taking several facility layers into account. The problem studied in [19] addressed the simultaneous location of plants and warehouses. It was further extended in [36] through the consideration of a general number of location layers. Many other papers can be found in the literature addressing this topic (see [32]). From the point of view of core location analysis, very little importance has been given to intra-layer material flows. Moreover, the possibility of direct flows from upper layers to customers (or to layers not immediately below) has been scarcely addressed in the literature.

Another aspect driven by real-life applications, and that has raised much attention in the literature, refers to multiple commodities. The pioneering work by [41] was a starting point for the development of new models (see [20] and references therein). The models developed in [11] and [13] combined both aspects – multiple layers and commodities – by considering two facility layers, capacitated facilities and different products. However, location decisions were restricted to the layer dedicated to warehousing.

In synthesis, the features captured by classical models are summarized as follows:

- Networks are too specific and although they include a categorization of facilities into levels, usually at most three levels are considered;
- Materials can only flow from one level to the next (e.g. from plants to DCs and/or from DCs to customers);
- Strategic decisions only focus on facility location and allocation of customers to the operating facilities;
- Facility location is usually restricted to one or two levels (plants and/or DCs);
- Demand is assumed to occur only at the lowest level of the network.

Although core facility location models, such as the UFLP and the CFLP, are a long way from approaching realistic problems in strategic supply chain planning, they (and many of their extensions) have been extremely helpful as a basis for building comprehensive models that include SCM decisions in addition to location. In the next section we describe a mathematical optimisation model that captures various practical aspects playing an important role in SCND.

3 A facility location model featuring supply chain aspects

We consider a supply chain network with a general structure as the one depicted in Figure 1. Location decisions concern the maintenance of existing facilities and the setup of new facilities. The latter are chosen from a pre-defined set of candidate sites. Furthermore, location planning may be conducted for different types of facilities simultaneously (e.g. plants and DCs). Strategic decisions also focus on procurement, production, distribution, capacity expansion, and customer demand satisfaction. A bill of materials (BOM) may be specified for each end product listing the requirements for components, subassemblies and raw materials. The objective is to determine the optimal network configuration so as to minimize total costs. These include fixed charges for opening new and closing existing facilities, and variable procurement, production, transportation, resource expansion, and penalty demand costs.

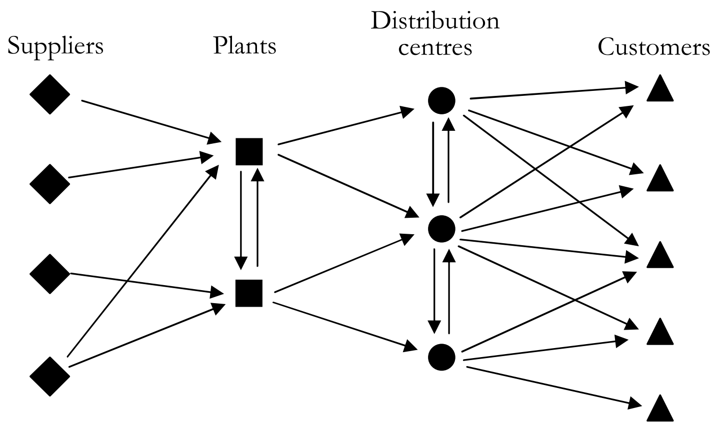

Fig. 1 A general supply chain network.

Let L denote the set of all facilities. These are categorized in so-called *selectable* and *non-selectable* facilities. Selectable facilities include both existing facilities (the set S^c), that may be closed, and potential sites for establishing new facilities (the set S^o). Observe that $S = S^c \cup S^o$, $S^c \cap S^o = \emptyset$ and $S \subseteq L$, with S denoting the subset of all selectable facilities. Non-selectable facilities form the set $L \setminus S$ and include those existing facilities that must remain in operation. Plants and warehouses that must continue supporting supply chain activities, and are therefore not subject of location decisions, belong to this set. Note that customers are also viewed as special non-selectable facilities having demand requirements for given commodities. Furthermore, let P denote the set of all product types ranging from raw materials and components to end products. The set of production resources is denoted by R^p and represents available production equipment. Moreover, resources required to handle commodities (e.g. material handling equipment such as forklifts) belong to the set R^h. Further notation is introduced as follows:

Costs

$BC_{\ell,p}$: unit cost of procuring product $p \in P$ at facility $\ell \in L$ from an external supplier
$MC_{\ell,p}$: unit cost of manufacturing product $p \in P$ at facility $\ell \in L$
$TC_{\ell,\ell',p}$: unit cost of transporting product $p \in P$ from facility $\ell \in L$ to facility $\ell' \in L \setminus \{\ell\}$
EPC_r : unit cost of expanding production resource $r \in R^p$
EHC_r : unit cost of expanding handling resource $r \in R^h$
$PDC_{\ell,p}$: unit penalty cost for not satisfying demand for product $p \in P$ at facility $\ell \in L$
SC_ℓ : fixed cost for closing the existing selectable facility $\ell \in S^c$
FC_ℓ : fixed cost for opening the new selectable facility $\ell \in S^o$

Parameters

$\mu_{\ell,r,p}$: number of units of production resource $r \in R^p$ required to manufacture one unit of product $p \in P$ at facility $\ell \in L$
$\lambda^i_{\ell,r,p}$: number of units of handling resource $r \in R^h$ consumed upon receiving one unit of product $p \in P$ at facility $\ell \in L$
$\lambda^o_{\ell,r,p}$: number of units of handling resource $r \in R^h$ consumed upon shipping one unit of product $p \in P$ out of facility $\ell \in L$
PR_r : available capacity of production resource $r \in R^p$
EPR_r : maximum allowed capacity expansion of production resource $r \in R^p$
HR_r : available capacity of handling resource $r \in R^h$
EHR_r : maximum allowed capacity expansion of handling resource $r \in R^h$
$D_{\ell,p}$: demand for product $p \in P$ at facility $\ell \in L$
$a_{\ell,q,p}$: number of units of product $q \in P$ required to produce one unit of product $p \in P$ $(q \neq p)$ at facility $\ell \in L$
M : arbitrarily large constant

Decision variables

$b_{\ell,p}$: number of units of product $p \in P$ procured by facility $\ell \in L$ from an external supplier
$m_{\ell,p}$: number of units of product $p \in P$ manufactured at facility $\ell \in L$
$t_{\ell,\ell',p}$: number of units of product $p \in P$ transported from facility $\ell \in L$ to facility $\ell' \in L \setminus \{\ell\}$
x_r : number of units of production resource $r \in R^p$ required above its normal capacity

y_r : number of units of handling resource $r \in R^h$ required above its normal capacity
$z_{\ell,p}$: number of units of unsatisfied demand for product $p \in P$ at facility $\ell \in L$
δ_ℓ = 1 if the selectable facility $\ell \in S$ is operated, and 0 otherwise

Under the assumption that all inputs are nonnegative, our SCND problem is formulated as a mixed integer program (MIP) as follows:

$$(SCNDP) \quad \text{MIN} \quad \sum_{\ell \in L}\sum_{p \in P} BC_{\ell,p}\, b_{\ell,p} + \sum_{\ell \in L}\sum_{p \in P} MC_{\ell,p}\, m_{\ell,p} + \sum_{\ell \in L}\sum_{\ell' \in L\setminus\{\ell\}}\sum_{p \in P} TC_{\ell,\ell',p}\, t_{\ell,\ell',p}$$
$$+ \sum_{r \in R^p} EPC_r\, x_r + \sum_{r \in R^h} EHC_r\, y_r + \sum_{\ell \in L}\sum_{p \in P} PDC_{\ell,p}\, z_{\ell,p} + \sum_{\ell \in S^o} FC_\ell\, \delta_\ell$$
$$+ \sum_{\ell \in S^c} SC_\ell\,(1-\delta_\ell) \tag{1}$$

$$s.to: \quad b_{\ell,p} + \sum_{\ell' \in L\setminus\{\ell\}} t_{\ell',\ell,p} + m_{\ell,p} =$$
$$\sum_{q \in P} a_{\ell,p,q}\, m_{\ell,q} + \sum_{\ell' \in L\setminus\{\ell\}} t_{\ell,\ell',p} + D_{\ell,p} - z_{\ell,p} \quad \forall \ell \in L, \forall p \in P, \tag{2}$$
$$\sum_{\ell \in L}\sum_{p \in P} \mu_{\ell,r,p}\, m_{\ell,p} \le PR_r + x_r \quad \forall r \in R^p, \tag{3}$$
$$\sum_{\ell \in L}\sum_{p \in P} \lambda^i_{\ell,r,p}\, b_{\ell,p} + \sum_{\ell \in L}\sum_{\ell' \in L\setminus\{\ell\}}\sum_{p \in P}\left(\lambda^o_{\ell,r,p} + \lambda^i_{\ell',r,p}\right) t_{\ell,\ell',p} \le HR_r + y_r \quad \forall r \in R^h, \tag{4}$$
$$0 \le x_r \le EPR_r \quad \forall r \in R^p, \tag{5}$$
$$0 \le y_r \le EHR_r \quad \forall r \in R^h, \tag{6}$$
$$0 \le z_{\ell,p} \le D_{\ell,p} \quad \forall \ell \in L, \forall p \in P, \tag{7}$$
$$0 \le b_{\ell,p} \le M\,\delta_\ell,\; 0 \le m_{\ell,p} \le M\,\delta_\ell,\; 0 \le t_{\ell,\ell',p} \le M\,\delta_\ell \quad \forall \ell \in S, \forall p \in P, \tag{8}$$
$$0 \le t_{\ell,\ell',p} \le M\,\delta_\ell \quad \forall \ell \in S, \forall \ell' \in L\setminus\{\ell\}, \forall p \in P, \tag{9}$$
$$0 \le t_{\ell,\ell',p} \le M\,\delta_\ell \quad \forall \ell \in L\setminus\{\ell'\}, \forall \ell' \in S, \forall p \in P, \tag{10}$$
$$b_{\ell,p} \ge 0,\; m_{\ell,p} \ge 0,\; t_{\ell,\ell',p} \ge 0 \quad \forall \ell, \ell' \in L\setminus S, \forall p \in P, \tag{11}$$
$$\delta_\ell \in \{0,1\} \quad \forall \ell \in S. \tag{12}$$

The objective function (1) describes the costs to be minimized. These include variable procurement, production, transportation, capacity expansion, and penalty costs. The latter are charged to non-supplied demand. In addition, fixed costs for opening and closing facilities are also incurred. Constraints (2) are the usual flow conservation conditions. The inbound flow to facility ℓ regarding some product p results from procurement and production operations at the facility as well as from the total amount of product p transported from other facilities. The outbound flow in equations (2) includes the production of new commodities using product p as raw material, the total amount of p shipped to other facilities and the total satisfied demand. Constraints (3) and (4) guarantee that the capacity of production and handling resources is not exceeded. Constraints (5) and (6) refer to the maximum allowed expansion of production and handling resources. Constrains (7) impose an upper bound on the amount of unsatisfied demand. Inequalities (8)–(10) ensure that procurement, production and transportation activities only take place at operating facilities. Finally, constraints (11) and (12) represent non-negativity and binary conditions.

The above formulation (*SCNDP*) describes a comprehensive model which links facility location decisions with typical supply chain decisions such as procurement and production. The following list highlights the features that can be modelled with (*SCNDP*).

- No strict categorization of facilities into echelons is imposed a priori. Moreover, any type of facility can be considered. As a result, any network configuration can be modelled (e.g. plants, central and regional warehouses, customers);
- Products may flow between any type of facility (e.g. direct shipments from plants to customers, transportation of semi-finished products to other plants to be transformed into end products);
- Demand for multiple commodities may occur in any facility;
- Unfilled demand is allowed at the expense of penalty costs;
- Multi-stage production is considered along with the corresponding BOMs;
- No restrictions are imposed on the type of facilities to open/close;
- In addition to classic location and transportation decisions, other strategic decisions regarding procurement and production of commodities can be modelled;
- Production and handling resources are site and product independent. As a result, a resource may be used by different products in different facilities, thus generalizing the classic way capacity availability is modelled in facility location problems, where each facility has its own capacity;
- Consumption of handling resources may differ for incoming and outgoing products in a facility;
- The available capacity of production and handling resources can be extended (e.g. through overtime work) at the expense of additional costs.

Table 1 summarizes the results obtained by solving 144 randomly generated instances of model (*SCNDP*) with the commercial optimization solver CPLEX 8.0 [18] on a Pentium III PC with a 850 MHz processor and 1 GB RAM. The test instances refer to networks comprising plants, DCs and customers. Facility location decisions concern 10 existing DCs (which may be closed) and a set of 20 candidate sites for establishing new DCs. Each test instance has five plants and a total number of customers ranging from 50 to 200 (by taking multiples of 50). The latter have demand requirements for 5, 10 or 15 commodities. The generated networks have 70-80% of the total number of possible arcs for the transportation of goods. Direct shipments from plants to customers are allowed. Costs were drawn at random from uniform distributions over given intervals and assigned to the following operations and facilities: procurement costs at plants and DCs, production costs at plants, transportation costs through the network, opening costs of new DCs, and closing costs of existing DCs. Finally, three different types of availability of production and handling resources were considered: (i) unlimited resource capacity yielding uncapacitated problems, (ii) medium resource availability meaning that in some cases resource extension is necessary in order to satisfy demand requirements, and (iii) large resource availability so that most customer demands are satisfied with the available capacities. In (ii) and (iii), resource expansion costs were randomly generated and penalty costs for partial customer demand satisfaction were assigned very large values.

Problem class		# Variables	# Constraints	CPU time (s)	LP-gap (%)
Uncapacitated	Avg.	12859.4	13027.3	29.0	4.5
	Min.	2791.0	2567.0	2.7	0.2
	Max.	29344.0	30414.0	68.3	14.1
Medium capacity	Avg.	13563.1	13907.7	189.1	0.0
	Min.	2952.0	3085.0	3.9	0.0
	Max.	30908.0	31471.0	2002.5	0.3
Large capacity	Avg.	13563.2	13907.8	3113.8	8.8
	Min.	2951.0	3088.0	20.4	1.6
	Max.	30908.0	31470.0	13599.0	20.6

Table 1 Size of the test instances and performance of the CPLEX solver.

Columns three and four in Table 1 describe the size of the test instances by specifying the average, minimum and maximum number of variables and constraints of the corresponding formulation (*SCNDP*). Column five indicates the CPU time (in seconds) required to obtain the optimal solution of each test instance. As can be observed, the size of capacity has a strong impact on the CPU time, with the uncapacitated problems being the easiest to solve, as expected. The number of customer demands supplied by multiple DCs drops as the resource availability increases. Therefore, decreases in resource capacities compel more facilities to be established to satisfy demands, and lead to higher expenditures in setting up new facilities. As a result, customers may be "closer" to facilities, thereby reducing the transportation costs. However, a minimum cost network needs to be selected among a large number of different possible network configurations, thus accounting for the larger CPU times reported for the class of problems with large capacities. All instances could be solved in less than four hours which is an acceptable computational effort for a strategic planning problem.

As a measure of the tightness of the MIP formulation, column six in Table 1 displays the relative percentage deviation ("LP-gap") between the optimal solution value and the lower bound given by the linear relaxation. During our computational study we observed that the first feasible solution identified by CPLEX had, on average, reasonable quality and was obtained in less than 3.5 minutes. This is an attractive feature from a practitioner's viewpoint, since instead of waiting for the branch-and-cut tree to be completely explored by CPLEX, the user may specify a desired time limit for a problem to be solved and expect to obtain a good solution.

Finally, we refer the interested reader to [4] for a description of the integration of the above MIP model into the optimization suite *mySAP Supply Chain Management* developed by the software company SAP (Germany).

4 Additional features in supply chain design

In addition to the features analyzed in the previous section, and which led to the comprehensive model (*SCNDP*), there are several other aspects that should be taken into account while developing a facility location model that is compatible with the planning needs of the supply chain environment.

The first (and most obvious) group of features needed as an extension of general facility location models concern decisions related to transportation. Along with product shipments between facilities in the same layer and direct deliveries from higher level facilities to customer locations, also the following aspects should be analyzed:

- choice of transportation modes and capacities,
- setup of transportation links,
- selection of single or multi-sourcing relationships between facilities and customers.

Among the few contributions dedicated to the study of transportation modes we refer to [6] and [42]. In an international context, this is a consequence of the natural options of transportation around the world: by air, by sea or by land, as considered in [3].

A further group of extensions to classical location models refer to multiple facility layers and "location layers", as well as multiple commodities. While the latter feature has been often considered (cf. Section 2), the former two aspects are seldom addressed in an SCM context. As reported in a recent review of hierarchical location models [32], facility location problems have been mostly studied for single-level systems. However, from Figure 1, it is clear that one of the main characteristics of a supply chain network is its multi-layer structure. Therefore, location decisions should be modelled on different layers. On the upper level of the network, this corresponds to locating manufacturing plants, in the intermediate level to locating additional assembly sites, and in the lower levels to locating warehouses, DCs or even depots. Model (*SCNDP*) takes all these aspects into account.

The third group of issues to be considered by facility location models refer to the integration of supply chain activities into these models. In addition to procurement, multi-stage production (taking the BOM structure into account) and capacity expansion as modelled in (*SCNDP*), the following features should also be considered:

- capacity issues:
  - size of capacity (i.e. reduction or expansion of existing facilities either through modular or continuous sizes),
  - technology and equipment choice,
  - selection of capacity levels,
  - minimum throughput levels for a meaningful operation of facilities,
- inventory,
- routing.

The last two categories of decision variables - inventory and routing - have received increasing attention in the last decade. As emphasized in [8], inventory management involves two crucial tasks: the first is to determine the number of stocking points (e.g. DCs and/or warehouses), while the second is to define the level of inventory to maintain at each of these points. To avoid sub-optimization, these decisions should be regarded in an integrated perspective, namely with location decisions.

At some point in the downstream part of the supply chain, the transport volumes to the next layer may no longer be large enough to justify full truck loads. In this case, customers (or intermediate facilities) are delivered through routes. However, by changing the type of delivery also the cost of servicing the demand of a customer changes. In order to take this aspect into account, location-routing models are required (see [2], [26] and references therein). Ideally, one would like to approximate for every warehouse the cost of each delivery route without having to compute the exact route.

As a result of economic globalization, models for the strategic design of international supply chains have gained increasing importance (see [21, 39]). Financial factors are among the aspects having a strong impact on the configuration of global supply chains. They include taxes, duties, tariffs, exchange rates, transfer prices, and local content rules. The interaction between international location and financing decisions was studied, for example, in [17], [40] and [42].

Another important extension regards the consideration of stochastic components in facility location. Typical sources of uncertainty include customer demands, costs, exchange rates, capacities, and transportation times. The literature integrating stochasticity with location decisions in an SCM context is still scarce as shown in [28] due to the high complexity of the resulting models.

Finally, a meaningful extension of classical facility location problems is to consider a planning horizon composed of several time periods. Facility location and supply chain decisions are then to be planned for each period of the extended horizon. This feature will be detailed in the next section. We complete this section by referring the interested reader to [24], where facility location models are discussed extensively in the context of SCND and the above listed factors are surveyed.

5 Multi-period supply chain planning

In a network design project, large amounts of capital are typically allocated to new facilities, thus making this type of investment a long-term project. Therefore, facilities that are located now are expected to operate for an extended time period. Moreover, many parameters such as customer demands and costs change during a facility lifetime which may turn a good location today into a bad one in the future. If forecasts for the future unknown parameters are available, they can be used to obtain a network design that can handle these future changes. As a result, a planning horizon divided into several time periods is typically considered, and the best timing and phasing of strategic decisions is to be planned.

Network design decisions are mostly triggered by changing market conditions rather than by the need to build a new supply chain from scratch. Due to economic globalization and advances in information technology, the reconfiguration of an existing supply chain has become more frequent and its efficiency more important. Expansion opportunities to new markets, mergers, acquisitions, and strategic alliances are among the factors triggering a network redesign process. In the course of this process, existing facilities may be relocated to areas with more favorable economic conditions (e.g. lower labour costs). Facility relocation is a costly and time-consuming project that must be carefully planned to avoid sudden network disruptions. This case is handled in [22], [23] and [27] through gradual capacity transfers from existing facilities to new sites during a multi-period horizon. In particular, the model proposed in [23] considers a multi-echelon network with no restriction on the number of facility and location layers. The underlying assumptions refer to a number of customer zones with known demands for various commodities in each period of the planning horizon, a number of potential sites where new facilities can be established, a number of existing facilities that can be relocated to the new sites through the gradual transfer of their capacities over the planning horizon, and a limited budget for investing in facility relocation, opening new facilities and closing existing facilities. Figure 2 illustrates the various possible cases for capacity to be transferred from existing locations to new sites during a given period.

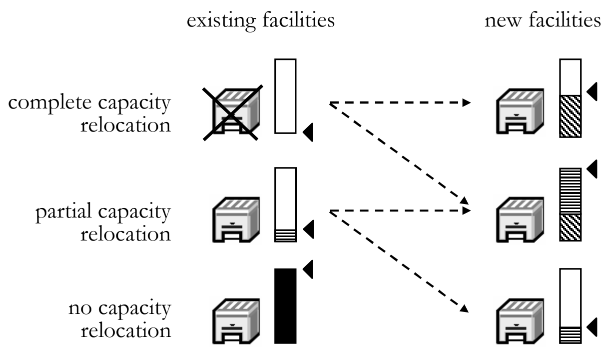

Fig. 2 The effect of capacity relocation.

The main strategic decisions to be made are outlined as follows:

- Which existing facilities should have their capacities partially or totally transferred and in which periods should relocation take place?
- How much capacity should be moved in each period?
- Which potential facility sites should be selected to receive the transferred capacities and when should they be established?
- How should commodities flow through the network and in particular, from which facilities should customer demands be satisfied in each period?

- Which facilities should hold stock? In which periods and how much should be held in stock in those facilities?
- How much of the available budget should be retained in each period to gain interest and be used in future investments?

The objective is to redesign the supply chain network during the planning horizon so as to minimize the sum of fixed and variable costs. The former include fixed facility operating costs, while the latter are associated with production/procurement operations at high level facilities (e.g. plants), the transportation of commodities across the network, and holding inventory at stocking points (e.g. warehouses).

The main constraints comprise: (i) product flow balance relations for each facility, commodity and time period (including demand satisfaction); (ii) facility relocation constraints ensuring that only feasible capacity transfers take place from existing facilities to new sites during the planning horizon; (iii) capacity limits with respect to the maximum amount of products that may flow through each facility and period; (iv) minimum throughput conditions stating that it is only meaningful to operate a facility if its throughput is above a pre-specified minimum level; (v) constraints allowing the configuration of each facility to change at most once during the time horizon: once closed, an existing facility cannot be re-opened and once open, a new facility cannot be closed; (vi) budget constraints limiting the investment made each period in capacity transfers, in setting up new facilities and in closing existing facilities upon complete relocation.

As shown in [23], the above problem can be formulated as a large-scale MIP. Furthermore, it generalizes many dynamic facility location models that have appeared in the literature, including those restricted to decisions on opening new facilities and closing existing facilities (no relocation opportunities). In addition, the new model can easily be extended to facility expansion and/or downsizing situations as well as to the relocation of facilities through discrete capacity transfers as opposed to continuous shifts.

5.1 A heuristic for the multi-period SCND problem

Although medium sized problems can be solved efficiently using the commercial CPLEX solver as reported in [23], it is clear that supply chain redesign problems of realistic size become intractable using off-the shelf solvers. On the other hand, most companies need an optimization-based decision support system capable of considering the complexity and the dynamic nature of their supply chains, and that allows them to rapidly prototype and evaluate alternative network configurations. In other words, companies need analytical tools with re-optimization capabilities for performing "what-if" analyzes in a reasonable amount of computing time. This calls for the development of heuristic methods with a good trade-off between solution quality and computational effort.

A promising methodology to solve the above problem is to apply a tabu search (TS) approach. Many computational experiments for hard combinatorial problems have established tabu search as a flexible optimization technique that can compete or even outperform classical methods. TS can be viewed as a neighbourhood search method. This is an iterative procedure in which a neighbourhood $N(s_i)$ is defined for the current solution s_i, and the next solution s_j is searched among the solutions in $N(s_i)$ (see [15]). Ideally, the new solution s_j satisfies the condition $z(s_j) < z(s_i)$, where $z(\cdot)$ denotes the objective function value of a minimization problem. Usual stopping criteria include reaching the maximum number of iterations allowed and not finding a better solution during a given number of iterations.

An important variant of TS is to include a *strategic oscillation* procedure which expands the search process so that infeasible solutions are permitted during the search (see [16]). By alternating the search between feasible and infeasible solutions, possibly short-cuts may be explored in the feasible space. This is particularly meaningful when reaching a good solution may require a long path through the feasible space, whereas if a solution path is allowed to enter infeasible regions, then an optimal (or near-optimal) solution can be found rather easily. A further benefit of using strategic oscillation is that it provides sufficient diversity in the search, which is a fundamental propriety of any heuristic procedure that aspires to find solutions of superior quality. Although allowed, infeasible solutions are penalized by a term that quantifies constraint violation. This leads to the introduction of the *fitness of a solution* s_i, which is a function defined by

$$z'(s_i) = z(s_i) + \alpha \cdot f(s_i) \tag{13}$$

where α denotes a penalty factor and $f(s_i)$ is an infeasibility measure of s_i. If $f(s_i) > 0$ then solution s_i is infeasible, otherwise $f(s_i) = 0$. The penalty factor α is dynamically adjusted during the search. If an infeasible solution is visited then α is increased in an attempt to move out of the infeasible region, thus discouraging further infeasible solutions. In contrast, α is decreased when a feasible solution has been found. With this dynamic mechanism different parts of the solution space are emphasized during the search process, thus improving the robustness of the method.

In the problem presented in [23], infeasibility arises through the violation of the budget constraints. Hence, network configurations resulting from investments in capacity relocation, setup of new facilities and shutdown of existing facilities that exceed the available budget in one or more periods are permitted. Whenever such a solution is obtained, it will be modified by exploring its neighbourhood. This entails determining the first period in the planning horizon with excess budget and then identifying the facilities responsible for budget consumption in that period. The largest expenditures are triggered by new facilities $\ell \in S^o$ through the payment of fixed opening costs and by existing facilities $k \in S^c$ due to fixed closing costs charged after their full relocation (recall the notation introduced in Section 3).

Let t denote the first period with excess budget and let s_i be the current (infeasible) solution. For each facility $\ell \in S^o$ requiring an investment in period t, its neighbourhood $N(s_i, \ell)$ is explored by visiting all solutions that differ from s_i with respect to the period in which facility ℓ is open. This can occur either after or before period t. Bringing the setup of facility ℓ forward is only considered if enough budget is available in that period. A third alternative is to not operate that facility during the entire planning horizon. Each neighbour solution is evaluated by the corresponding fitness function (13).

For each existing facility $k \in S^c$, its neighbourhood $N(s_i, k)$ is also explored by visiting all solutions that differ from s_i by changing the period in which facility k is closed. This can take place prior or after period t. The former case is only studied provided enough budget is available to cover the corresponding closing costs. A third alternative is to keep facility k in operation throughout the planning horizon. Again, the fitness function (13) is used to assess the quality of the neighbour solutions.

Among the neighbours in $N(s_i, \ell)$ and $N(s_i, k)$, the best solution s_j is selected. If the budget constraints are not violated then s_j is a feasible solution of the original problem. The penalty factor α is decreased and the search process is intensified by exploring the neighbourhood of s_j in an attempt to identify an overall best feasible solution. Otherwise, s_j becomes the new incumbent solution, the penalty factor α is increased and a new iteration of the TS algorithm is performed. To improve the efficiency of the search process, not only the best solution s_j is kept but also the next two best solutions are saved. This is necessary if in the next iteration the neighbourhood of solution s_j turns out to be empty (i.e. no feasible solutions of the problem with relaxed budget constraints exist). In this case, the search is restarted with the second best neighbour. Empirical experiments with the TS algorithm showed that in very few cases it is required to return to the third best neighbour.

Before starting the algorithm, the linear relaxation of the original MIP is solved. Each fractional value of a facility variable in the LP-solution is then rounded either to zero (no operation of the facility in a given period) or to one (the facility operates in the period corresponding to the variable). The search procedure is initialized with this solution. The algorithm stops either upon reaching a maximum number of iterations or when a feasible solution with an LP-gap below 1% is identified.

The heuristic described above can be summarized as follows:

STEP 1: Solve the linear relaxation of the problem
STEP 2: Apply the rounding procedure to the binary variables
STEP 3: Apply the tabu search procedure

Table 2 Heuristic for solving the multi-period SCND problem.

To study the computational performance and solution quality of the TS approach, 49 problems were randomly generated for supply chain networks with three facility layers in addition to customers: plants or suppliers, central DCs and regional DCs. Facility relocation decisions concern both DC layers. The test instances have 3–8 periods, 5–50 products, 50–200 customers, 4–12 central DCs, and 10–30 regional DCs. Networks with five plants or 50 suppliers were generated. Details about the test instances and the fine tuning of parameters in the TS algorithm are provided in [10]. On average, problems with 107,000 continuous variables, 247 binary variables and 7,650 constraints were solved.

A scatter plot of the results obtained is given in Figure 3. To evaluate the quality of the solutions identified by the TS algorithm, each problem was also solved with the CPLEX 7.5 solver on a Pentium III PC with a 2.6 GHz processor and 2 GB RAM. A time limit of five hours was applied to CPLEX runs. However, upon identification of a feasible solution with a maximum gap of 1% to the optimum, the solver was stopped. The *y*-axis of the scatter plot represents the percentage time deviation which is given by $100\% \cdot (T_H - T_C)/T_C$ with T_H denoting the time required by the heuristic procedure and T_C the time required by CPLEX. The *x*-axis corresponds to the percentage solution deviation given by $100\% \cdot (z_H - z_C)/z_C$, where z_H denotes the objective value of the best solution identified by the TS heuristic and z_C is the objective value of the best solution found by CPLEX.

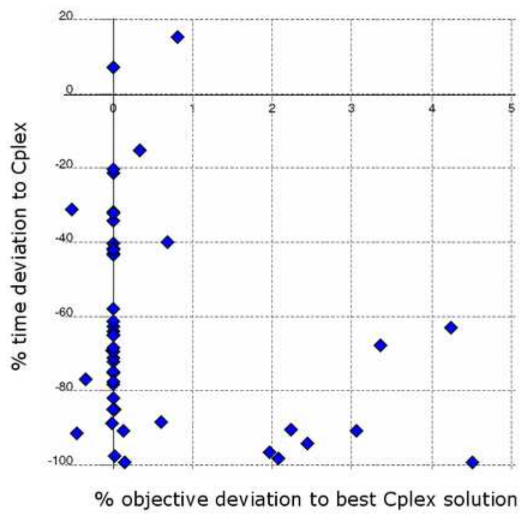

Fig. 3 Comparison of the TS algorithm with CPLEX.

As seen from Figure 3, substantial less computational effort is required by the TS algorithm compared with CPLEX except for two instances. Regarding the solution quality, the TS heuristic identifies solutions as good as those provided by CPLEX for 65% of the problems. In three cases the TS approach even finds slightly better solutions than CPLEX. In the remaining problems, the solutions obtained are less than 5% more expensive than those given by CPLEX. These are remarkably good results which show that allowing temporary infeasibility often leads to a more rapid descent to high-quality feasible solutions.

6 Conclusions

In this chapter, we discussed network design decisions in SCM. We provided an overview of classical facility location models and presented a model featuring various strategic SCM decisions in addition to facility location decisions. We reported on computational experience showing that the proposed model can be solved optimally with an off-the-shelf MIP solver for instances of realistic size within reasonable time. Furthermore, we extended the discussion on SCND by identifying classes of decisions that should be included in a more comprehensive model for strategic supply chain planning. A crucial aspect regards the multi-period nature of many SCND decisions. Due to its importance, this feature was embedded in an SCND model that considers facility relocation decisions along with other important strategic decisions. A novel tabu search heuristic procedure was proposed for solving the multi-period problem. The results from our computational experience have shown that the new solution approach identifies high quality solutions. Furthermore, it is a computationally attractive strategy compared to a well-known commercial solver, even when the latter is used to find near-optimal solutions.

Many approaches can be employed to solve SCND problems. The heuristic we proposed is an example of a successful algorithm for solving the multi-period problem described in Section 5. In a recent review (see [24]), different approaches to solve SCND problems have been surveyed. Figure 4 summarizes the basic statistics regarding the solution methodology that can be found in the literature (see [24] for details). We distinguish between problems solved with a general-purpose solver (such as CPLEX) and those solved with a specifically tailored algorithm. Within each category, two classes are further identified: problems for which finding an optimal solution is the primary goal, and problems for which identifying a heuristic solution is the main target. This categorization leads to the four groups displayed in Figure 4.

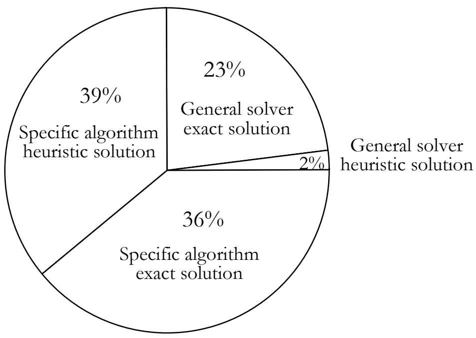

Fig. 4 Solution methodology for SCND problems.

It can be observed that the large majority of the solution approaches have been specifically designed for each problem. Nevertheless, many exact procedures have also been developed for these problems. This shows that there is still much room for improving existing models, namely by making them more comprehensive.

Despite all the work that has been developed for SCND problems, too few applications have been reported in the literature. In [24], a survey is presented on the applied works that have appeared. Table 3 displays the number of published papers according to two categories: the type of industry the application comes from and the type of data used. The latter category either refers to a real-life scenario, even if it was not implemented in practice (*Case study*), or to a study where randomly generated data for a specific industry was used (*Industrial context*).

Industry		Number of papers
Automotive	Case study	2
	Industrial context	1
Chemicals	Case study	4
	Industrial context	1
Food	Case study	4
	Industrial context	1
Forestry	Case study	3
	Industrial context	1
Hardware	Case study	2
	Industrial context	3
Military	Case study	2
Sand	Case study	2
Other	Case study	9
	Industrial context	5

Table 3 Applications of SCND problems.

It can be seen that 70% of the articles report on case studies while the remaining 30% use randomly generated data in an industrial context. A possible explanation for this difference is that once enough knowledge and data on strategic supply chain planning are gathered, it becomes more rewarding to focus on a case study.

One aim of this chapter is to stimulate new applications to emerge in the context of SCND. Furthermore, there is an increasing need for comprehensive models that can capture simultaneously many relevant aspects of real-life problems. The general modelling framework presented in this chapter for single and multi-period SCND problems gives a contribution in this direction. Nevertheless, there are still many opportunities for the development of new models and solution techniques to support decision-making in strategic supply chain planning.

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