Fraunhofer Institut Techno- und Wirtschaftsmathematik

T. Melo, S. Nickel, F. Saldanha da Gama

Facility Location and Supply Chain Management – A comprehensive review

Berichte des Fraunhofer ITWM, Nr. 130 (2007)

© Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM 2007

ISSN 1434-9973

Bericht 130 (2007)

Alle Rechte vorbehalten. Ohne ausdrückliche schriftliche Genehmigung des Herausgebers ist es nicht gestattet, das Buch oder Teile daraus in irgendeiner Form durch Fotokopie, Mikrofilm oder andere Verfahren zu reproduzieren oder in eine für Maschinen, insbesondere Datenverarbeitungsanlagen, verwendbare Sprache zu übertragen. Dasselbe gilt für das Recht der öffentlichen Wiedergabe.

Warennamen werden ohne Gewährleistung der freien Verwendbarkeit benutzt.

Die Veröffentlichungen in der Berichtsreihe des Fraunhofer ITWM können bezogen werden über:

Fraunhofer-Institut für Techno- und
Wirtschaftsmathematik ITWM
Fraunhofer-Platz 1

67663 Kaiserslautern
Germany

Telefon: +49(0)631/31600-0
Telefax: +49(0)631/31600-1099
E-Mail: info@itwm.fraunhofer.de
Internet: www.itwm.fraunhofer.de

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

Facility Location and Supply Chain Management - A comprehensive review

M.T. Melo[a,b], S. Nickel[b,c], F. Saldanha da Gama[d,*]

[a] *Department of Business Administration, University of Applied Sciences, D 66123 Saarbrücken, Germany*
[b] *Department of Optimization, Fraunhofer Institute for Industrial Mathematics (ITWM), D 67663 Kaiserslautern, Germany*
[c] *Chair of Operations Research and Logistics, Saarland University, D 66041 Saarbrücken, Germany*
[d] *Department of Statistics and Operations Research, University of Lisbon, P 1749-016 Lisbon, Portugal*

November 23, 2007

Abstract

Facility location decisions play a critical role in the strategic design of supply chain networks. In this paper, an extensive literature review of facility location models in the context of supply chain management is given. Following a brief review of core models in facility location, we identify basic features that such models must capture to support decision-making involved in strategic supply chain planning. In particular, the integration of location decisions with other decisions relevant to the design of a supply chain network is discussed. Furthermore, aspects related to the structure of the supply chain network, including those specific to reverse logistics, are also addressed. Significant contributions to the current state-of-the-art are surveyed taking into account numerous factors. Supply chain performance measures and optimization techniques are also reviewed. Applications of facility location models to supply chain network design ranging across various industries are discussed. Finally, a list of issues requiring further research are highlighted.

Keywords: Facility location, Supply Chain Management. Network design.

1 Introduction

Facility location is and has been a well established research area within Operations Research (OR). Numerous papers and books are witnesses of this fact (see e.g. Drezner and Hamacher [36] and references therein). The American Mathematical Society (AMS) even created specific

*Corresponding author. *E-mail address*: fsgama@fc.ul.pt

codes for location problems (90B80 for discrete location and assignment, and 90B85 for continuous location). Nevertheless, the question of the applicability of location models has always been under discussion. In contrast, the practical usefulness of logistics was never an issue. One of the areas in logistics which has attracted much attention is Supply Chain Management (SCM) (see e.g. Simchi-Levi et al. [144] and references therein). In fact, the development of SCM started independently of OR and only step by step did OR enter into SCM (see e.g. Chopra and Meindl [25]). As a consequence, facility location models have been gradually proposed within the supply chain context (including reverse logistics), thus opening up an extremely interesting and fruitful application domain. There are naturally several questions which immediately arise during such a development, namely

- What properties does a facility location model have to fulfill to be acceptable within the supply chain context?
- Are there existing facility location models which already fit into the supply chain context?
- Does SCM need facility location models at all?

As the number of papers has increased tremendously in the last few years and even the Association of European Operational Research Societies (EURO) has recently devoted a Winter institute to this topic [44], we felt that the time was ripe to have a review paper looking exactly at the role of facility location models within SCM. Before starting the review we briefly define our two main objects of investigation, namely facility location and SCM.

A general facility location problem involves a set of spatially distributed customers and a set of facilities to serve customer demands (see e.g. Drezner and Hamacher [36], Nickel and Puerto [113]). Moreover, distances, times or costs between customers and facilities are measured by a given metric (see ReVelle and Eiselt [121]). The questions to be answered are:

- Which facilities should be used (opened)?
- Which customers should be serviced from which facility (or facilities) so as to minimize the total costs?

In addition to this generic setting, a number of constraints arise from the specific application domain. For recent reviews on facility location we refer to Klose and Drexl [74] and ReVelle et al. [123].

SCM is the process of planning, implementing and controlling the operations of the supply chain as efficiently as possible. 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 Simchi-Levi et al. [144] and the Council of Supply Chain Management Professionals [28]). 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. In addition to the generic facility location setup also other areas such as procurement, production, inventory, distribution, and routing have to be considered (see Cordeau et al. [27]). Historically, researchers have focused relatively early on the design of distribution systems (see Geoffrion and Powers [52]), but without considering the supply chain as a whole.

Since it is not possible to survey all the literature associated both with facility location and SCM, we will concentrate our review on articles that go beyond location-allocation decisions (and thus, we will exclude simple single facility location and pure resource allocation models). Moreover, we will only consider discrete models. Although continuous facility location models may as well play a role in our context, they often have a macroeconomics flavour which would lead us away from the typical SCM perspective. With this scope in mind, our search covered the major journals in OR, management science and operations management. In total, we identified approximately 150 articles spanning from the late 60's, which were marked by the seminal work by Ballou [11], to 2007 (a few papers that will appear in 2008 were also selected). Further screening yielded 115 articles from over 28 journals that address relevant aspects to our analysis. Of these, 63 were published after 2004, which clearly shows the recent progress this research area is experiencing. For example, compared to the year 2002, the number of publications doubled in 2007 (22 against 11). In particular, the *European Journal of Operational Research* has been a major forum for the presentation of new developments and research results (in total 50 articles were identified). Other journals such as *Computers & Operations Research* (20 papers), *Interfaces* (nine papers), *Transportation Research* (seven papers), and *Omega*, *Operations Research*, and *IEE Transactions* (each with six articles) have also given an important contribution to this emerging research field.

The remainder of the paper is organized as follows. Core models in facility location are discussed in Section 2. Section 3 focuses on the relation between facility location and SCM in more detail. Section 4 is devoted to reviewing facility location papers in strategic SCM. In Section 5 papers dealing with some specific SCM characteristics are discussed. Optimization methods for solving facility location problems in a supply chain context are reviewed in Section 6.

Section 7 addresses practical applications of location models in SCM. The paper ends with some conclusions and possible directions for future research.

2 Core models in discrete facility location

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. Daskin [31], Drezner and Hamacher [36], ReVelle and Eiselt [121]). This setting assumes that all candidate sites are equivalent in terms of the setup cost for locating a new facility. When this is not the case, the objective function can be extended with a term for fixed facility location costs and as a result, the number of facilities to be established 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 Mirchandani and Francis [110] and ReVelle et al. [123]. In both the p-median problem and the UFLP, each customer is allocated to the open facility that minimizes his 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 (see Sridharan [150]). 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. However, these models are clearly insufficient to cope with many realistic facility location settings. Therefore, many extensions to the basic problems have been considered and extensively studied.

Ballou [11] introduced the first multi-period location problem to approach situations in which parameters change over time in a predictable way. The goal is to adapt the configuration of the facilities to these parameters. Thereby, a planning horizon divided into several time periods is usually considered. Extensive literature on these problems can be found, for instance, in Erlenkotter [42], Roodman and Schwarz [126, 127], Shulman [142], and Van Roy and Erlenkotter [162].

Another important extension regards the inclusion of stochastic components in facility location models (see the seminal papers by Louveaux [87], and Louveaux and Peeters [88] as well as the recent survey by Snyder [146]). This is motivated by the uncertainty that often can be associated with some of the parameters such as future customer demands and costs. Owen and Daskin [116] provide an overview of research on facility location which, through the consideration of time and uncertainty, has led to more realistic models.

A crucial aspect of many realistic 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 and with the same role is usually denoted by a layer or an echelon, thus defining a level in the hierarchy of facilities. Starting with the pioneering article by Kaufman et al. [71], new facility location models emerged taking several facility layers into account. The problem studied by Kaufman et al. [71], which addressed the simultaneous location of plants and warehouses, was further extended by Tcha and Lee [155] through the consideration of a general number of location layers. Many other papers can be found in the literature addressing this topic (see the recent survey by Sahin and Süral [129]). 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 (see Sahin and Süral [129] as well as Figure 1 in Section 3).

Another aspect driven by real-life applications, and that has raised much attention, regards the necessity to cope with multi-commodity problems. The pioneering work by Warszawski [171] was a starting point for the development of new models (see Klose and Drexl [74] and references therein).

Elson [39] as well as Geoffrion and Graves [51] combined both aspects – multiple layers and commodities – by considering two facility layers, capacitated facilities and different products. In the studied problem, location decisions were restricted to one layer (warehousing).

A conclusion that can be drawn from the literature devoted to the UFLP and its extensions is that this research field has somehow evolved without really taking the SCM context into account. Features like multiple facility layers or capacities have been included in the models in a rather general way and specific aspects, that are crucial to SCM, were disregarded. In fact, extensions seem to have been mostly guided by solution methods. For instance, in multi-layer models, intra-layer flows are often not considered because this feature destroys the structure of the constraint matrix, thus not allowing decomposition methods to be used.

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 have been extremely helpful as a basis for building comprehensive models that include SCM decisions in addition to location. In the next section we discuss relevant aspects in SCM that need to be embedded in facility location models.

3 Facility location and SCM

In this section we take a closer look at the relation between facility location and SCM. We also review some essential papers dedicated or especially relevant to this topic. As mentioned in the introduction, facility location models play an important role in supply chain planning. Typically, three planning levels are distinguished depending on the time horizon: strategic, tactical and operational (see Bender et al. [15], Vidal and Goetschalckx [166]). Simchi-Levi et al. [144] state that "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. In some books and papers, the terms *network design* and *supply chain network design* (SCND) are employed as synonyms of strategic supply chain planning (see Altiparmak et al. [6], Chopra and Meindl [25], Meixell and Gargeya [97], Simchi-Levi et al. [143]). 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 (among others).

The globalization of economic activities together with fast developments in information technologies have led to shorter product life cycles, smaller lot sizes and a very dynamic customer behaviour in terms of preferences. These aspects have contributed to growing demand uncertainty and as a result, a robust and well designed supply chain network has become even more important. According to Teo and Shu [156], "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 level.

Figure 1 depicts a generic supply chain network. In addition to different types of facilities (suppliers, plants, distribution centres and customers), the flow of materials is highlighted in the figure. In contrast to classical location problems, the flows between facilities of the same layer are prevalent in many supply chains, as discussed in the previous section. These flows are us

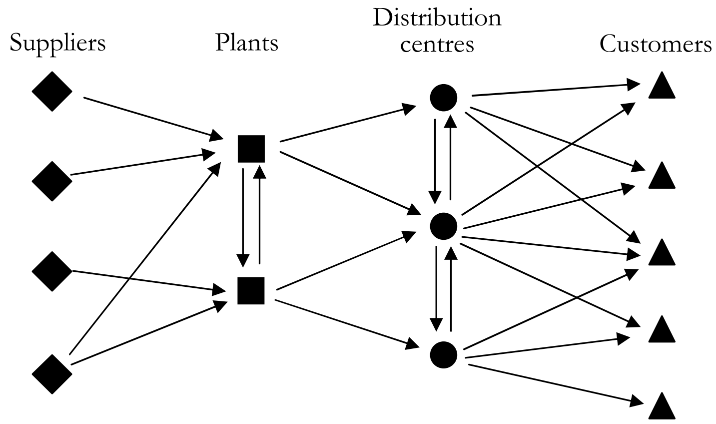

Figure 1: A generic supply chain network.

From the above reasoning it becomes clear that good location models are needed to support the SCND phase. However, certain aspects have to 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 taken into account in an iterative manner. The approach followed by Talluri and Baker [154] is such an example of non-integrated decision-making in SCND: first, the candidate locations are selected 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 has to do with 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 Erengüç et al. [40], Goetschalckx et al. [54]).

In the following we present a list of important issues that enable a facility location model to become compatible with SCND requirements and give references to the corresponding core location models. The first (and most obvious) group of issues needed as an extension of general facility location models concern decisions related to transportation. These include

- the choice of transportation modes and capacities,
- the setup of transportation links,
- the direct shipment of commodities from higher level facilities to customer locations,
- the material flows between facilities in the same layer (e.g. semi-finished products moved to other plants to be transformed into end products),
- single or multi-sourcing relationships between facilities and customers.

Although the term *supply chain design* was coined much later, the development of facility location models for distribution systems started more than two decades ago. As early as 1985, Aikens [3] reviewed some important mixed-integer linear formulations for production-distribution systems. However, these models had limited scope and could not deal with a supply chain structure as the one presented in Figure 1. Later in the 90's, Geoffrion and Powers [52] argued that the first steps towards embedding several 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; (iv) piecewise linear approximations to non-linear costs; (v) the ability to locate plants as well as distribution centres; (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, ReVelle and Laporte [122] also suggested additional features that should be included 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.

The second group of relevant aspects to be considered by facility location models refer to the integration of supply chain activities into these models. These include

- capacity issues, such as:
  - expansion or reduction of existing facilities (either through modular or continuous sizes),
  - technology and equipment choice,
  - choice of capacity levels,

– minimum throughput levels for a meaningful operation of facilities,

- procurement,
- multi-stage production taking bills of materials (BOM) into account,
- inventory,
- routing.

Capacity expansion is an old issue in location analysis (see e.g. Klose and Drexl [74], Luss [91], Manne [93]). In contrast, procurement and production decisions are often not included in facility location models. In particular, the BOM structure in multi-stage production systems is disregarded in most models (this aspect will be discussed in more detail in Section 5). One of the main reasons is that the majority of the researchers focus on the distribution aspect and neglect the operations involved in the upstream part of the supply chain. First models and a review taking these aspects into account can be found in Bender et al. [15] and Melo et al. [102].

One of the most important tasks in SCM is to avoid unnecessary large amounts of inventory. Therefore, a significant number of research articles are concerned with inventory models for SCM. It may be argued that especially in multi-period facility location models inventory issues should be taken into account as well. As a result, some location models have included this feature. This extension can occur on an inventory preservation level (see, for example, Hinojosa et al. [60] and Melo et al. [102]) or by incorporating inventory control policies into the location model (see, for example, Shen and Qi [137]).

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, recently researchers have focused on location-routing models (see Albareda-Sambola et al. [5], Nagy and Salhi [112] and references therein). Ideally, one would like to know for every warehouse the approximate cost of each delivery route without having to compute the route.

Another group of extensions that impact the whole supply chain structure are as follows:

- multiple facility layers and "location layers",
- national and international factors,

• reverse logistics.

In their review of hierarchical location models, Sahin and Süral [129] refer that facility location problems have been mostly studied for single-level systems. However, from Figure 1 it is clear that multi-layer networks are necessary in SCM (see also Kotzab et al. [76]). If we have multiple layers in a supply chain network, we also have location decisions on different layers. On the upper level of the network we may consider the location of manufacturing plants, in the middle part additional assembly sites and in the lower levels warehouses, distribution centres or even depots. We have seen in Section 2 that although multi-layer location models exist, most of them do not allow intra-layer transports or direct deliveries. Verter and Dincer [165] are among the few researchers who address multi-layer aspects for global supply chains. In particular, they consider international factors such as taxes, duties and exchange rates. Furthermore, the reviews by Verter and Dincer [165], Meixell and Gargeya [97], and Vidal and Goetschalckx [166] discuss the impact of supply chain globalization on facility location. Since SCM is typically done on a global scale, naturally SCND has to be modelled on a global level too. This aspect will be addressed in Section 5.

In the last ten years, reverse logistics has received growing attention within SCM. In this context, the network structure needs to be extended with transportation links for return flows from customer locations to sites where repair, remanufacturing and/or recycling activities take place (e.g. warehouses, remanufacturing plants). An early article on the role of OR in reverse logistics is due to Fleischmann et al. [48]. Recently, Srivastava [151] reviewed the literature on SCND and reverse logistics.

The last group of extensions is concerned with the number of commodities. Here we can simply distinguish between single and multiple commodities. As mentioned in the previous section, Warszawski [171] was the first to address multi-commodity aspects in location analysis. Until now many more papers dealing with multiple commodities have been published (this aspect will be addressed in more depth in the next section). However, still the majority of facility location models deals with a single product type.

Finally, the interested reader is referred to some important reviews where facility location issues in the context of SCND are discussed: Bhatnagar and Sohal [16] (regarding the impact of location factors, uncertainty and manufacturing practices in supply chain competitiveness), Daskin et al. [30], Min and Zhou [105], and Owen and Daskin [116].

Having introduced in this section a number of features that are relevant to strategic supply chain planning, and therefore should be considered by facility location models, we review the facility location literature from a supply chain perspective in the next section.

4 Strategic supply chain planning

As suggested by Figure 1, a supply chain is a network of facilities that perform a set of operations ranging from the acquisition of raw materials, the transformation of these materials into intermediate and finished products, to the distribution of the finished goods to the customers (see Min and Zhou [105], Simchi-Levi et al. [145], Stadtler and Kilger [152]). As mentioned in Section 3, network design belongs to the strategic planning level and therefore, involves decisions concerning the number, location, capacity, and technology of facilities (see Ghiani et al. [53], Miller [103], Santoso et al. [132], Shapiro [135]). Altiparmak et al. [6] stress the fact that this problem is one of "the most comprehensive strategic decision problems that need to be optimized for long-term efficient operation of the whole supply chain". In general, a network design project starts with the identification of potentially interesting sites for new facilities and of the required capacities. Typically, large amounts of capital must be allocated to a new facility, 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, changes of various nature during a facility lifetime may turn a good location today into a bad one in the future.

In this section we give a synthesis of the existing literature in terms of essential aspects and decisions (strategic as well as tactical/operational) that should be included in facility location models to support the decision-making process in SCM.

4.1 Network structure and basic features

It is now clear that two aspects can hardly be avoided in strategic supply chain planning: a multi-layer network and multiple commodities. Therefore, appropriate models for strategic decision-making must consider these features.

A supply chain network is supposed to be in use for a considerable time during which many parameters can change. If a probabilistic behaviour is associated with the uncertain parameters (either by using probability distributions or by considering a set of discrete scenarios each of which with some subjective probability of occurrence), then a stochastic model may be the most appropriate for this situation. Another modelling possibility arises when some parameters change over time in a predictable way (e.g. demand levels and costs). In this case, if forecasts for the unknown parameters are known, they can be included in the model to obtain a network design that can cope with these future changes. A single-period facility location model may be enough to find a "robust" network design as well as a robust set of tactical/operational decisions. Alternatively, a compromise may be possible in which the strategic location decisions are implemented at the beginning of the planning horizon but other decisions (namely tactical/operational), such as the allocation of customer demands to facilities, may change over time (see e.g. Dogan and Goetschalckx [35], Gunnarsson et al. [57], Vila et al. [168], Wilhelm et al. [172]).

By nature, strategic decisions should last for a considerable amount of time. In fact, due to the large investments normally associated with this type of decisions, stability with respect to the configuration of the supply chain network is a highly desirable feature. Nevertheless, in some cases, it may be important to consider the possibility of making future adjustments in the network configuration to allow gradual changes in the supply chain structure and/or in the capacities of the facilities. In this case, a planning horizon divided into several time periods is typically considered and strategic decisions are to be planned for each period. Such situation occurs, for instance, when the large facility investments are limited by the budget available in each period (see Melo et al. [102] for a deeper discussion about the factors leading to multi-period facility location problems). Naturally, large changes in the configuration of the facilities make more sense for facilities requiring relatively small investments such as warehouses. In addition, it is also possible to combine multi-period planning with stochasticity. This is the situation when the probabilistic behaviour of the uncertain parameters changes itself over time.

Taking into account the previous arguments together with those presented in Section 3, we identify four basic features that may be included in a facility location model to make it useful in strategic supply chain planning: multi-layer facilities, multiple commodities, single/multiple period(s), deterministic/stochastic parameters. Table 1 classifies the surveyed literature according to these aspects.

The fact that multiple facility layers are considered does not mean that location decisions are allowed in all of them. Therefore, Table 1 specifies both the number of facility layers and the number of layers in which location decisions are made. It should be noted that when location decisions do not include all facility layers, they usually concern the intermediate layers, which are normally associated with distribution centres or warehouses.

It can be seen from Table 1 that the more we move towards the upper left corner of the table, the richer the literature becomes. In fact, most of the literature deals with single-period problems (approximately 82% of the surveyed papers). Another important conclusion that can

			Single-period		Multi-period	
			Deterministic	Stochastic	Deterministic	Stochastic
Single layer	Single location layer	Single commodity	[10] [11] [12] [29] [94] [101] [138] [149] [156] [159] [169] [174]	[23] [55] [85] [88] [89] [137] [139] [148]	[18] [19] [24] [34] [98] [106] [142] [162]	
		Multiple commodities	[22] [78] [80] [96] [104] [163]		[47] [62] [160]	
2 Layers	Single location layer	Single commodity	[4] [21] [37] [41] [43] [46] [73] [99] [100] [125] [133] [140] [170]	[32] [63] [83] [108] [109] [141] [161]		[2]
		Multiple commodities	[17] [39] [51] [58] [67] [72] [167] [173]		[20]	
	2 Location layers	Single commodity	[1] [13] [49] [50] [57] [68] [71] [81] [82] [90] [95] [107] [124]			
		Multiple commodities	[8] [9] [65] [66] [70] [77] [118] [119] [120] [153]	[56]	[59] [60] [151] [168]	
≥ 3 Layers	Single location layer	Single commodity	[115]			
		Multiple commodities	[35]			
	2 Location layers	Single commodity	[6] [14] [92] [158]			
		Multiple commodities	[64] [84]	[86] [128]	[75]	
	≥ 3 Location layers	Single commodity	[155]		[7] [157]	
		Multiple commodities	[27] [117] [130] [172] [175]	[131] [132]	[102]	

Table 1: Supply chain structure featuring the number of commodities, the nature of the planning horizon (single/multi-period) and the type of data (deterministic/stochastic).

be drawn from Table 1 refers to the large number of deterministic models when compared with stochastic ones (approximately 82% against 18%). As pointed out by Sabri and Beamon [128], uncertainty is one of the most challenging but important problems in SCM. However, the literature integrating stochasticity with location decisions in an SCM context is still scarce as the table shows. Different sources of uncertainty can be found in the literature presented in Table 1, namely

- customer demands (Aghezzaf [2], Chan et al. [23], Daskin et al. [32], Goh et al. [55], Guillén et al. [56], Listeș [85], Miranda and Garrido [108, 109], Sabri and Beamon [128], Salema et al. [131], Shen and Qi [137], Shen et al. [139], Shu et al. [141], van Ommeren et al. [161]),
- exchange rates (Goh et al. [55], Lowe et al. [89]),
- travel times (Hwang [63]),
- amount of returns in reverse logistics (Lieckens and Vandaele [83], Listeș [85], Listeș and Dekker [86], Salema et al. [131]).

Some articles include several stochastic components simultaneously. Sabri and Beamon [128] consider uncertainty in demand as well as in production and supply lead times. Louveaux and Peeters [88] deal with uncertainty on demand, selling prices, and production and transportation costs. Santoso et al. [132] model uncertainty in processing/transportation costs, demand, supply, and capacities. Finally, Snyder et al. [148] address general stochastic parameters which may include shipment costs, lead times, holding costs, and others.

Two main approaches can be found in the literature to model uncertainty. One possibility is to consider a discrete set of scenarios or a discrete probability function. This is the case in Aghezzaf [2], Goh et al. [55], Guillén et al. [56], Listeș [85], Listeș and Dekker [86], Louveaux and Peeters [88], Lowe et al. [89], Salema et al. [131], Santoso et al. [132], and Snyder et al. [148]. Another possibility is to assume a continuous distribution function associated with the uncertain parameters. This approach is followed by Daskin et al. [32], Hwang [63], Miranda and Garrido [108, 109], Sabri and Beamon [128], Shen and Qi [137], Shen et al. [139], Shu et al. [141], and van Ommeren et al. [161]. Often, in the latter case, only the mean value and variance of the random variables are considered. In Chan et al. [23] and Lieckens and Vandaele [83] uncertainty in demand is modelled using stochastic processes.

Some conclusions can also be drawn from Table 1 concerning the multi-layer network structure. Around 80% of the surveyed papers refer to one or two location layers and among these, around two thirds model location decisions in only one layer. Moreover, as mentioned in Section 2, in core location problems it is generally assumed that customers can only be supplied from the closest layer. This assumption is not valid in many SCND problems, where it may be possible to have direct shipments from upper layer facilities to customers or to facilities not in the layer immediately below (e.g. due to very large shipments). These aspects were considered in Ambrosino and Scutellà [7], Barros et al. [14], Canel et al. [20], Carlsson and Rönnqvist [21], Cordeau et al. [27], Eskigun et al. [43], Farahani and Asgari [46], Gunnarsson et al. [57], Lee and Dong [81], Melo et al. [102], Troncoso and Garrido [157], and Vila et al. [168]. Another important characteristic of many supply chain networks regards intra-layer flows. Aghezzaf [2], Carlsson and Rönnqvist [21], Cordeau et al. [27], Melo et al. [102], Troncoso and Garrido [157], Vila et al. [168], and Wouda et al. [173] introduced explicitly this feature into their models. One characteristic that has also had significant coverage in the literature refers to multiple commodities. Around 40% of the papers presented in Table 1 include this aspect.

Nevertheless, the above table clearly shows that the more we move towards the combination of several issues relevant to SCM, the less literature we find integrating location decisions with these issues. For instance, only a few articles combine stochastic elements with multi-layer aspects.

In addition to the features displayed in Table 1, further constraints can be found in many of the surveyed papers and which are also related to the network structure. One of them is a p-median type of constraint imposing an exact number of facilities to be operated. Although not very frequent, this type of constraint is included in the models developed by Keskin and Ülster [72, 73], Lee and Dong [81], Syam [153], and Wang et al. [169]. Another possibility to control the number of operating facilities is to set a lower and/or an upper limit to the number of facilities to open/close. A constraint ensuring that at least a given number of facilities will be operated can be found in Jayaraman et al. [68] and Min et al. [106, 107]. Hinojosa et al. [59, 60] impose a lower bound on the number of facilities in each location layer both in the first and in the last period of the planning horizon. An upper limit to the number of facilities that can be opened is considered by Altiparmak et al. [6], Jang et al. [64], Jayaraman and Pirkul [65], Jayaraman and Ross [66], Jayaraman et al. [67], Pati et al. [117], and Wouda et al. [173]. Hugo and Pistikopoulos [62] present a multi-period problem in which the number of installations and the number of capacity expansions are controlled by pre-defined minimum and maximum values.

One important aspect distinguishing multi-period problems regards the possibility of opening and closing the same facility more than once during the planning horizon. This aspect is explored by Canel and Khumawala [18, 19], Canel et al. [20], Chardaire et al. [24], Dias et al. [34], Min et al. [106], and Srivastava [151]. In Ko and Evans [75] this feature is allowed under certain conditions. However, most articles dealing with multi-period problems do not permit the configuration of the facilities to change more than once during the planning horizon (see Fleischmann et al. [47], Hinojosa et al. [59, 60], Hugo and Pistikopoulos [62], Melachrinoudis and Min [98], Melo et al. [102], Shulman [142], Troncoso and Garrido [157], and Van Roy and Erlenkotter [162]). Ulstein et al. [160] present a multi-period model in which a facility that is removed cannot be reopened in the same location.

4.2 Decision variables in supply chain network design

The complexity of the supply chains has also led to the inclusion of several planning decisions in addition to the classical location-allocation decisions. In many cases, the need for additional decisions is a consequence of the multi-layer structure of the supply chain network. Table 2 classifies the literature according to the typical supply chain decisions discussed in Section 3, namely capacity, inventory, procurement, production, routing, and the choice of transportation modes.

Article	Capacity	Inventory	Procurement	Production	Routing	Transportation modes
Aghezzaf [2]	√	√				
Aksen and Altinkemer [4]					√	
Ambrosino and Scutellà [7]		√			√	
Amiri [8]	√					
Arntzen et al. [9]		√		√		√
Avittathur et al. [10]		√				
Barahona and Jensen [12]		√				
Carlsson and Rönnqvist [21]						√
Chakravarty [22]				√		
Chan et al. [23]					√	
Cordeau et al. [27]			√	√		√
Daskin et al. [32]		√				
Dogan and Goetschalckx [35]		√		√		
Elson [39]	√					
Erlebacher and Meller [41]		√				
Eskigun et al. [43]						√
Fleischmann et al. [47]	√			√		
Geoffrion and Graves [51]				√		
Guillén et al. [56]	√	√		√		
Hinojosa et al. [60]		√	√			
Hugo and Pistikopoulos [62]	√			√		
Hwang [63]					√	

Table 2: Supply chain decisions in addition to the typical location-allocation decisions.

Article	Capacity	Inventory	Procurement	Production	Routing	Transportation modes
Jang et al. [64]		√	√	√		
Jayaraman and Pirkul [65]				√		
Jayaraman et al. [67]		√		√		
Ko and Evans [75]	√					
Kouvelis and Rosenblatt [77]				√		
Levén and Segerstedt [82]	√	√				
Lieckens and Vandaele [83]	√	√				
Lin et al. [84]		√				
Lowe et al. [89]	√			√		
Ma and Davidrajuh [92]		√			√	
Melachrinoudis and Min [98]	√					
Melachrinoudis and Min [99]				√		
Melachrinoudis et al. [100]	√			√		
Melo et al. [102]	√	√	√	√		
Min and Melachrinoudis [104]		√				
Min et al. [106]		√				
Miranda and Garrido [108]		√				
Miranda and Garrido [109]		√				
Nozick and Turnquist [115]		√				
Pirkul and Jayaraman [119]				√		
Pooley [120]				√		
Romeijn et al. [125]		√				
Sabri and Beamon [128]				√		
Schultmann et al. [133]	√					
Shen and Qi [137]		√				
Shen [138]		√				
Shen et al. [139]		√				
Shu et al. [141]		√				
Shulman [142]	√					
Snyder et al. [148]		√				
Sourirajan et al. [149]		√				
Srivastava [151]	√					
Syam [153]		√				
Teo and Shu [156]		√	√			
Tuzun and Burke [159]					√	
Ulstein et al. [160]	√					
van Ommeren et al. [161]	√	√				
Verter and Dasci [163]				√		
Vila et al. [168]	√	√		√		
Wang et al. [170]		√				
Wilhelm et al. [172]		√	√	√		√
Wouda et al. [173]				√		
Wu et al. [174]					√	
Yan et al. [175]			√	√		

Table 2: Supply chain decisions in addition to the typical location-allocation decisions (cont.)

It should be noted that 48 papers that are cited in Table 1 do not appear in Table 2 since they do not feature any decision in addition to the classical location-allocation ones. Table 2 clearly shows that facility location is frequently combined with inventory and production decisions. In contrast, procurement, routing and the choice of transportation modes (alone or integrated with other types of decisions) have not received much attention.

One important aspect mentioned in the previous section regards the possibility of adjusting the network structure to future conditions or, in the case that the network already exists, to redesign it in order to cope with expected future changes. One way of handling this situation is to gradually change the capacity of the facilities. This may be performed by expandind/reducing the operating capacity or even by transferring capacity from one location to another. In their recent survey dedicated to capacity expansion, Julka et al. [69] discuss multi-factor capacity expansion models for manufacturing plants. The possibility of expanding capacity is considered by Aghezzaf [2], Fleischmann et al. [47], Hugo and Pistikopoulos [62], Ko and Evans [75], Schultmann et al. [133], Shulman [142], Srivastava [151], and Troncoso and Garrido [157]. With the exception of Schultmann et al. [133], these articles combine capacity expansion with multi-period location decisions. Some authors confine capacity decisions to just one specific layer. This is the case of van Ommeren et al. [161], where capacity is to be decided only for the upper layer facilities, and of Aghezzaf [2] where capacity expansion is allowed in the upper layer facilities. In contrast, Lowe et al. [89] model the capacity reduction case. The simultaneous consideration of capacity expansion and reduction is studied by Elson [39], Levén and Segerstedt [82], Melachrinoudis and Min [98], Melo et al. [102], and Vila et al. [168]. Melachrinoudis et al. [100] consider the problem of warehouse consolidation in which the total capacity available in one location is relocated at once to another site. Capacity decisions may also concern the installation of modules with pre-defined sizes as in van Ommeren et al. [161], Melo et al. [102], Shulman [142], Ulstein et al. [160], and Vila et al. [168].

A decision that is usually strongly associated with capacity decisions regards the choice of equipment and/or technology. In fact, the latter frequently determines the former. This aspect is addressed by Dogan and Goetschalckx [35], Karabakal et al. [70], Lee [80], Mazzola and Neebe [96], Ulstein et al. [160], and Verter and Dasci [163]. Vila et al. [168] consider the choice of the facilities' layout as a decision to be made.

As emphasized by Shu et al. [141] and Daskin et al. [32], managing inventory involves two crucial tasks: the first is to determine the number of stocking points (e.g. distribution centres and/or warehouses), while the second is to define the level of inventory to maintain at each of these points. Again, to avoid sub-optimization these decisions should be regarded in an integrated perspective, namely with location decisions. In the literature devoted to inventory planning, this type of decision is mostly focused on exactly one layer, namely the one referring to warehouses or distribution centres. Nevertheless, a few models have been proposed in which inventory decisions are included in several layers. This is the case in Arntzen et al. [9], Jang et al.

[64], Melo et al. [102], Syam [153], van Ommeren et al. [161], and Vila et al. [168]. However, none of these models considers full coordination of replenishment activities in different layers, which is a relevant aspect in SCM. In contrast, full coordination was attempted by Romeijn et al. [125] and Teo and Shu [156]. The latter article was, in fact, pioneering work in this field.

As mentioned above, the choice of transportation modes is an aspect that has not received much attention in the literature. In Table 2 only five papers feature this decision. These articles can be divided into those that allow several transportation modes to be chosen for the same link/arc in the network and those that only allow one transportation mode in each link. Contributions to the first case include Cordeau et al. [27] and Wilhelm et al. [172]. The remaining papers fall into the second category. In an international context, different transportation modes are usually a consequence of the natural options of transportation around the world: by air, by sea or by land. This is the case in Arntzen et al. [9] and Carlsson and Rönnqvist [21].

Routing decisions can be found in seven papers cited in Table 2. Typically, multi-depot problems arise when it is possible to have several facilities (the origins/depots for the routing problem) operating. The exception to this rule is the article by Ma and Davidrajuh [92] in which routing decisions are made only after assigning the customers to the retailers. Although routing decisions are not integrated with location decisions, the authors try to overcome this shortcoming by considering a solution procedure that iterates between the strategic and tactical/operational decisions.

Due to the multi-layer structure of a supply chain network, some articles study the routing problem associated with more than one layer. This is the case in Ambrosino and Scutellà [7] and Hwang [63]. The surveyed literature can also be divided into those papers that assume a homogeneous fleet (see Aksen and Altinkemer [4] and Ma and Davidrajuh [92]) and those that consider vehicles of different types/capacities (Ambrosino and Scutellà [7], Chan et al. [23], Hwang [63], Tuzun and Burke [159], Wu et al. [174]). Another important aspect regards the possibility of having a customer serviced by more than one vehicle. This is explored by Aksen and Altinkemer [4] and Chan et al. [23]. Finally, apart from the paper by Ma and Davidrajuh [92], the vehicles are assumed to be capacitated.

Concerning procurement decisions, the articles listed in Table 2 can be split into those in which procurement refers to raw material and those that consider procurement of finished products from an outside supplier. Contributions to the first category include Cordeau et al. [27], Jang et al. [64], Wilhelm et al. [172], and Yan et al. [175]. The models proposed by

Hinojosa et al. [60], Melo et al. [102] and Teo and Shu [156] fall into the second category.

The small number of papers integrating decisions regarding procurement, routing and the choice of transportation modes with other decisions, in particular those focusing on the strategic planning level, show that the existing literature is still far from combining many aspects relevant to SCM. In fact, this integration leads to much more complex models due to the large size of the problems that may result. This holds in particular when tactical/operational decisions are integrated with strategic ones.

4.3 Reverse logistics

Reverse logistics refers to all activities concerned with the collection and/or recovery of product returns. The importance of reverse logistics activities is stressed in a recent article by Srivastava [151]. Three aspects can be mentioned to justify this type of activities (see Srivastava [151], Wang et al. [170]): economic aspects (the possibility of recapturing value of used products), government directives (e.g. the European Union WEEE Directive [45]) and consumer pressure (e.g. return of defective products).

As mentioned in Section 3, planning for reverse activities has been experiencing a strong development in the last decade. New models have been developed to support decision-making in this area. The early articles by Barros et al. [14], Fleischmann et al. [48] and Jayaraman et al. [67] encouraged much of the subsequent research in this recent field. Furthermore, the significant development of supply chain planning has also led to more attention being paid to reverse activities that must follow the typical "forward activities" encompassed by SCM (see Dekker et al. [33], Dyckhoff et al. [38] and Lebreton [79]).

Reverse logistics activities are often supported by specific facilities. These can be of two different main types (see Srivastava [151]): collection centres (i.e. facilities where customers hand in used products) and recovery/remanufacturing facilities (i.e. facilities where returned products are refurbished/remanufactured). As a result, a network can be associated with the reverse activities leading to a so-called *reverse network*. Such network may include several layers of facilities.

The literature can be divided into planning problems where the reverse network is integrated with the forward network and those that fully concentrate on recovery activities. We use the term *closed-loop network* to refer to a supply chain in the first case and denote the latter by *recovery network*. Figure 2 shows the generic form of a closed-loop network. Observe that reverse flows as well as specific facilities for reverse activities were added to the forward network presented in Figure 1.

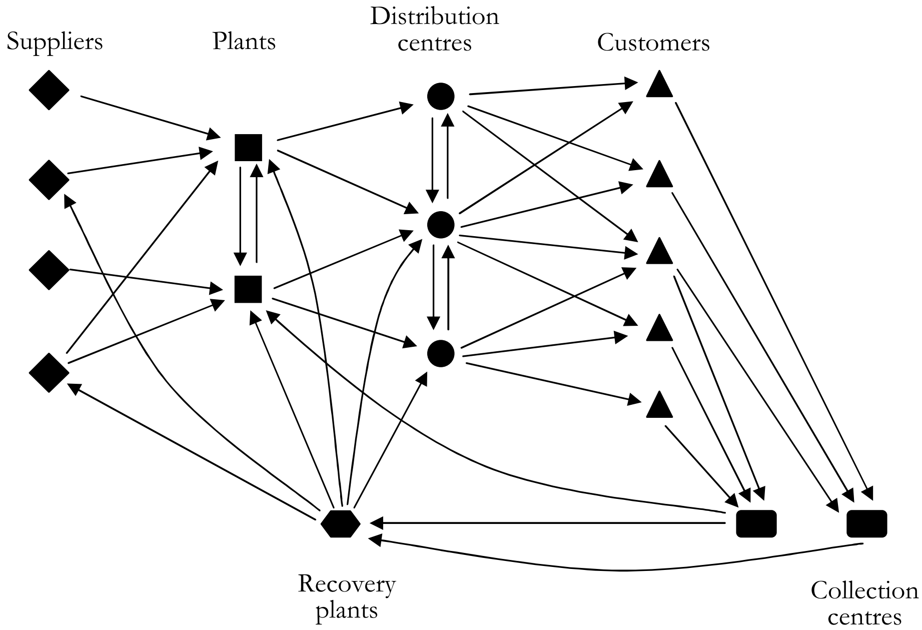

Figure 2: A generic closed-loop supply chain network.

Several aspects distinguish a forward from a reverse network (see Listeș and Dekker [86] and Fleischmann et al. [48]). A reverse network has a convergent structure, where products flow from many sources to few destinations, as opposed to the divergent structure of a forward network where products flow from few sources to many destinations. Moreover, uncertainty is normally unavoidable in reverse networks since the amount of returned products is hardly deterministic. In many cases, the return/disposal rate (that is, the proportion of the direct flow that will return through the reverse network) is estimated.

The integration of reverse and forward networks leads to even more complex network design problems. For instance, the number of facility layers is increased by the layers associated with recovery facilities as shown in Figure 2. Table 3 summarizes the surveyed literature on SCND with respect to the network structure (recovery or closed-loop), the type of facilities that support reverse activities and the type of facilities for which location decisions are to be made.

Barros et al. [14] present the first multi-echelon recovery facility location problem. Stochasticity is included in the models developed by Listeș [85], Listeș and Dekker [86], and Salema et al. [131]. Lu and Bostel [90] consider a layer of disposal facilities that receive returned

		Specific facilities supporting reverse activities	
Article	Network structure	Layers	Location decisions
Barros et al. [14]	recovery	collection, rework	collection, rework
Du and Evans [37]	recovery	collection, rework	rework
Jayaraman et al. [67]	closed-loop	collection	-
Jayaraman et al. [68]	recovery	collection, rework	collection, rework
Ko and Evans [75]	closed-loop	collection	collection
Lee and Dong [81]	closed-loop	-	-
Lieckens and Vandaele [83]	recovery	rework	rework
Listeș [85]	closed-loop	rework	rework
Listeș and Dekker [86]	recovery	collection, rework	collection, rework
Lu and Bostel [90]	closed-loop	collection, rework, disposal	collection, rework
Marín and Pelegrin [94]	closed-loop	-	-
Min et al. [106]	recovery	collection, rework	collection
Min et al. [107]	recovery	collection, rework	collection, rework
Pati et al. [117]	recovery	collection, rework	collection, rework
Salema et al. [130]	closed-loop	rework	rework
Salema et al. [131]	closed-loop	rework	rework
Schultmann et al. [133]	recovery	collection, rework	collection
Wang et al. [170]	closed-loop	collection	collection

Table 3: Classification of the literature dedicated to reverse logistics within the supply chain context.

products which cannot be recovered.

Marín and Pelegrin [94] do not model specific facilities for the reverse activities. The reverse flows go directly to plants for re-use in production. Similarly, in Lee and Dong [81] there are no specific facilities dedicated to reverse activities. Return products are treated in the same facilities that support direct activities. In Jayaraman et al. [67], location decisions are made only for facilities supporting "forward" activities. In Wang et al. [170], the collection centres are in fact checking points where customers hand in the purchased products in case they are unsatisfied and wish to be refunded. This article addresses the singularities that E-commerce has introduced into SCM in general and into reverse logistics in particular. Pati et al. [117] present a recovery network with four facility layers, the first three of which are (nested) collection centres and the last one refers to rework facilities. The reverse flows in the context of the growing importance of post-sale services are given particular emphasis by Du and Evans [37] and Wang et al. [170].

Table 3 shows that only a few papers introduce comprehensive models with both forward and reverse flows as well as facilities (closed-loop networks). In fact, strategic supply chain planning for recovery networks bears strong resemblance with the planning activities in a forward network. The main differences refer to the fact that the flows are reversed and the type of facilities changes. However, so far, the existing literature has not been able to show that the differences mentioned above between forward and recovery networks can yield different methodologies for treating the resulting models. Therefore, only closed-loop networks seem to clearly capture the complexity of SCND problems in comparison with the "traditional" forward networks.

5 Other supply chain characteristics

Economic globalization has created new opportunities for companies to grow their businesses by marketing their products and offering their services all over the world. As a consequence of this development, models for the strategic design of international supply chains have gained increasing importance. Such models address global features common to an international scenario in which the business activities of a company are geographically dispersed throughout multiple countries. Early literature reviews on analytical models relevant to facility location decisions for a global company are by Verter and Dincer [164, 165]. Cohen and Mallik [26] stress in their review that coordination of activities and flexibility in responding to changing market conditions are crucial elements for global supply chains. Recently, Meixell and Gargeya [97] evaluated the appropriateness of existing models to support global SCND decisions.

Financial factors are among the issues that have a strong impact on the configuration of global supply chains. In Table 4 these factors are divided into three categories. International factors comprise the first category and include taxes, duties, tariffs, exchange rates, transfer prices, and local content rules. Early research devoted to the interaction between international location and financing decisions is due to Hodder and Dincer [61], who incorporated uncertainties in prices and exchange rates into a facility location model. As with most of the early models (see also Verter and Dincer [164]), the network structure was rather simple (one facility layer and a single product) and therefore, the model was far from capturing the complexity of a general international setting. Later contributions gradually attempted at overcoming this drawback by proposing realistic models. For example, Avittathur et al. [10] integrate location and inventory decisions in a multi-commodity problem with varying inter-state sales taxes in India. Canel and Khumawala [18, 19] include tariffs, exchange rates and transfer prices in a multi-period planning horizon. Transfer prices, that is, prices charged by a unit of a company for providing goods or services to another unit of the same company, are part of the decision space in the models developed by Goetschalckx et al. [54] and Vidal and Goetschalckx [167], which also consider tariffs and corporate income taxes. One aspect that has received little attention due to its complexity refers to local content which requires manufacturers of a partic-

	Financial aspects			Risk management			Other aspects		
Article	Int. factors	Incentives	Budget const.	Robustness	Reliability	Risk pooling	Relocation	BOM	Multi-period factors
Aghezzaf [2]				√					
Arntzen et al. [9]	√		√					√	√
Avittathur et al. [10]	√								
Ballou [11]							√		
Canel and Khumawala [18, 19]	√	√							
Carlsson and Rönnqvist [21]							√		
Chakravarty [22]	√		√						
Cordeau et al. [27]								√	
Daskin et al. [32]						√			
Dogan and Goetschalckx [35]									√
Erlebacher and Meller [41]						√			
Fleischmann et al. [47]			√					√	
Goetschalckx et al. [54]	√							√	
Goh et al. [55]	√				√				√
Gunnarsson et al. [57]									√
Jang et al. [64]								√	
Kouvelis and Rosenblatt [77]	√	√	√					√	√
Lowe et al. [89]	√						√		
Melachrinoudis and Min [98]		√	√				√		
Melachrinoudis and Min [99]							√		
Melachrinoudis et al. [100]		√					√		
Melo et al. [102]			√				√		
Min and Melachrinoudis [104]		√					√		
Miranda and Garrido [108]						√			
Pati et al. [117]			√						
Shen et al. [139]						√			
Shu et al. [141]						√			
Snyder et al. [148]						√			
Teo and Shu [156]									√
Vidal and Goetschalckx [167]	√							√	
Vila et al. [168]	√							√	√
Wang et al. [169]			√						
Wilhelm et al. [172]	√							√	√
Wouda et al. [173]								√	
Yan et al. [175]								√	

Table 4: Additional features of facility location models in an SCM environment.

ular product to obtain domestically a specified minimum percentage of their raw materials and components. Wilhelm et al. [172] present a comprehensive model that addresses local content rules, exchange rates, transfer prices, and other financing aspects in a business environment under the North American Free Trade Agreement (NAFTA). Local content was also considered by Chakravarty [22].

The second category of international aspects comprises financing and taxation incentives offered by governments to attract facility investments in certain countries or regions. Tax (Melachrinoudis et al. [100], Min and Melachrinoudis [104]) and export incentives (Canel and Khumawala [18, 19]) as well as loans at reduced interest rates (Kouvelis and Rosenblatt [77]) are often used to amortize large facility investments.

The last category of financial factors refers to investment expenditures which are usually limited by the total available budget. This aspect is modelled by budget constraints for opening and closing facilities. When the planning horizon includes multiple periods as in Fleischmann et al. [47], Melachrinoudis and Min [98], and Melo et al. [102], the budget limitations vary from period to period, thus constraining not only the location of facilities but also other strategic supply chain decisions.

A recent research stream incorporates risk management into the design phase of global supply chains. We classify this feature in Table 4 according to three categories. The most well-known form of risk refers to uncertainties in customer demands and costs. Although many facility location models have been developed taking stochastic parameters into account (recall the discussion in Section 4.1), the issue of robustness in SCND has not received much attention as shown in Table 4. Snyder [146] discusses the meaning of the term *robustness*, describes various robustness measures in a pure facility location context, and reviews the existing literature. To hedge against uncertain demand, Aghezzaf [2] develops a multi-period model integrating supply chain decisions concerning distribution, inventory and capacity expansion under various demand scenarios. Although the problem settings are rather simple (a single commodity and one type of facilities are assumed), intra-warehouse flows are allowed. Robustness is measured in terms of obtaining a network configuration that is nearly optimal in all demand scenarios.

Another form of risk management refers to preventing supply chain disruption. Risks of disruption and delay may be caused, for example, by currency fluctuations, political uncertainties, strikes, trade barriers, the policies of local governments, and natural catastrophes (see Snyder and Daskin [147] for recent examples and their impact). Investing in slack capacity and excess inventory, and purchasing large insurance policies are common ways to protect supply chains against such risks. Although reliability issues can be considered during the strategic planning phase, they have not received much attention in the literature since decision makers often argue that disruptions may be only occasional. Reliability has been studied in a pure facility location context (see Snyder and Daskin [147] and references therein), while the literature focusing on SCND is rather scarce as Table 4 shows.

Another form of considering randomness is to account for risk pooling effects due to stochastic demands. This feature arises when inventory control policies are included in a facility location problem. The articles listed in Table 4 that address this combination of tactical and strategic decisions are basically extensions of the classical UFLP and CFLP. Multi-layer models are restricted to two types of facilities and only the intermediate layer is subject to location decisions (see Daskin et al. [32], Erlebacher and Meller [41], Miranda and Garrido [108], and Shu et al. [141]).

The last three columns of Table 4 refer to additional aspects that have been addressed by a few articles. As a result of economic globalization, network redesign processes have become more frequent and have gained increasing importance. Network redesign is often triggered by expansion opportunities to new markets, mergers, acquisitions, and strategic alliances. Moreover, fierce competition may also force companies to change the configuration of their supply chains through the relocation of some facilities to areas with more favourable economic conditions (e.g. with lower labour costs). Facility relocation is a time-consuming process that must be carefully planned to avoid supply chain disruptions. Only many years after the pioneering article of Ballou [11] did new models appear that handle this situation through gradual capacity transfers from existing locations to new sites during a multi-period horizon and under variable capacity moving costs (see Melachrinoudis and Min [98] and Melo et al. [102]). In particular, Melo et al. [102] study this case for multi-echelon networks with no restriction on the number of location layers.

An important aspect that has started receiving some attention in the past six years refers to expanding the set of production decisions in strategic supply chain planning. Production decisions used to be confined to finished goods and their relation to the production or supply of subassemblies and components used to be ignored (a notable exception is the early article by Arntzen et al. [9]). The explicit integration of the BOM into SCND has been recognized as an important feature. In fact, about 30% of the papers in Table 4 consider this aspect.

The last column of Table 4 addresses the situation in which future changes in some parameters are explicitly considered in the model. Naturally, in all papers with multi-period location decisions we can find multi-period factors (otherwise it would make no sense to search for multi-period location decisions). Therefore, in the last column of Table 4 we only refer to those papers in which some parameters change over time but the strategic location decisions are to be made at once at the beginning of the planning horizon. Recall from the discussion presented in Section 4.1 that although this approach may yield a sub-optimal network configuration it has been followed by some authors in an attempt to find a robust single-period configuration. This is the case with the papers mentioned in Table 4.

Finally, it should be noted that only a few models consider several of the features listed in Table 4 simultaneously. This is certainly explained by the fact that the development of an SCND model must be based on a sensible trade-off between realism, scope, complexity, and solvability.

6 Supply chain optimization

We complete our comprehensive review of the literature on facility location models in an SCM environment by first analyzing the type of supply chain performance measures that have been used (see Section 6.1) and then discussing the methodology used for solving SCND problems (see Section 6.2).

6.1 Performance measures

To assess the efficiency and/or effectiveness of the network configuration associated with given values of the decision variables, appropriate performance measures are required. In OR models applied to SCND, quantitative key performance indicators are usually based on financial objectives (either cost or profit oriented). Figure 3 summarizes the information regarding the type of objective considered in the articles presented in Table 1. Cost minimization is the most widely used objective (90 out of 115 papers). Moreover, it is typically expressed as a single objective through the sum of various cost components that depend on the set of decisions modelled. Hence, the aim of the majority of the articles surveyed is to determine the network configuration with the least total cost.

In contrast, profit maximization has received much less attention. This is rather surprising since most business activities are profit-oriented. Two different categories of profit maximization can be found in the literature: (a) maximization of revenues minus costs, and (b) after-tax profit maximization. Contributions belonging to the first category include Aardal et al. [1], Barros

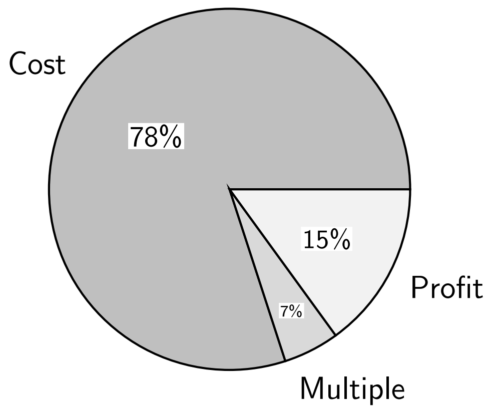

Figure 3: Supply chain performance measures.

and Labbé [13], Listeş and Dekker [86], Ma and Davidrajuh [92], Srivastava [151], Ulstein et al. [160], and Wang et al. [170]. Furthermore, under profit maximization it may not always be attractive to a company to satisfy all customer demands. This occurs when servicing certain customers yields additional costs that are higher than the corresponding revenues. Moreover, in some cases a company may intentionally loose customers when the costs of maintaining them are prohibitively high. Lieckens and Vandaele [83] and Shen [138] modelled this situation by including penalty costs in the objective function for unsatisfied demands. However, one may argue that it is rather difficult to provide a realistic estimate of loss of customer goodwill.

After-tax profit, the second category, is determined by the difference between sales revenues and total costs, and taxes. The latter are closely linked to international financing factors (recall Section 5). Therefore, it is not surprising that nine of the 12 papers listed in Table 4 use this criterion, namely Canel and Khumawala [18, 19], Chakravarty [22], Goetschalckx et al. [54], Goh et al. [55], Kouvelis and Rosenblatt [77], Vidal and Goetschalckx [167], Vila et al. [168], and Wilhelm et al. [172].

The last and smallest group of articles refers to models with multiple and conflicting objectives (see Figure 3). In this case, in addition to economic factors also measures based on resource utilization and customer responsiveness are considered. The latter include fill rate maximization (that is, the fraction or amount of customer demands satisfied within the promised delivery time is maximized) and product lateness minimization (that is, the amount of time between the promised and the actual product delivery date is minimized). In the context of reverse logistics, specific customer service measures are defined. This is the case of Du and Evans [37], who in addition to minimizing the total supply chain costs also minimize the total tardiness of cycle time. Cycle time is determined by the time required to transport returned products from collection centres to repair facilities and the time necessary to repair the faulty products. The positive deviation between the actual cycle time and the cycle time expected by the customers is then minimized. For a paper recycling network, Pati et al. [117] consider the total costs associated with the recovery of recyclable wastepaper from various possible sources and their deviation to a given budget is to be minimized. This objective is combined with an indirect customer service measure through the maximization of product quality which is influenced by the extent to which lower grade wastepaper is separated at the source. The third objective considered by Pati et al. [117] aims at maximizing the environmental benefits of wastepaper recovery through increased collected volume at the source. Environmental measures are also addressed by Hugo and Pistikopoulos [62] through the minimization of the potential ecological impact (e.g. emissions, waste) of a chemical supply chain network. This objective is traded-off against economic measures that take the expected profit (i.e. earnings after taxation and depreciation) into account.

Other multi-objective models were proposed by Altiparmak et al. [6], and Sabri and Beamon [128]. In both models, fixed and variable supply chain costs are to be minimized in conjunction with balancing capacity utilization at the operating facilities. The latter objective is measured by Sabri and Beamon [128] as the difference between the actual capacity of each facility and its utilization, while Altiparmak et al. [6] ensure that customer demands are fairly distributed among the open facilities. Altiparmak et al. [6] also consider a third objective related to product lateness minimization. This objective was addressed by Melachrinoudis and Min [98] and Melachrinoudis et al. [100], who combined it with financial objectives and local incentives for locating warehouses. The latter account for labour quality and tax incentives. The objectives considered by Guillén et al. [56] include profit, demand satisfaction and financial risk. While the first two objectives are maximized, the last refers to the probability of not meeting a given target profit and therefore is minimized. Finally, Farahani and Asgari [46] followed a different approach by minimizing the number of open facilities and maximizing the quality of the locations chosen for the new facilities. The latter objective is measured by a large group of attributes.

6.2 Solution methodology

In general, discrete SCND problems are formulated as mathematical programming models. In particular, mixed-integer linear programming (MILP) models are among the most widely used. In most cases, binary variables are associated with strategic network design decisions, typically related to location and capacity decisions, while continuous variables are associated with tactical and operational decisions. The latter capture the material flow and the supply-demand relationships in the supply chain. Therefore, they are influenced by the number of commodities, the number of layers in the network and as a result, by the arc density for the transportation of goods, and the number of planning periods. Nevertheless, the presence of integer variables usually dramatically increases the computational complexity of the model compared with the continuous variables.

In spite of the computational hurdle that the resulting models pose (most problems are NP-hard and therefore extremely difficult to solve to optimality for instances of realistic size), there has been an impressive increase in the number of problems that can be solved to optimality in a reasonable time nowadays. On one hand, this is due to the development of powerful general-purpose mathematical programming software. In the past ten years a strong improvement in speed and robustness has been observed, in particular with commercial software tools. On the other hand, the continuous development of new solution methods and refinement of existing general techniques has also led to the positive development in solving MILP problems.

Figure 4 gives an overview of the type of solution methodology that has been used for solving single-objective SCND problems. We distinguish between those problems solved with general-purpose software (either commercial or not) and those solved with a specially tailored algorithm. Within each class, two further cases are identified. The category *General solver - exact solution* refers to the use of mathematical programming software to solve a problem either to optimality or until a solution is obtained within a pre-specified gap reflecting the "worst" quality accepted by the decision maker. Cordeau et al. [27] argue that solving a real-life problem to optimality is usually not meaningful due to errors contained in the data estimates. Since the error margin tends to be larger than 1%, the authors claim that it is adequate to run the mathematical solver until a feasible solution within 1% optimality is identified. In this way, large computation times can be avoided. This form of reasoning is shared by several authors which explains the significant percentage of articles in the category *General solver - exact solution*. Alternatively, an off-the-shelf solver can be run until a given time limit is reached. We denote this case by *General solver - heuristic solution*. This approach has only been used twice, namely by Ambrosino and Scutellà [7], and Melkote and Daskin [101].

The class dedicated to specially tailored solution algorithms is further divided into two categories: *Specific algorithm - exact solution* and *Specific algorithm - heuristic solution*. The first

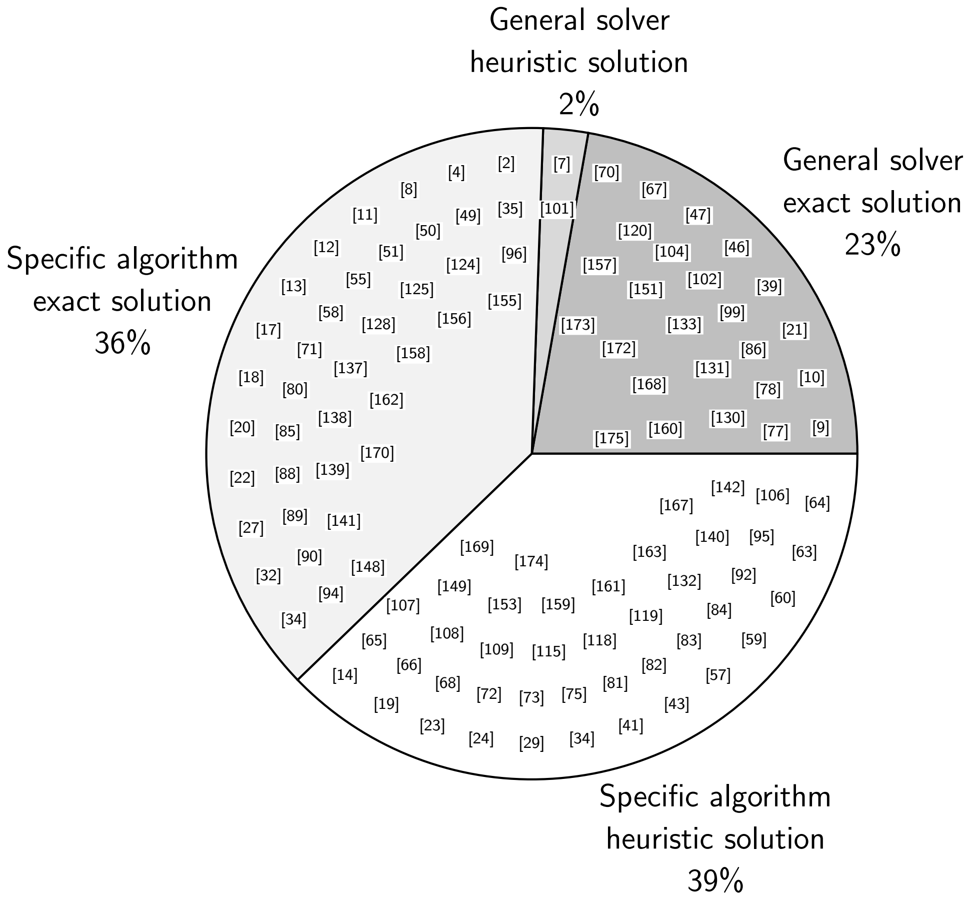

Figure 4: Solution approaches for single-objective problems.

category includes special-purpose techniques such as branch-and-bound, branch-and-cut, column generation, and decomposition methods. Among the exact approaches branch-and-bound algorithms have been a popular solution scheme, sometimes also combined with Lagrangian relaxation or heuristic procedures to obtain bounds. Discrete facility location problems are attractive candidates for decomposition techniques (see Mirchandani and Francis [110]) due to the presence of the above mentioned two types of inherently different decisions. Once the discrete-choice location decisions have been made, the resulting problem only contains continuous variables and is typically much simpler to solve. Nevertheless, the use of decomposition as a solution procedure has not been widely adopted in SCND. For example, following the early application of Benders decomposition to a multi-commodity, two-layer distribution network by Geoffrion and Graves [51], little attention has been paid to this technique. Recently, Cordeau et al. [27] and Dogan and Goetschalckx [35] showed the usefulness of this method for an SCND problem, while Santoso et al. [132] embedded Benders decomposition in a sample average approximation scheme. The lack of more decomposition schemes may be explained by the fact that due to the multi-layer structure of a supply chain network and the interaction of strategic decisions across several layers, it becomes more difficult to decompose the problem into "easier" sub-problems. In contrast, it is well known that Lagrangian, Benders and cross decomposition have been used to solve successfully core facility location models to optimality (see Mirchandani and Francis [110]).

While integer programming techniques are often able to provide optimal or near-optimal solutions to SCND problems in a reasonable time, efficient heuristic procedures have also been developed for solving this type of problems. They are particularly useful when decision makers wish to obtain "good" solutions with reduced computing time. Moreover, when the number of discrete variables is large, and this often occurs when the strategic location decisions refer to more than one facility layer in the supply chain network, then the resulting models are comparatively more complex and realistically sized problems can only be solved with a heuristic method. The articles that fall into this category are listed in Figure 4 in *Specific algorithm - heuristic solution*.

Lagrangian relaxation has proved to be a popular technique to design heuristic algorithms (see e.g. Eskigun et al. [43], Hinojosa et al. [60], Jayaraman and Pirkul [65], Marín and Pelegrin [95], Miranda and Garrido [108, 109], Pirkul and Jayaraman [118, 119], Shulman [142], Sourirajan et al. [149], Syam [153], and Wang et al. [169]). Other techniques that also make explicit use of the model's structure are based on the linear relaxation (see e.g. Barros et al. [14], Gunnarsson et al. [57], Vidal and Goetschalckx [167]), and on alternating between the primal and dual problems (see Dias et al. [34]). Other solution approaches include greedy (see e.g. Lin et al. [84], Nozick and Turnquist [115]), and local search algorithms (see e.g. van Ommeren et al. [161]). Metaheuristics are among the most effective solution strategies for solving optimization problems and have been applied to a very large variety of problems. This trend is also observed in SCND. In particular, the following approaches have been used: tabu search (see Lee and Dong [81], Tuzun and Burke [159], Wang et al. [169]), genetic algorithms (see Ko and Evans [75], Min et al. [106, 107]), simulated annealing (see Jayaraman et al. [68], Syam [153]), and scatter search (see Keskin and Ülster [72, 73]). In some cases, the development of a heuristic procedure combines different techniques. This is the case, for example, of Jang et al. [64] who use Lagrangian relaxation and a genetic algorithm. It is interesting to note that among the application-oriented articles (which will be reviewed in the next section) about 60% of the problems are solved with a heuristic procedure and the remaining 40% with a general-purpose solver.

Finally, problems with multiple objectives are solved with a specific methodology which does not always guarantee the identification of pareto optimal solutions. This is the case when the multiple objectives are transformed into a single objective by a weighted sum of the criteria (see Melachrinoudis and Min [98]) or when goal programming is used (see Pati et al. [117]). The ϵ-constraint method, which was employed by Guillén et al. [56], Hugo and Pistikopoulos [62], and Sabri and Beamon [128], also combines the different objectives into a single one. The individual objectives are constrained by a parameter ϵ (that may differ from one objective to another), which reflects the relative importance given by the decision maker. A different approach is followed by Melachrinoudis et al. [100] who use a method called linear physical programming. Pareto optimal solutions are determined by Altiparmak et al. [6] with a genetic algorithm and by Du and Evans [37] with a sophisticated strategy based on scatter search.

7 Applications

In this section we review some papers which explicitly address the application of facility location models to strategic supply chain planning. We distinguish between papers dedicated to a case study and papers that describe a potential real-life application scenario.

In Table 5 the articles we found are classified according to two criteria: the type of industry the application comes from and its context. The latter has two attributes: the category *Case study* refers to a real-life scenario, even if it was not implemented in practice, while the category *Industrial context* stands for randomly generated data for a specific industry. As can be seen from the table, each cell dedicated to a given industry has more or less an equally small number of papers. Furthermore, 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 large 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. In the remainder of this section we briefly highlight some of the characteristics of the case studies.

Fleischmann et al. [47] developed a comprehensive model for the automobile manufacturer BMW to optimize the production and distribution of cars over a 12-year planning horizon. Facility location decisions are restricted to increasing the available capacity through discrete expansion sizes. Multi-stage production, taking the BOM into account, and investment plan-

Industry	Context	Article
Automotive	Case study	Fleischmann et al. [47]
		Karabakal et al. [70]
	Industrial context	Nozick and Turnquist [115]
Chemicals	Case study	Canel and Khumawala [18, 19]
		Jayaraman and Ross [66]
		Pooley [120]
	Industrial context	Lowe et al. [89]
Food	Case study	Geoffrion and Graves [51]
		Levén and Segerstedt [82]
		Tüshaus and Wittmann [158]
		Wouda et al. [173]
	Industrial context	Avittathur et al. [10]
Forestry	Case study	Carlsson and Rönnqvist [21]
		Gunnarsson et al. [57]
		Troncoso and Garrido [157]
	Industrial context	Vila et al. [168]
Hardware	Case study	Arntzen et al. [9]
		Laval et al. [78]
	Industrial context	Sheu [140]
		Wilhelm et al. [172]
		Yan et al. [175]
Military	Case study	Chan et al. [23]
		Farahani and Asgari [46]
Sand	Case study	Barros et al. [14]
		Listeș and Dekker [86]
Other	Case study	Altiparmak et al. [6]
		Camm et al. [17]
		Dogan and Goetschalckx [35]
		Farahani and Asgari [46]
		Melachrinoudis and Min [98, 99]
		Melachrinoudis et al. [100]
		Nickel et al. [114]
		Ulstein et al. [160]
	Industrial context	Pati et al. [117]
		Salema et al. [130, 131]
		Schultmann et al. [133]
		Wang et al. [170]

Table 5: Applications of facility location in a supply chain context.

ning are included in the model. Karabakal et al. [70] optimized the distribution network of Volkswagen of America by locating new distribution and processing centres in order to improve customer service levels and simultaneously reduce total costs.

In the context of agricultural chemicals, Canel and Khumawala [18, 19] focused on international facilities location problems and gave particular emphasis to financial factors in a multi-period planning horizon. Motivated by a strategic planning problem faced by Walgreens, a chain of drugstores in the U.S., Jayaraman and Ross [66] developed the PLOT (Production, Logistics, Outbound, Transportation) design system. The tool supports decisions regarding the location of new stores and the allocation of the required resources to respond to growing customer demand for multiple commodities. The supply chain network includes a central manufacturing plant, multiple distribution centres and cross-docking sites, and retail outlets. In a study carried out for Canada's largest dairy company, Pooley [120] investigated the impact of changing the configuration of the distribution network in order to improve financial performance without reducing customer service. The study reported by Wouda et al. [173] also refers to the dairy industry and focused on the location of new plants for Nutricia Hungary. Recently, Levén and Segerstedt [82] conducted a study for Polarica, a Swedish worldwide distributor of wild berries, to determine the best location of additional storage facilities. Tüshaus and Wittmann [158] developed two facility location models for a producer of non-perishable food in Switzerland. In particular, the various steps required for data collection and preparation are described.

SCM and optimization are gaining increasing importance in the forest industry. Carlsson and Rönnqvist [21] described five projects carried out at Södra, one of the largest Swedish forest companies. In particular, one of the projects concerned the merger of two distribution networks. As a result, terminals for the distribution of pulp products by vessels had to be consolidated. In Gunnarsson et al. [57], a two-level facility location model is developed for the problem of converting forest residues into forest fuel. The distribution network consists of harvest areas or saw-mills, terminals and heating plants. The latter represent the customer level and have given demands for forest fuel. Strategic decisions include the selection of harvest areas and terminals. Troncoso and Garrido [157] present a mathematical model to determine the optimal location and size of a new saw-mill in Chile.

Arntzen et al. [9] developed a multi-period, multi-commodity MILP model to optimize the global supply chain of Digital Equipment Corporation. Their comprehensive model includes offset trade, local content and duty considerations in an international supply chain as well as multi-stage production for multiple assemblies and end products. Laval et al. [78] solved a complex supply chain design problem for the imaging and printing group of Hewlett-Packard.

Chan et al. [23] formulated a stochastic multi-depot, multi-vehicle, location-routing problem in the context of a medical-evacuation case study of the U.S. Air Force. Farahani and Asgari [46] addressed the location of warehouses and distribution centres in a real-world military logistics system.

Barros et al. [14] developed an MILP model to determine the location of regional depots and treatment facilities for recycling of sand collected from construction sites in the Netherlands. The study was motivated by new legislation forcing the reduction of waste disposal, thus encouraging recycling. The model was later extended by Listeș and Dekker [86] through the consideration of uncertainty in the demand for clean sand.

Further applications of facility location models to strategic supply chain planning can be found in other industrial settings. Altiparmak et al. [6] propose a multi-objective model for a producer of plastic products in Turkey. Both new plants and distribution centres are to be located to satisfy known customer demands. In Camm et al. [17], a distribution network design problem arising at Procter & Gamble is modelled. The aim is to optimize the North American distribution operations. The study conducted by Dogan and Goetschalckx [35] focused on the determination of the number, location and capacities of warehouses for a manufacturer of cardboard packages. Melachrinoudis and Min [98] and Melachrinoudis et al. [100] considered a real-world application involving the relocation and phase-out of a combined manufacturing plant and warehousing facility. Recently, Melachrinoudis and Min [99] solved a warehouse relocation problem for a company that manufactures and distributes rolls of film and related materials. In Nickel et al. [114], a multi-period supply chain optimization model was developed for the consolidation of a manufacturing and distribution network. The study was motivated by the merger of two large steel companies. Finally, for the largest supplier of silicon metal and ferrosilicon in the world, Ulstein et al. [160] developed a multi-period model to select the optimal location of new plants, to decide which existing plants should be closed and to determine the investments on specific equipment that should be performed at each operating plant.

In addition to the articles listed in Table 5, we also refer to Bender et al. [15] who describe the connection between location planning and Geographic Information Systems. Moreover, the integration of location models into the optimization suite *mySAP Supply Chain Management* developed by the software company SAP (Germany) is also discussed.

In spite of the applications described above, there are still many potential areas for facility location models within the SCM context that have not been addressed so far. Shah [134], for example, emphasizes the importance of using supply chain optimization techniques in the pharmaceutical industry. Possible reasons for the lack of more application papers include:

- The disclosure of company data is not allowed;
- More importance is often given to modelling the real-world problem than developing sophisticated solution methods. Indeed one can find some correlation between closeness to reality and simplicity of the solution approach;
- Difficulty of managers in using quantitative models for strategic decision support (see Shapiro [136]). In fact, there is no tradition in developing and applying quantitative methods for strategic planning yet;
- Difficulty in collecting data or even no data is available;
- When data is available, preparation and aggregation tasks are rather time-consuming.

By individually reviewing the case studies in this section we hope that more application-oriented papers will be stimulated.

8 Conclusions and directions for further research

In this paper we reviewed the literature on facility location analysis within the context of SCM and discussed the general relation between facility location models and strategic supply chain planning. Moreover, we identified the characteristics that a facility location model should have to adequately address SCM planning needs. We devoted separate sections to the relation between facility location and SCM, facility location models within SCM, solution methods as well as applications.

As can be easily seen from the various tables throughout the review, many research directions still require intensive research. Stochasticity in SCM is one of them. The literature integrating uncertainty in SCM with location decisions is still scarce. In particular, very few papers address stochastic parameters combined with other aspects such as a multi-layer network structure.

Many relevant tactical/operational decisions in SCM, as it is the case with procurement, routing and the choice of transportation modes, are far from being integrated with location decisions. Still a few papers can be found which include these aspects (recall Section 4.2).

However, in most of them the structure of the supply chain network is considerably simplified (e.g. a single product and a single location layer are usually assumed).

Another aspect that requires more attention is the full integration of forward and reverse activities in SCM. As we can conclude from the surveyed literature, only few papers attempt at this integration and, again, significant simplifications are made (e.g. a single product or deterministic parameters are considered).

One aspect that has been scarcely considered in (integrated) supply chain planning concerns postponement decisions, which refer to the possibility of not filling customer demands on time. As a result, backorders are generated that incur penalty costs. This issue was explicitly integrated with strategic decisions by Wilhelm et al. [172]. Clearly, more research is needed on this aspect, whose importance has been raised by SCM. In particular, it is important to consider the impact that it may have on strategic decisions.

In addition to these findings, we note that the large majority of location models within SCM is mostly cost-oriented. This somewhat contradicts the fact that SCND decisions involve large monetary sums and investments are usually evaluated based on their return rate. One of the few models addressing this issue was proposed by Sheu [140] who focused on maximizing the potential return on facility investment. Moreover, substantial investments lead to a period of time without profit. Companies may which to invest under the constraint that a minimum return will be gradually achieved (e.g. at least a pre-defined amount should be earned within a given time limit, see Shapiro [136]). By considering profit-oriented objective functions, it also makes sense to understand, anticipate and react to customer behaviour in order to maximize profit or revenue. This means bringing revenue management ideas into strategic supply chain planning. The contribution by Mitra [111] is the only example we found that considers revenue management for remanufactured products in reverse logistics.

Regarding the methodology that has been developed to solve SCND problems, we can observe a rich and varied group of available solution techniques. This aspect associated with the continuous development of more computing power makes it possible to handle comprehensive models. Hence, although the incorporation of the various features discussed above would naturally increase the complexity of the resulting models, the possibility of solving real-life problems seems quite promising.

The main conclusion that can be drawn from this review is that we can find a growing stream of research aiming at the integration of strategic and tactical/operational decisions in supply chain planning. Moreover, the role of facility location is decisive in supply chain network planning and this role is becoming more important with the increasing need for more comprehensive models that capture simultaneously many aspects that are relevant to real-life problems. Nevertheless, much research is still needed in order to include in the existing models many issues that so far have not received adequate attention in the literature. Therefore, there is still much room for the development of new models (and solution techniques) for helping the decision-making process in integrated supply chain planning.

References

[1] K. Aardal, M. Labbé, J. Leung, and M. Queyrane. On the two-level uncapacitated facility location problem. *INFORMS Journal on Computing*, 8:289–301, 1996.

[2] E. Aghezzaf. Capacity planning and warehouse location in supply chains with uncertain demands. *Journal of the Operational Research Society*, 56:453–462, 2005.

[3] C.H. Aikens. Facility location models for distribution planning. *European Journal of Operational Research*, 22:263–279, 1985.

[4] D. Aksen and K. Altinkemer. A location-routing problem for the conversion to the "click-and-mortar" retailing: The static case. *European Journal of Operational Research*, 186: 554–575, 2008.

[5] M. Albareda-Sambola, E. Fernández, and G. Laporte. Heuristic and lower bound for a stochastic location-routing problem. *European Journal of Operational Research*, 179: 940–955, 2007.

[6] F. Altiparmak, M. Gen, L. Lin, and T. Paksoy. A genetic algorithm approach for multi-objective optimization of supply chain networks. *Computers & Industrial Engineering*, 51: 197–216, 2006.

[7] D. Ambrosino and M.G. Scutellà. Distribution network design: New problems and related models. *European Journal of Operational Research*, 165:610–624, 2005.

[8] A. Amiri. Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European Journal of Operational Research*, 171:567–576, 2006.

[9] B.C. Arntzen, G.G. Brown, T.P. Harrison, and L.L. Trafton. Global supply chain management at Digital Equipment Corporation. *Interfaces*, 25:69–93, 1995.

[10] B. Avittathur, J. Shah, and O.K. Gupta. Distribution centre location modelling for differential sales tax structure. *European Journal of Operational Research*, 162:191–205, 2005.

[11] R.H. Ballou. Dynamic warehouse location analysis. *Journal of Marketing Research*, 5: 271–271, 1968.

[12] F. Barahona and D. Jensen. Plant location with minimum inventory. *Mathematical Programming*, 83:101–111, 1998.

[13] A.I. Barros and M. Labbé. A general model for the uncapacitated facility and depot location problem. *Location Science*, 2:173–191, 1994.

[14] A.I. Barros, R. Dekker, and V. Scholten. A two-level network for recycling sand: A case study. *European Journal of Operational Research*, 110:199–214, 1998.

[15] T. Bender, H. Hennes, J. Kalcsics, M.T. Melo, and S. Nickel. Location software and interface with GIS and supply chain management. In Z. Drezner and H.W. Hamacher, editors, *Facility location: Applications and theory*, chapter 8, pages 233–274. Springer, 2002.

[16] R. Bhatnagar and A.S. Sohal. Supply chain competitiveness: Measuring the impact of location factors, uncertainty and manufacturing practices. *Technovation*, 25:443–456, 2005.

[17] J.D. Camm, T.E. Chorman, F.A. Dill, J.R. Evans, D.J. Sweeney, and G.W. Wegryn. Blending OR/MS, judgment, and GIS: Restructuring P&G's supply chain. *Interfaces*, 27: 128–142, 1997.

[18] C. Canel and B.M. Khumawala. Multi-period international facilities location: An algorithm and application. *International Journal of Production Economics*, 35:1891–1910, 1997.

[19] C. Canel and B.M. Khumawala. International facilities location: A heuristic procedure for the dynamic uncapacitated problem. *International Journal of Production Research*, 39:3975–4000, 2001.

[20] C. Canel, B.M. Khumawala, J. Law, and A. Loh. An algorithm for the capacitated, multi-commodity multi-period facility location problem. *Computers & Operations Research*, 28: 411–427, 2001.

[21] D. Carlsson and M. Rönnqvist. Supply chain management in forestry - case studies at södra cell AB. *European Journal of Operational Research*, 163:589–616, 2005.

[22] A.K. Chakravarty. Global plant capacity and product allocation with pricing decisions. *European Journal of Operational Research*, 165:157–181, 2005.

[23] Y. Chan, W.B. Carter, and M.D. Burnes. A multiple-depot, multiple-vehicle, location-routing problem with stochastically processed demands. *Computers & Operations Research*, 28:803–826, 2001.

[24] P. Chardaire, A. Sutter, and M.-C. Costa. Solving the dynamic facility location problem. *Networks*, 28:117–124, 1996.

[25] S. Chopra and P. Meindl. *Supply chain management: Strategy, planning and operations*. Prentice Hall, 2007.

[26] M.A. Cohen and S. Mallik. Global supply chains: Research and applications. *Production and Operations Management*, 6:193–210, 1997.

[27] J.-F. Cordeau, F. Pasin, and M.M. Solomon. An integrated model for logistics network design. *Annals of Operations Research*, 144:59–82, 2006.

[28] Council of Supply Chain Management Professionals. Website: http://cscmp.org, 2007.

[29] A. Dasci and V. Verter. A continuous model for production-distribution system design. *European Journal of Operational Research*, 129:287–298, 2001.

[30] M. Daskin, L. Snyder, and R. Berger. Facility location in supply chain design. In A. Langevin and D. Riopel, editors, *Logistics systems: Design and optimization*, chapter 2, pages 39–65. Springer, 2005.

[31] M.S. Daskin. *Network and Discrete Location: Models, Algorithms, and Applications*. Wiley, 1995.

[32] M.S. Daskin, C. Coullard, and Z.-J.M. Shen. An inventory-location model: Formulation, solution algorithm and computational results. *Annals of Operations Research*, 110:83–106, 2002.

[33] R. Dekker, L.N. Van Wassenhove, and K. Indurfurth. *Reverse logistics*. Springer, 2004.

[34] J. Dias, M.E. Captivo, and J. Clímaco. Efficient primal-dual heuristic for a dynamic location problem. *Computers & Operations Research*, 34:1800–1823, 2007.

[35] K. Dogan and M. Goetschalckx. A primal decomposition method for the integrated design of multi-period production-distribution systems. *IIE Transactions*, 31:1027–1036, 1999.

[36] Z. Drezner and H.W. Hamacher, editors. *Facility location: Applications and theory*. Springer, 2004.

[37] F. Du and G.W. Evans. A bi-objective reverse logistics network analysis for post-sale service. *Computers & Operations Research*. doi: 10.1016/j.cor.2006.12.020.

[38] H. Dyckhoff, R. Lackes, and J. Reese, editors. *Supply chain management and reverse logistics*. Springer, 2003.

[39] D.G. Elson. Site location via mixed-integer programming. *Operational Research Quarterly*, 23:31–43, 1972.

[40] S.S. Erengüç, N.C. Simpson, and A.J. Vakharia. Integrated production/distribution planning in supply chains: An invited review. *European Journal of Operational Research*, 115: 219–236, 1999.

[41] S.J. Erlebacher and R.D. Meller. The interaction of location and inventory in designing distribution systems. *IIE Transactions*, 32:155–166, 2000.

[42] D. Erlenkotter. A comparative study of approaches to dynamic location problems. *European Journal of Operational Research*, 6:133–143, 1981.

[43] E. Eskigun, R. Uzsoy, P.V. Preckel, G. Beaujon, S. Krishnan, and J.D. Tew. Outbound supply chain network design with mode selection, lead times and capacitated vehicle distribution centers. *European Journal of Operational Research*, 165:182–206, 2005.

[44] EURO Winter Institute on Location and Logistics. Website: http://ewi2007.fc.ul.pt, 2007.

[45] European Union WEEE Directive. Website: http://ec.europa.eu/environment/waste/weee/index_en.htm, 2007.

[46] R.Z. Farahani and N. Asgari. Combination of MCDM and covering techniques in a hierarchical model for facility location: A case study. *European Journal of Operational Research*, 176:1839–1858, 2007.

[47] B. Fleischmann, S. Ferber, and P. Henrich. Strategic planning of BMW's global production network. *Interfaces*, 36:194–208, 2006.

[48] M. Fleischmann, J.M. Bloemhof-Ruwaard, R. Dekker, E. van der Laan, J.A.E.E. van Nunen, and L.N. Van Wassenhove. Quantitative models for reverse logistics: A review. *European Journal of Operational Research*, 103:1–17, 1997.

[49] L.-L. Gao and E.P. Robinson Jr. A dual-based optimization procedure for the two-echelon uncapacitated facility location problem. *Naval Research Logistics*, 39:191–212, 1992.

[50] L.-L. Gao and E.P. Robinson Jr. Uncapacitated facility location: General procedure and computational experience. *European Journal of Operational Research*, 76:410–427, 1994.

[51] A.M. Geoffrion and G.W. Graves. Multicommodity distribution system design by Benders decomposition. *Management Science*, 20:822–844, 1974.

[52] A.M. Geoffrion and R.F. Powers. Twenty years of strategic distribution system design: An evolutionary perspective. *Interfaces*, 25:105–127, 1995.

[53] G. Ghiani, G. Laporte, and R. Musmanno. *Introduction to Logistics Systems Planning and Control*. Wiley, 2004.

[54] M. Goetschalckx, C.J. Vidal, and K. Dogan. Modeling and design of global logistics systems: A review of integrated strategic and tactical models and design algorithms. *European Journal of Operational Research*, 143:1–18, 2002.

[55] M. Goh, J.I.S. Lim, and F. Meng. A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research*, 182:164–173, 2007.

[56] G. Guillén, F.D. Mele, M.J. Bagajewicz, A.Espuña, and L. Puigjaner. Multiobjective supply chain design under uncertainty. *Chemical Engineering Science*, 60:1535–1553, 2005.

[57] H. Gunnarsson, M. Rönnqvist, and J.T. Lundgren. Supply chain modelling of forest fuel. *European Journal of Operational Research*, 158:103–123, 2004.

[58] K.S. Hindi and T. Basta. Computationally efficient solution of a multiproduct, two-stage distribution-location problem. *Journal of the Operational Research Society*, 45: 1316–1323, 1994.

[59] Y. Hinojosa, J. Puerto, and F.R. Fernández. A multiperiod two-echelon multi-commodity capacitated plant location problem. *European Journal of Operational Research*, 123: 271–291, 2000.

[60] Y. Hinojosa, J. Kalcsics, S. Nickel, J. Puerto, and S. Velten. Dynamic supply chain design with inventory. *Computers & Operations Research*, 35:373–391, 2008.

[61] J.E. Hodder and M.C. Dincer. A multifactor model for international plant location and financing under uncertainty. *Computers & Operations Research*, 13:601–609, 1986.

[62] A. Hugo and E.N. Pistikopoulos. Environmentally conscious long-range planning and design of supply chain networks. *Journal of Cleaner Production*, 13:1471–1491, 2005.

[63] H.-S. Hwang. Design of supply-chain logistics system considering service level. *Computers & Industrial Engineering*, 43:283–297, 2002.

[64] Y.-J. Jang, S.-Y. Jang, B.-M. Chang, and J. Park. A combined model of network design and production/distribution planning for a supply network. *Computers & Industrial Engineering*, 43:263–281, 2002.

[65] V. Jayaraman and H. Pirkul. Planning and coordination of production and distribution facilities for multiple commodities. *European Journal of Operational Research*, 133:394–408, 2001.

[66] V. Jayaraman and A. Ross. A simulated annealing methodology to distribution network design and management. *European Journal of Operational Research*, 144:629–645, 2003.

[67] V. Jayaraman, V. Guide Jr., and R. Srivastava. A closed-loop logistics model for remanufacturing. *Journal of the Operational Research Society*, 50:497–508, 1999.

[68] V. Jayaraman, R.A. Patterson, and E. Rolland. The design of reverse distribution networks: Models and solution procedures. *European Journal of Operational Research*, 150: 128–149, 2003.

[69] N. Julka, T. Baines, B. Tjahjono, P. Lendermann, and V. Vitanov. A review of multi-factor capacity expansion models for manufacturing plants: Searching for a holistic decision aid. *International Journal of Production Economics*, 106:607–621, 2007.

[70] N. Karabakal, A. Günal, and W. Ritchie. Supply-chain analysis at Volkswagen of America. *Interfaces*, 30:46–55, 2000.

[71] L. Kaufman, M.V. Eeede, and P. Hansen. A plant and warehouse location problem. *Operational Research Quarterly*, 28:547–554, 1977.

[72] B.B. Keskin and H. Ülster. Meta-heuristic approaches with memory and evolution for a multi-product production/distribution system design problem. *European Journal of Operational Research*, 182:663–682, 2007.

[73] B.B. Keskin and H. Ülster. A scatter search-based heuristic to locate capacitated transshipment points. *Computers & Operations Research*, 34:3112–3125, 2007.

[74] A. Klose and A. Drexl. Facility location models for distribution system design. *European Journal of Operational Research*, 162:4–29, 2005.

[75] H.J. Ko and G.W. Evans. A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. *Computers & Operations Research*, 34:346–366, 2007.

[76] H. Kotzab, S.A. Seuring, M. Müller, and G. Reiner, editors. *Research methodologies in supply chain management*. Springer, 2005.

[77] P. Kouvelis and M.J. Rosenblatt. A mathematical programming model for global supply chain management: Conceptual approach and managerial insights. In J. Geunes, P.M. Pardalos, and H.E. Romeijn, editors, *Supply Chain Management: Models, Applications, and Research directions*, Applied Optimization, chapter 10, pages 245–277. Kluwer, 2002.

[78] C. Laval, M. Feyhl, and S. Kakouros. Hewlett-Packard combined OR and expert knowledge to design its supply chains. *Interfaces*, 35:238–247, 2005.

[79] B. Lebreton. *Strategic closed-loop supply chain management*. Springer, 2007.

[80] C.Y. Lee. A cross decomposition algorithm for a multiproduct-multitype facility location problem. *Computers & Operations Research*, 20:527–540, 1993.

[81] D.-H. Lee and M. Dong. A heuristic approach to logistics network design for end-of-lease computer products recovery. *Transportation Research Part E: Logistics and Transportation Review*, 2007. doi: 10.1016/j.tre.2006.11.003.

[82] E. Levén and A. Segerstedt. Polarica's wild berries: An example of a required storage capacity calculation and where to locate this inventory. *Supply Chain Management*, 9: 213–218, 2004.

[83] K. Lieckens and N. Vandaele. Reverse logistics network design with stochastic lead times. *Computers & Operations Research*, 34:395–416, 2007.

[84] J.-R. Lin, L.K. Nozick, and M.A. Turnquist. Strategic design of distribution systems with economies of scale in transportation. *Annals of Operations Research*, 144:161–180, 2006.

[85] O. Listeş. A generic stochastic model for supply-and-return network design. *Computers & Operations Research*, 34:417–442, 2007.

[86] O. Listeş and R. Dekker. A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research*, 160:268–287, 2005.

[87] F.V. Louveaux. Stochastic location analysis. *Location Science*, 1:127–154, 1993.

[88] F.V. Louveaux and D. Peeters. A dual-based procedure for stochastic facility location. *Operations Research*, 40:564–573, 1992.

[89] T.J. Lowe, R.E Wendell, and G. Hu. Screening location strategies to reduce exchange rate risk. *European Journal of Operational Research*, 136:573–590, 2002.

[90] Z. Lu and N. Bostel. A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. *Computers & Operations Research*, 34: 299–323, 2007.

[91] H. Luss. Operations research and capacity expansion problems: A survey. *Operations Research*, 30:907–947, 1982.

[92] H. Ma and R. Davidrajuh. An iterative approach for distribution chain design in agile virtual environment. *Industrial Management and Data Systems*, 105:815–834, 2005.

[93] A.S. Manne. *Investments for capacity expansion: Size, Location and Time-Phasing*. MIT Press, Cambridge, MA, 1967.

[94] A. Marín and B. Pelegrin. The return plant location problem: Modelling and resolution. *European Journal of Operational Research*, 104:375–392, 1998.

[95] A. Marín and B. Pelegrin. Applying lagrangian relaxation to the resolution of two-stage location problems. *Annals of Operations Research*, 86:179–198, 1999.

[96] J.B. Mazzola and A.W. Neebe. Lagrangian-relaxation-based solution procedures for a multiproduct capacitated facility location problem with choice of facility type. *European Journal of Operational Research*, 115:285–299, 1999.

[97] M.J. Meixell and V.B. Gargeya. Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review*, 41:531–550, 2005.

[98] E. Melachrinoudis and H. Min. The dynamic relocation and phase-out of a hybrid, two-echelon plant/warehousing facility: A multiple objective approach. *European Journal of Operational Research*, 123:1–15, 2000.

[99] E. Melachrinoudis and H. Min. Redesigning a warehouse network. *European Journal of Operational Research*, 176:210–229, 2007.

[100] E. Melachrinoudis, A. Messac, and H. Min. Consolidating a warehouse network: A physical programming approach. *International Journal of Production Economics*, 97: 1–17, 2005.

[101] S. Melkote and M.S. Daskin. Capacitated facility location/network design problems. *European Journal of Operational Research*, 129:481–495, 2001.

[102] M.T. Melo, S. Nickel, and F. Saldanha da Gama. Dynamic multi-commodity capacitated facility location: A mathematical modeling framework for strategic supply chain planning. *Computers & Operations Research*, 33:181–208, 2005.

[103] T. Miller. *Hierarchical operations and supply chain planning*. Springer, 2001.

[104] H. Min and E. Melachrinoudis. The relocation of a hybrid manufacturing/distribution facility from supply chain perspectives: A case study. *Omega*, 27:75–85, 1999.

[105] H. Min and G. Zhou. Supply chain modeling: Past, present and future. *Computers & Industrial Engineering*, 43:231–249, 2002.

[106] H. Min, C.S. Ko, and H.J. Ko. The spatial and temporal consolidation of returned products in a closed-loop supply chain network. *Computers & Industrial Engineering*, 51: 309–320, 2006.

[107] H. Min, H.J. Ko, and C.S. Ko. A genetic algorithm approach to developing the multi-echelon reverse logistics network for product returns. *Omega*, 34:56–69, 2006.

[108] P.A. Miranda and R.A. Garrido. Incorporating inventory control decisions into a strategic distribution network design model with stochastic demand. *Transportation Research Part E: Logistics and Transportation Review*, 40:183–207, 2004.

[109] P.A. Miranda and R.A. Garrido. Valid inequalities for lagrangian relaxation in an inventory location problem with stochastic capacity. *Transportation Research Part E: Logistics and Transportation Review*, 44:47–65, 2008.

[110] P.B. Mirchandani and R.L. Francis, editors. *Discrete Location Theory*. Wiley, 1990.

[111] S. Mitra. Revenue management for remanufactured products. *Omega*, 35:553–562, 2007.

[112] G. Nagy and S. Salhi. Location-routing: Issues, models and methods. *European Journal of Operational Research*, 177:649–672, 2007.

[113] S. Nickel and J. Puerto. *Location theory: A unified approach*. Springer, 2005.

[114] S. Nickel, S. Velten, and G. Weimerskirch. Strategische Supply-Chain Entscheidungen in der Stahlindustrie - Eine Fallstudie. In H.-O. Günther, D.C. Mattfeld, and L. Suhl, editors, *Supply Chain Management und Logistik*, pages 157–177. Springer, 2006.

[115] L.K. Nozick and M.A. Turnquist. Integrating inventory impacts into a fixed-charge model for locating distribution centers. *Transportation Research Part E: Logistics and Transportation Review*, 34:173–186, 1998.

[116] S.H. Owen and M.S. Daskin. Strategic facility location: A review. *European Journal of Operational Research*, 111:423–447, 1998.

[117] R.K. Pati, P. Vrat, and P. Kumar. A goal programming model for paper recycling system. *Omega*, 36:405–417, 2008.

[118] H. Pirkul and V. Jayaraman. Production, transportation, and distribution planning in a multi-commodity tri-echelon system. *Transportation Science*, 30:291–302, 1996.

[119] H. Pirkul and V. Jayaraman. A multi-commodity, multi-plant, capacitated facility location problem: Formulation and efficient heuristic solution. *Computers & Operations Research*, 25:869–878, 1998.

[120] J. Pooley. Integrated production and distribution facility planning at Ault Foods. *Interfaces*, 24:113–121, 1994.

[121] C.S. ReVelle and H.A. Eiselt. Location analysis: A synthesis and survey. *European Journal of Operational Research*, 165:1–19, 2005.

[122] C.S. ReVelle and G. Laporte. The plant location problem: New models and research prospects. *Operations Research*, 44:864–874, 1996.

[123] C.S. ReVelle, H.A. Eiselt, and M.S. Daskin. A bibliography for some fundamental problem categories in discrete location science. *European Journal of Operational Research*, 184: 817–848, 2008.

[124] H.-B. Ro and D.-W. Tcha. A branch-and-bound algorithm for the two-level uncapacitated facility location problrem with some side constraints. *European Journal of Operational Research*, 18:349–358, 1984.

[125] H.E. Romeijn, J. Shu, and C.-P. Teo. Designing two-echelon supply networks. *European Journal of Operational Research*, 178:449–462, 2007.

[126] G.M. Roodman and L.B. Schwarz. Optimal and heuristic facility phase-out strategies. *AIIE Transactions*, 7:177–184, 1975.

[127] G.M. Roodman and L.B. Schwarz. Extensions of the multi-period facility phase-out model: New procedures and application to a phase-in/phase-out problem. *AIIE Transactions*, 9:103–107, 1977.

[128] E.H. Sabri and B.M. Beamon. A multi-objective approach to simultaneous strategic and operational planning in supply chain design. *Omega*, 28:581–598, 2000.

[129] G. Sahin and H. Süral. A review of hierarchical facility location models. *Computers & Operations Research*, 34:2310–2331, 2007.

[130] M.I. Salema, A.P.B. Póvoa, and A.Q. Novais. A warehouse-based design model for reverse logistics. *Journal of the Operational Research Society*, 57:615–629, 2006.

[131] M.I. Salema, A.P. Barbosa-Póvoa, and A.Q. Novais. An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty. *European Journal of Operational Research*, 179:1063–1077, 2007.

[132] T. Santoso, S. Ahmed, M. Goetschalckx, and A. Shapiro. A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research*, 167:96–115, 2005.

[133] F. Schultmann, B. Engels, and O. Rentz. Closed-loop supply chains for spent batteries. *Interfaces*, 33:57–71, 2003.

[134] N. Shah. Pharmaceutical supply chains: Key issues and strategies for optimisation. *Computers & Chemical Engineering*, 28:929–941, 2004.

[135] J.F. Shapiro. *Modeling the supply chain*. Brooks/Cole-Thomson, 2001.

[136] J.F. Shapiro. Challenges of strategic supply chain planning and modeling. *Computers & Chemical Engineering*, 28:855–861, 2004.

[137] Z.-J. Shen and L. Qi. Incorporating inventory and routing costs in strategic location models. *European Journal of Operational Research*, 179:372–389, 2007.

[138] Z.-J. M. Shen. A profit-maximizing supply chain network design model with demand choice flexibility. *Operations Research Letters*, 34:673–682, 2006.

[139] Z.-J.M. Shen, C. Coullard, and M.S. Daskin. A joint location-inventory model. *Transportation Science*, 37:40–55, 2003.

[140] J.-B. Sheu. Locating manufacturing and distribution centers: An integrated supply-chain based spatial interaction approach. *Transportation Research Part E: Logistics and Transportation Review*, 39:381–397, 2003.

[141] J. Shu, C.-P. Teo, and Z.-J.M. Shen. Stochastic transportation-inventory network design problem. *Operations Research*, 53:48–60, 2005.

[142] A. Shulman. An algorithm for solving dynamic capacitated plant location problems with discrete expansion sizes. *Operations Research*, 39:423–436, 1991.

[143] D. Simchi-Levi, P. Kaminsky, and E. Simchi-Levi. *Designing and managing the supply chain: Concepts, strategies, and cases*. McGraw-Hill, 1999.

[144] D. Simchi-Levi, P. Kaminsky, and E. Simchi-Levi. *Managing the Supply Chain: The definitive guide for the business professional*. McGraw-Hill, 2004.

[145] D. Simchi-Levi, X. Chen, and J. Bramel. *The Logic of Logistics: Theory, Algorithms, and Applications for Logistics Management*. Springer, second edition, 2005.

[146] L.V. Snyder. Facility location under uncertainty: A review. *IIE Transactions*, 38:537–554, 2006.

[147] L.V. Snyder and M.S. Daskin. Models for reliable supply chain network design. In A.T. Murray and T. Grubesic, editors, *Critical Infrastructure: Reliability and Vulnerability*, Advances in Spatial Science, chapter 13, pages 257–290. Springer, 2007.

[148] L.V. Snyder, M.S. Daskin, and C.-P. Teo. The stochastic location model with risk pooling. *European Journal of Operational Research*, 179:1221–1238, 2007.

[149] K. Sourirajan, L. Ozsen, and R. Uzsoy. A single-product network design model with lead time and safety stock considerations. *IIE Transactions*, 39:411–424, 2007.

[150] R. Sridharan. The capacitated plant location problem. *European Journal of Operational Research*, 87:203–213, 1995.

[151] S.K. Srivastava. Network design for reverse logistics. *Omega*, 36:535–548, 2008.

[152] H. Stadtler and C. Kilger. *Supply Chain Management and advanced planning*. Springer, 2000.

[153] S.S. Syam. A model and methodologies for the location problem with logistical components. *Computers & Operations Research*, 29:1173–1193, 2002.

[154] S. Talluri and R.C. Baker. A multi-phase mathematical programming approach for effective supply chain design. *European Journal of Operational Research*, 141:544–558, 2002.

[155] D.-W. Tcha and B.-I. Lee. A branch-and-bound algorithm for the multi-level uncapacitated facility location problem. *European Journal of Operational Research*, 18:35–43, 1984.

[156] C.-P. Teo and J. Shu. Warehouse-retailer network design problem. *Operations Research*, 52:396–408, 2004.

[157] J.J. Troncoso and R.A. Garrido. Forestry production and logistics planning: An analysis using mixed-integer programming. *Forest Policy and Economics*, 7:625–633, 2005.

[158] U. Tüshaus and S. Wittmann. Strategic logistic planning by means of simple plant location: A case study. In B. Fleischmann, J.A.E.E. van Neunen, M.G. Speranza, and P. Stähly, editors, *Advances in distribution logistics*, pages 241–263. Springer, 1998.

[159] D. Tuzun and L.I. Burke. A two-phase tabu search approach to the location routing problem. *European Journal of Operational Research*, 116:87–99, 1999.

[160] N.L. Ulstein, M. Christiansen, R. Gronhaug, N. Magnussen, and M.M. Solomon. Elkem uses optimization in redesigning its supply chain. *Interfaces*, 36:314–325, 2006.

[161] J.C.W. van Ommeren, A.F. Bumb, and A.V. Sleptchenko. Locating repair shops in a stochastic environment. *Computers & Operations Research*, 33:1575–1594, 2006.

[162] T.J. Van Roy and D. Erlenkotter. A dual-based procedure for dynamic facility location. *Management Science*, 28:1091–1105, 1982.

[163] V. Verter and A. Dasci. The plant location and flexible technology acquisition problem. *European Journal of Operational Research*, 136:366–382, 2002.

[164] V. Verter and C. Dincer. Integrated evaluation of facility location, capacity acquisition, and technology selection for designing global manufacturing strategies. *European Journal of Operational Research*, 60:1–18, 1992.

[165] V. Verter and M.C. Dincer. Global manufacturing strategy. In Z. Drezner, editor, *Facility location: A survey of applications and methods*, chapter 12, pages 263–282. Springer, 1995.

[166] C.J. Vidal and M. Goetschalckx. Strategic production-distribution models: A critical review with emphasis on global supply chain models. *European Journal of Operational Research*, 98:1–18, 1997.

[167] C.J. Vidal and M. Goetschalckx. A global supply chain model with transfer pricing and transportation cost allocation. *European Journal of Operational Research*, 129:134–158, 2001.

[168] D. Vila, A. Martel, and R. Beauregard. Designing logistics networks in divergent process industries: A methodology and its application to the lumber industry. *International Journal of Production Economics*, 102:358–378, 2006.

[169] Q. Wang, R. Batta, J. Bhadury, and C.M. Rump. Budget constrained location problem with opening and closing of facilities. *Computers & Operations Research*, 30:2047–2069, 2003.

[170] Z. Wang, D.-Q. Yao, and P. Huang. A new location-inventory policy with reverse logistics applied to B2C e-markets of China. *International Journal of Production Economics*, 107: 350–363, 2007.

[171] A. Warszawski. Multi-dimensional location problems. *Operational Research Quarterly*, 24:165–179, 1973.

[172] W. Wilhelm, D. Liang, B. Rao, D. Warrier, X. Zhu, and S. Bulusu. Design of international assembly systems and their supply chains under NAFTA. *Transportation Research Part E: Logistics and Transportation Review*, 41:467–493, 2005.

[173] F.H.E. Wouda, P.l van Beek, J.G.A.J. van der Vorst, and H. Tacke. An application of mixed-integer linear programming models on the redesign of the supply network of Nutricia Dairy & Drinks Group in Hungary. *OR Spectrum*, 24:449–465, 2002.

[174] T.-H. Wu, C. Low, and J.-W. Bai. Heuristic solutions to multi-depot location-routing problems. *Computers & Operations Research*, 29:1393–1415, 2002.

[175] H. Yan, Z. Yu, and T.C.E. Cheng. A strategic model for supply chain design with logical constraints: formulation and solution. *Computers & Operations Research*, 30:2135–2155, 2003.

Published reports of the Fraunhofer ITWM

The PDF-files of the following reports are available under:
www.itwm.fraunhofer.de/de/zentral__berichte/berichte

1. D. Hietel, K. Steiner, J. Struckmeier
A Finite - Volume Particle Method for Compressible Flows
(19 pages, 1998)

2. M. Feldmann, S. Seibold
Damage Diagnosis of Rotors: Application of Hilbert Transform and Multi-Hypothesis Testing
Keywords: Hilbert transform, damage diagnosis, Kalman filtering, non-linear dynamics
(23 pages, 1998)

3. Y. Ben-Haim, S. Seibold
Robust Reliability of Diagnostic Multi-Hypothesis Algorithms: Application to Rotating Machinery
Keywords: Robust reliability, convex models, Kalman filtering, multi-hypothesis diagnosis, rotating machinery, crack diagnosis
(24 pages, 1998)

4. F.-Th. Lentes, N. Siedow
Three-dimensional Radiative Heat Transfer in Glass Cooling Processes
(23 pages, 1998)

5. A. Klar, R. Wegener
A hierarchy of models for multilane vehicular traffic
Part I: Modeling
(23 pages, 1998)

Part II: Numerical and stochastic investigations
(17 pages, 1998)

6. A. Klar, N. Siedow
Boundary Layers and Domain Decomposition for Radiative Heat Transfer and Diffusion Equations: Applications to Glass Manufacturing Processes
(24 pages, 1998)

7. I. Choquet
Heterogeneous catalysis modelling and numerical simulation in rarified gas flows Part I: Coverage locally at equilibrium
(24 pages, 1998)

8. J. Ohser, B. Steinbach, C. Lang
Efficient Texture Analysis of Binary Images
(17 pages, 1998)

9. J. Orlik
Homogenization for viscoelasticity of the integral type with aging and shrinkage
(20 pages, 1998)

10. J. Mohring
Helmholtz Resonators with Large Aperture
(21 pages, 1998)

11. H. W. Hamacher, A. Schöbel
On Center Cycles in Grid Graphs
(15 pages, 1998)

12. H. W. Hamacher, K.-H. Küfer
Inverse radiation therapy planning - a multiple objective optimisation approach
(14 pages, 1999)

13. C. Lang, J. Ohser, R. Hilfer
On the Analysis of Spatial Binary Images
(20 pages, 1999)

14. M. Junk
On the Construction of Discrete Equilibrium Distributions for Kinetic Schemes
(24 pages, 1999)

15. M. Junk, S. V. Raghurame Rao
A new discrete velocity method for Navier-Stokes equations
(20 pages, 1999)

16. H. Neunzert
Mathematics as a Key to Key Technologies
(39 pages (4 PDF-Files), 1999)

17. J. Ohser, K. Sandau
Considerations about the Estimation of the Size Distribution in Wicksell's Corpuscle Problem
(18 pages, 1999)

18. E. Carrizosa, H. W. Hamacher, R. Klein, S. Nickel
Solving nonconvex planar location problems by finite dominating sets
Keywords: Continuous Location, Polyhedral Gauges, Finite Dominating Sets, Approximation, Sandwich Algorithm, Greedy Algorithm
(19 pages, 2000)

19. A. Becker
A Review on Image Distortion Measures
Keywords: Distortion measure, human visual system
(26 pages, 2000)

20. H. W. Hamacher, M. Labbé, S. Nickel, T. Sonneborn
Polyhedral Properties of the Uncapacitated Multiple Allocation Hub Location Problem
Keywords: integer programming, hub location, facility location, valid inequalities, facets, branch and cut
(21 pages, 2000)

21. H. W. Hamacher, A. Schöbel
Design of Zone Tariff Systems in Public Transportation
(30 pages, 2001)

22. D. Hietel, M. Junk, R. Keck, D. Teleaga
The Finite-Volume-Particle Method for Conservation Laws
(16 pages, 2001)

23. T. Bender, H. Hennes, J. Kalcsics, M. T. Melo, S. Nickel
Location Software and Interface with GIS and Supply Chain Management
Keywords: facility location, software development, geographical information systems, supply chain management
(48 pages, 2001)

24. H. W. Hamacher, S. A. Tjandra
Mathematical Modelling of Evacuation Problems: A State of Art
(44 pages, 2001)

25. J. Kuhnert, S. Tiwari
Grid free method for solving the Poisson equation
Keywords: Poisson equation, Least squares method, Grid free method
(19 pages, 2001)

26. T. Götz, H. Rave, D. Reinel-Bitzer, K. Steiner, H. Tiemeier
Simulation of the fiber spinning process
Keywords: Melt spinning, fiber model, Lattice Boltzmann, CFD
(19 pages, 2001)

27. A. Zemitis
On interaction of a liquid film with an obstacle
Keywords: impinging jets, liquid film, models, numerical solution, shape
(22 pages, 2001)

28. I. Ginzburg, K. Steiner
Free surface lattice-Boltzmann method to model the filling of expanding cavities by Bingham Fluids
Keywords: Generalized LBE, free-surface phenomena, interface boundary conditions, filling processes, Bingham viscoplastic model, regularized models
(22 pages, 2001)

29. H. Neunzert
»Denn nichts ist für den Menschen als Menschen etwas wert, was er nicht mit Leidenschaft tun kann«
Vortrag anlässlich der Verleihung des Akademiepreises des Landes Rheinland-Pfalz am 21.11.2001
Keywords: Lehre, Forschung, angewandte Mathematik, Mehrskalenanalyse, Strömungsmechanik
(18 pages, 2001)

30. J. Kuhnert, S. Tiwari
Finite pointset method based on the projection method for simulations of the incompressible Navier-Stokes equations
Keywords: Incompressible Navier-Stokes equations, Meshfree method, Projection method, Particle scheme, Least squares approximation
AMS subject classification: 76D05, 76M28
(25 pages, 2001)

31. R. Korn, M. Krekel
Optimal Portfolios with Fixed Consumption or Income Streams
Keywords: Portfolio optimisation, stochastic control, HJB equation, discretisation of control problems
(23 pages, 2002)

32. M. Krekel
Optimal portfolios with a loan dependent credit spread
Keywords: Portfolio optimisation, stochastic control, HJB equation, credit spread, log utility, power utility, non-linear wealth dynamics
(25 pages, 2002)

33. J. Ohser, W. Nagel, K. Schladitz
The Euler number of discretized sets – on the choice of adjacency in homogeneous lattices
Keywords: image analysis, Euler number, neighborhod relationships, cuboidal lattice
(32 pages, 2002)

34. I. Ginzburg, K. Steiner
Lattice Boltzmann Model for Free-Surface flow and Its Application to Filling Process in Casting
Keywords: Lattice Boltzmann models; free-surface phenomena; interface boundary conditions; filling processes; injection molding; volume of fluid method; interface boundary conditions; advection-schemes; upwind-schemes
(54 pages, 2002)

35. M. Günther, A. Klar, T. Materne, R. Wegener
Multivalued fundamental diagrams and stop and go waves for continuum traffic equations
Keywords: traffic flow, macroscopic equations, kinetic derivation, multivalued fundamental diagram, stop and go waves, phase transitions
(25 pages, 2002)

36. S. Feldmann, P. Lang, D. Prätzel-Wolters
Parameter influence on the zeros of network determinants
Keywords: Networks, Equicofactor matrix polynomials, Realization theory, Matrix perturbation theory
(30 pages, 2002)

37. K. Koch, J. Ohser, K. Schladitz
Spectral theory for random closed sets and estimating the covariance via frequency space
Keywords: Random set, Bartlett spectrum, fast Fourier transform, power spectrum
(28 pages, 2002)

38. D. d'Humières, I. Ginzburg
Multi-reflection boundary conditions for lattice Boltzmann models
Keywords: lattice Boltzmann equation, boudary condistions, bounce-back rule, Navier-Stokes equation
(72 pages, 2002)

39. R. Korn
Elementare Finanzmathematik
Keywords: Finanzmathematik, Aktien, Optionen, Portfolio-Optimierung, Börse, Lehrerweiterbildung, Mathematikunterricht
(98 pages, 2002)

40. J. Kallrath, M. C. Müller, S. Nickel
Batch Presorting Problems: Models and Complexity Results
Keywords: Complexity theory, Integer programming, Assigment, Logistics
(19 pages, 2002)

41. J. Linn
On the frame-invariant description of the phase space of the Folgar-Tucker equation
Key words: fiber orientation, Folgar-Tucker equation, injection molding
(5 pages, 2003)

42. T. Hanne, S. Nickel
A Multi-Objective Evolutionary Algorithm for Scheduling and Inspection Planning in Software Development Projects
Key words: multiple objective programming, project management and scheduling, software development, evolutionary algorithms, efficient set
(29 pages, 2003)

43. T. Bortfeld , K.-H. Küfer, M. Monz, A. Scherrer, C. Thieke, H. Trinkaus
Intensity-Modulated Radiotherapy - A Large Scale Multi-Criteria Programming Problem
Keywords: multiple criteria optimization, representative systems of Pareto solutions, adaptive triangulation, clustering and disaggregation techniques, visualization of Pareto solutions, medical physics, external beam radiotherapy planning, intensity modulated radiotherapy
(31 pages, 2003)

44. T. Halfmann, T. Wichmann
Overview of Symbolic Methods in Industrial Analog Circuit Design
Keywords: CAD, automated analog circuit design, symbolic analysis, computer algebra, behavioral modeling, system simulation, circuit sizing, macro modeling, differential-algebraic equations, index
(17 pages, 2003)

45. S. E. Mikhailov, J. Orlik
Asymptotic Homogenisation in Strength and Fatigue Durability Analysis of Composites
Keywords: multiscale structures, asymptotic homogenization, strength, fatigue, singularity, non-local conditions
(14 pages, 2003)

46. P. Domínguez-Marín, P. Hansen, N. Mladenovi´c , S. Nickel
Heuristic Procedures for Solving the Discrete Ordered Median Problem
Keywords: genetic algorithms, variable neighborhood search, discrete facility location
(31 pages, 2003)

47. N. Boland, P. Domínguez-Marín, S. Nickel, J. Puerto
Exact Procedures for Solving the Discrete Ordered Median Problem
Keywords: discrete location, Integer programming
(41 pages, 2003)

48. S. Feldmann, P. Lang
Padé-like reduction of stable discrete linear systems preserving their stability
Keywords: Discrete linear systems, model reduction, stability, Hankel matrix, Stein equation
(16 pages, 2003)

49. J. Kallrath, S. Nickel
A Polynomial Case of the Batch Presorting Problem
Keywords: batch presorting problem, online optimization, competetive analysis, polynomial algorithms, logistics
(17 pages, 2003)

50. T. Hanne, H. L. Trinkaus
knowCube for MCDM – Visual and Interactive Support for Multicriteria Decision Making
Key words: Multicriteria decision making, knowledge management, decision support systems, visual interfaces, interactive navigation, real-life applications.
(26 pages, 2003)

51. O. Iliev, V. Laptev
On Numerical Simulation of Flow Through Oil Filters
Keywords: oil filters, coupled flow in plain and porous media, Navier-Stokes, Brinkman, numerical simulation
(8 pages, 2003)

52. W. Dörfler, O. Iliev, D. Stoyanov, D. Vassileva
On a Multigrid Adaptive Refinement Solver for Saturated Non-Newtonian Flow in Porous Media
Keywords: Nonlinear multigrid, adaptive refinement, non-Newtonian flow in porous media
(17 pages, 2003)

53. S. Kruse
On the Pricing of Forward Starting Options under Stochastic Volatility
Keywords: Option pricing, forward starting options, Heston model, stochastic volatility, cliquet options
(11 pages, 2003)

54. O. Iliev, D. Stoyanov
Multigrid – adaptive local refinement solver for incompressible flows
Keywords: Navier-Stokes equations, incompressible flow, projection-type splitting, SIMPLE, multigrid methods, adaptive local refinement, lid-driven flow in a cavity
(37 pages, 2003)

55. V. Starikovicius
The multiphase flow and heat transfer in porous media
Keywords: Two-phase flow in porous media, various formulations, global pressure, multiphase mixture model, numerical simulation
(30 pages, 2003)

56. P. Lang, A. Sarishvili, A. Wirsen
Blocked neural networks for knowledge extraction in the software development process
Keywords: Blocked Neural Networks, Nonlinear Regression, Knowledge Extraction, Code Inspection
(21 pages, 2003)

57. H. Knaf, P. Lang, S. Zeiser
Diagnosis aiding in Regulation Thermography using Fuzzy Logic
Keywords: fuzzy logic,knowledge representation, expert system
(22 pages, 2003)

58. M. T. Melo, S. Nickel, F. Saldanha da Gama
Largescale models for dynamic multi-commodity capacitated facility location
Keywords: supply chain management, strategic planning, dynamic location, modeling
(40 pages, 2003)

59. J. Orlik
Homogenization for contact problems with periodically rough surfaces
Keywords: asymptotic homogenization, contact problems
(28 pages, 2004)

60. A. Scherrer, K.-H. Küfer, M. Monz, F. Alonso, T. Bortfeld
IMRT planning on adaptive volume structures – a significant advance of computational complexity
Keywords: Intensity-modulated radiation therapy (IMRT), inverse treatment planning, adaptive volume structures, hierarchical clustering, local refinement, adaptive clustering, convex programming, mesh generation, multi-grid methods
(24 pages, 2004)

61. D. Kehrwald
Parallel lattice Boltzmann simulation of complex flows
Keywords: Lattice Boltzmann methods, parallel computing, microstructure simulation, virtual material design, pseudo-plastic fluids, liquid composite moulding
(12 pages, 2004)

62. O. Iliev, J. Linn, M. Moog, D. Niedziela, V. Starikovicius
On the Performance of Certain Iterative Solvers for Coupled Systems Arising in Discretization of Non-Newtonian Flow Equations
Keywords: Performance of iterative solvers, Preconditioners, Non-Newtonian flow
(17 pages, 2004)

63. R. Ciegis, O. Iliev, S. Rief, K. Steiner
On Modelling and Simulation of Different Regimes for Liquid Polymer Moulding
Keywords: Liquid Polymer Moulding, Modelling, Simulation, Infiltration, Front Propagation, non-Newtonian flow in porous media
(43 pages, 2004)

64. T. Hanne, H. Neu
Simulating Human Resources in Software Development Processes
Keywords: Human resource modeling, software process, productivity, human factors, learning curve
(14 pages, 2004)

65. O. Iliev, A. Mikelic, P. Popov
Fluid structure interaction problems in deformable porous media: Toward permeability of deformable porous media
Keywords: fluid-structure interaction, deformable porous media, upscaling, linear elasticity, stokes, finite elements
(28 pages, 2004)

66. F. Gaspar, O. Iliev, F. Lisbona, A. Naumovich, P. Vabishchevich
On numerical solution of 1-D poroelasticity equations in a multilayered domain
Keywords: poroelasticity, multilayered material, finite volume discretization, MAC type grid
(41 pages, 2004)

67. J. Ohser, K. Schladitz, K. Koch, M. Nöthe
Diffraction by image processing and its application in materials science
Keywords: porous microstructure, image analysis, random set, fast Fourier transform, power spectrum, Bartlett spectrum
(13 pages, 2004)

68. H. Neunzert
Mathematics as a Technology: Challenges for the next 10 Years
Keywords: applied mathematics, technology, modelling, simulation, visualization, optimization, glass processing, spinning processes, fiber-fluid interaction, trubulence effects, topological optimization, multicriteria optimization, Uncertainty and Risk, financial mathematics, Malliavin calculus, Monte-Carlo methods, virtual material design, filtration, bio-informatics, system biology
(29 pages, 2004)

69. R. Ewing, O. Iliev, R. Lazarov, A. Naumovich
On convergence of certain finite difference discretizations for 1D poroelasticity interface problems
Keywords: poroelasticity, multilayered material, finite volume discretizations, MAC type grid, error estimates
(26 pages,2004)

70. W. Dörfler, O. Iliev, D. Stoyanov, D. Vassileva
On Efficient Simulation of Non-Newtonian Flow in Saturated Porous Media with a Multigrid Adaptive Refinement Solver
Keywords: Nonlinear multigrid, adaptive renement, non-Newtonian in porous media
(25 pages, 2004)

71. J. Kalcsics, S. Nickel, M. Schröder
Towards a Unified Territory Design Approach – Applications, Algorithms and GIS Integration
Keywords: territory desgin, political districting, sales territory alignment, optimization algorithms, Geographical Information Systems
(40 pages, 2005)

72. K. Schladitz, S. Peters, D. Reinel-Bitzer, A. Wiegmann, J. Ohser
Design of acoustic trim based on geometric modeling and flow simulation for non-woven
Keywords: random system of fibers, Poisson line process, flow resistivity, acoustic absorption, Lattice-Boltzmann method, non-woven
(21 pages, 2005)

73. V. Rutka, A. Wiegmann
Explicit Jump Immersed Interface Method for virtual material design of the effective elastic moduli of composite materials
Keywords: virtual material design, explicit jump immersed interface method, effective elastic moduli, composite materials
(22 pages, 2005)

74. T. Hanne
Eine Übersicht zum Scheduling von Baustellen
Keywords: Projektplanung, Scheduling, Bauplanung, Bauindustrie
(32 pages, 2005)

75. J. Linn
The Folgar-Tucker Model as a Differetial Algebraic System for Fiber Orientation Calculation
Keywords: fiber orientation, Folgar–Tucker model, invariants, algebraic constraints, phase space, trace stability
(15 pages, 2005)

76. M. Speckert, K. Dreßler, H. Mauch, A. Lion, G. J. Wierda
Simulation eines neuartigen Prüfsystems für Achserprobungen durch MKS-Modellierung einschließlich Regelung
Keywords: virtual test rig, suspension testing, multibody simulation, modeling hexapod test rig, optimization of test rig configuration
(20 pages, 2005)

77. K.-H. Küfer, M. Monz, A. Scherrer, P. Süss, F. Alonso, A. S. A. Sultan, Th. Bortfeld, D. Craft, Chr. Thieke
Multicriteria optimization in intensity modulated radiotherapy planning
Keywords: multicriteria optimization, extreme solutions, real-time decision making, adaptive approximation schemes, clustering methods, IMRT planning, reverse engineering
(51 pages, 2005)

78. S. Amstutz, H. Andrä
A new algorithm for topology optimization using a level-set method
Keywords: shape optimization, topology optimization, topological sensitivity, level-set
(22 pages, 2005)

79. N. Ettrich
Generation of surface elevation models for urban drainage simulation
Keywords: Flooding, simulation, urban elevation models, laser scanning
(22 pages, 2005)

80. H. Andrä, J. Linn, I. Matei, I. Shklyar, K. Steiner, E. Teichmann
OPTCAST – Entwicklung adäquater Strukturoptimierungsverfahren für Gießereien Technischer Bericht (KURZFASSUNG)
Keywords: Topologieoptimierung, Level-Set-Methode, Gießprozesssimulation, Gießtechnische Restriktionen, CAE-Kette zur Strukturoptimierung
(77 pages, 2005)

81. N. Marheineke, R. Wegener
Fiber Dynamics in Turbulent Flows Part I: General Modeling Framework
Keywords: fiber-fluid interaction; Cosserat rod; turbulence modeling; Kolmogorov's energy spectrum; double-velocity correlations; differentiable Gaussian fields
(20 pages, 2005)

Part II: Specific Taylor Drag
Keywords: flexible fibers; k-ε turbulence model; fiber-turbulence interaction scales; air drag; random Gaussian aerodynamic force; white noise; stochastic differential equations; ARMA process
(18 pages, 2005)

82. C. H. Lampert, O. Wirjadi
An Optimal Non-Orthogonal Separation of the Anisotropic Gaussian Convolution Filter
Keywords: Anisotropic Gaussian filter, linear filtering, orientation space, nD image processing, separable filters
(25 pages, 2005)

83. H. Andrä, D. Stoyanov
Error indicators in the parallel finite element solver for linear elasticity DDFEM
Keywords: linear elasticity, finite element method, hierarchical shape functions, domain decom-position, parallel implementation, a posteriori error estimates
(21 pages, 2006)

84. M. Schröder, I. Solchenbach
Optimization of Transfer Quality in Regional Public Transit
Keywords: public transit, transfer quality, quadratic assignment problem
(16 pages, 2006)

85. A. Naumovich, F. J. Gaspar
On a multigrid solver for the three-dimensional Biot poroelasticity system in multilayered domains
Keywords: poroelasticity, interface problem, multigrid, operator-dependent prolongation
(11 pages, 2006)

86. S. Panda, R. Wegener, N. Marheineke
Slender Body Theory for the Dynamics of Curved Viscous Fibers
Keywords: curved viscous fibers; fluid dynamics; Navier-Stokes equations; free boundary value problem; asymptotic expansions; slender body theory
(14 pages, 2006)

87. E. Ivanov, H. Andrä, A. Kudryavtsev
Domain Decomposition Approach for Automatic Parallel Generation of Tetrahedral Grids
Key words: Grid Generation, Unstructured Grid, Delaunay Triangulation, Parallel Programming, Domain Decomposition, Load Balancing
(18 pages, 2006)

88. S. Tiwari, S. Antonov, D. Hietel, J. Kuhnert, R. Wegener
A Meshfree Method for Simulations of Interactions between Fluids and Flexible Structures
Key words: Meshfree Method, FPM, Fluid Structure Interaction, Sheet of Paper, Dynamical Coupling
(16 pages, 2006)

89. R. Ciegis , O. Iliev, V. Starikovicius, K. Steiner
Numerical Algorithms for Solving Problems of Multiphase Flows in Porous Media
Keywords: nonlinear algorithms, finite-volume method, software tools, porous media, flows
(16 pages, 2006)

90. D. Niedziela, O. Iliev, A. Latz
On 3D Numerical Simulations of Viscoelastic Fluids
Keywords: non-Newtonian fluids, anisotropic viscosity, integral constitutive equation
(18 pages, 2006)

91. A. Winterfeld
Application of general semi-infinite Programming to Lapidary Cutting Problems
Keywords: large scale optimization, nonlinear programming, general semi-infinite optimization, design centering, clustering
(26 pages, 2006)

92. J. Orlik, A. Ostrovska
Space-Time Finite Element Approximation and Numerical Solution of Hereditary Linear Viscoelasticity Problems
Keywords: hereditary viscoelasticity; kern approximation by interpolation; space-time finite element approximation, stability and a priori estimate
(24 pages, 2006)

93. V. Rutka, A. Wiegmann, H. Andrä
EJIIM for Calculation of effective Elastic Moduli in 3D Linear Elasticity
Keywords: Elliptic PDE, linear elasticity, irregular domain, finite differences, fast solvers, effective elastic moduli
(24 pages, 2006)

94. A. Wiegmann, A. Zemitis
EJ-HEAT: A Fast Explicit Jump Harmonic Averaging Solver for the Effective Heat Conductivity of Composite Materials
Keywords: Stationary heat equation, effective thermal conductivity, explicit jump, discontinuous coefficients, virtual material design, microstructure simulation, EJ-HEAT
(21 pages, 2006)

95. A. Naumovich
On a finite volume discretization of the three-dimensional Biot poroelasticity system in multilayered domains
Keywords: Biot poroelasticity system, interface problems, finite volume discretization, finite difference method
(21 pages, 2006)

96. M. Krekel, J. Wenzel
A unified approach to Credit Default Swaption and Constant Maturity Credit Default Swap valuation
Keywords: LIBOR market model, credit risk, Credit Default Swaption, Constant Maturity Credit Default Swap-method
(43 pages, 2006)

97. A. Dreyer
Interval Methods for Analog Circiuts
Keywords: interval arithmetic, analog circuits, tolerance analysis, parametric linear systems, frequency response, symbolic analysis, CAD, computer algebra
(36 pages, 2006)

98. N. Weigel, S. Weihe, G. Bitsch, K. Dreßler
Usage of Simulation for Design and Optimization of Testing
Keywords: Vehicle test rigs, MBS, control, hydraulics, testing philosophy
(14 pages, 2006)

99. H. Lang, G. Bitsch, K. Dreßler, M. Speckert
Comparison of the solutions of the elastic and elastoplastic boundary value problems
Keywords: Elastic BVP, elastoplastic BVP, variational inequalities, rate-independency, hysteresis, linear kinematic hardening, stop- and play-operator
(21 pages, 2006)

100. M. Speckert, K. Dreßler, H. Mauch
MBS Simulation of a hexapod based suspension test rig
Keywords: Test rig, MBS simulation, suspension, hydraulics, controlling, design optimization
(12 pages, 2006)

101. S. Azizi Sultan, K.-H. Küfer
A dynamic algorithm for beam orientations in multicriteria IMRT planning
Keywords: radiotherapy planning, beam orientation optimization, dynamic approach, evolutionary algorithm, global optimization
(14 pages, 2006)

102. T. Götz, A. Klar, N. Marheineke, R. Wegener
A Stochastic Model for the Fiber Lay-down Process in the Nonwoven Production
Keywords: fiber dynamics, stochastic Hamiltonian system, stochastic averaging
(17 pages, 2006)

103. Ph. Süss, K.-H. Küfer
Balancing control and simplicity: a variable aggregation method in intensity modulated radiation therapy planning
Keywords: IMRT planning, variable aggregation, clustering methods
(22 pages, 2006)

104. A. Beaudry, G. Laporte, T. Melo, S. Nickel
Dynamic transportation of patients in hospitals
Keywords: in-house hospital transportation, dial-a-ride, dynamic mode, tabu search
(37 pages, 2006)

105. Th. Hanne
Applying multiobjective evolutionary algorithms in industrial projects
Keywords: multiobjective evolutionary algorithms, discrete optimization, continuous optimization, electronic circuit design, semi-infinite programming, scheduling
(18 pages, 2006)

106. J. Franke, S. Halim
Wild bootstrap tests for comparing signals and images
Keywords: wild bootstrap test, texture classification, textile quality control, defect detection, kernel estimate, nonparametric regression
(13 pages, 2007)

107. Z. Drezner, S. Nickel
Solving the ordered one-median problem in the plane
Keywords: planar location, global optimization, ordered median, big triangle small triangle method, bounds, numerical experiments
(21 pages, 2007)

108. Th. Götz, A. Klar, A. Unterreiter, R. Wegener
Numerical evidance for the non-existing of solutions of the equations desribing rotational fiber spinning
Keywords: rotational fiber spinning, viscous fibers, boundary value problem, existence of solutions
(11 pages, 2007)

109. Ph. Süss, K.-H. Küfer
Smooth intensity maps and the Bortfeld-Boyer sequencer
Keywords: probabilistic analysis, intensity modulated radiotherapy treatment (IMRT), IMRT plan application, step-and-shoot sequencing
(8 pages, 2007)

110. E. Ivanov, O. Gluchshenko, H. Andrä, A. Kudryavtsev
Parallel software tool for decomposing and meshing of 3d structures
Keywords: a-priori domain decomposition, unstructured grid, Delaunay mesh generation
(14 pages, 2007)

111. O. Iliev, R. Lazarov, J. Willems
Numerical study of two-grid preconditioners for 1d elliptic problems with highly oscillating discontinuous coefficients
Keywords: two-grid algorithm, oscillating coefficients, preconditioner
(20 pages, 2007)

112. L. Bonilla, T. Götz, A. Klar, N. Marheineke, R. Wegener
Hydrodynamic limit of the Fokker-Planck-equation describing fiber lay-down processes
Keywords: stochastic dierential equations, Fokker-Planck equation, asymptotic expansion, Ornstein-Uhlenbeck process
(17 pages, 2007)

113. S. Rief
Modeling and simulation of the pressing section of a paper machine
Keywords: paper machine, computational fluid dynamics, porous media
(41 pages, 2007)

114. R. Ciegis, O. Iliev, Z. Lakdawala
On parallel numerical algorithms for simulating industrial filtration problems
Keywords: Navier-Stokes-Brinkmann equations, finite volume discretization method, SIMPLE, parallel computing, data decomposition method
(24 pages, 2007)

115. N. Marheineke, R. Wegener
Dynamics of curved viscous fibers with surface tension
Keywords: Slender body theory, curved viscous bers with surface tension, free boundary value problem
(25 pages, 2007)

116. S. Feth, J. Franke, M. Speckert
Resampling-Methoden zur mse-Korrektur und Anwendungen in der Betriebsfestigkeit
Keywords: Weibull, Bootstrap, Maximum-Likelihood, Betriebsfestigkeit
(16 pages, 2007)

117. H. Knaf
Kernel Fisher discriminant functions – a concise and rigorous introduction
Keywords: wild bootstrap test, texture classification, textile quality control, defect detection, kernel estimate, nonparametric regression
(30 pages, 2007)

118. O. Iliev, I. Rybak
On numerical upscaling for flows in heterogeneous porous media
Keywords: numerical upscaling, heterogeneous porous media, single phase flow, Darcy's law, multiscale problem, effective permeability, multipoint flux approximation, anisotropy
(17 pages, 2007)

119. O. Iliev, I. Rybak
On approximation property of multipoint flux approximation method
Keywords: Multipoint flux approximation, finite volume method, elliptic equation, discontinuous tensor coefficients, anisotropy
(15 pages, 2007)

120. O. Iliev, I. Rybak, J. Willems
On upscaling heat conductivity for a class of industrial problems
Keywords: Multiscale problems, effective heat conductivity, numerical upscaling, domain decomposition
(21 pages, 2007)

Status quo: November 2007

121. R. Ewing, O. Iliev, R. Lazarov, I. Rybak
On two-level preconditioners for flow in porous media
Keywords: Multiscale problem, Darcy's law, single phase flow, anisotropic heterogeneous porous media, numerical upscaling, multigrid, domain decomposition, efficient preconditioner
(18 pages, 2007)

122. M. Brickenstein, A. Dreyer
POLYBORI: A Gröbner basis framework for Boolean polynomials
Keywords: Gröbner basis, formal verification, Boolean polynomials, algebraic cryptoanalysis, satisfiability
(23 pages, 2007)

123. O. Wirjadi
Survey of 3d image segmentation methods
Keywords: image processing, 3d, image segmentation, binarization
(20 pages, 2007)

124. S. Zeytun, A. Gupta
A Comparative Study of the Vasicek and the CIR Model of the Short Rate
Keywords: interest rates, Vasicek model, CIR-model, calibration, parameter estimation
(17 pages, 2007)

125. G. Hanselmann, A. Sarishvili
Heterogeneous redundancy in software quality prediction using a hybrid Bayesian approach
Keywords: reliability prediction, fault prediction, non-homogeneous poisson process, Bayesian model averaging
(17 pages, 2007)

126. V. Maag, M. Berger, A. Winterfeld, K.-H. Küfer
A novel non-linear approach to minimal area rectangular packing
Keywords: rectangular packing, non-overlapping constraints, non-linear optimization, regularization, relaxation
(18 pages, 2007)

127. M. Monz, K.-H. Küfer, T. Bortfeld, C. Thieke
Pareto navigation – systematic multi-criteria-based IMRT treatment plan determination
Keywords: convex, interactive multi-objective optimization, intensity modulated radiotherapy planning
(15 pages, 2007)

128. M. Krause, A. Scherrer
On the role of modeling parameters in IMRT plan optimization
Keywords: intensity-modulated radiotherapy (IMRT), inverse IMRT planning, convex optimization, sensitivity analysis, elasticity, modeling parameters, equivalent uniform dose (EUD)
(18 pages, 2007)

129. A. Wiegmann
Computation of the permeability of porous materials from their microstructure by FFF-Stokes
Keywords: permeability, numerical homogenization, fast Stokes solver
(24 pages, 2007)

130. T. Melo, S. Nickel, F. Saldanha da Gama
Facility Location and Supply Chain Management – A comprehensive review
Keywords: facility location, supply chain management, network design
(54 pages, 2007)