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Invited Review

Facility location and supply chain management – A review

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ABSTRACT

Facility location decisions play a critical role in the strategic design of supply chain networks. In this paper, a literature review of facility location models in the context of supply chain management is given. 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 presented. Finally, a list of issues requiring further research are highlighted.

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. [29] and references therein). The American Mathematical Society (AMS) even created specific 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. [114] 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. [18]). As a consequence, facility location models have been gradually proposed within the supply chain context (including reverse logistics), thus opening an extremely interesting and fruitful application domain. There are naturally several questions which immediately arise during such a development, namely: (i) What properties does a facility location model have to fulfill to be acceptable within the supply chain context? (ii) Are there existing facility location models which already fit into the supply chain context? (iii) 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 [35], 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. [29,90]). Moreover, distances, times or costs between customers and facilities are measured by a given metric (see [96]). Possible questions to be answered are: (i) Which facilities should be used (opened)? (ii) 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 [58] and ReVelle et al. [97].

SCM is the process of planning, implementing and controlling the operations of the supply chain in an efficient way. 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 [114] and the Council of Supply Chain Management Professionals [21]). Part of the planning processes in SCM aims at finding the best possible supply chain configuration. In addition to the generic facility location setup, also other areas such as procurement, production, inventory, distribution, and routing have to be considered (see [20]). Historically, researchers have focused relatively early on the design of distribution systems (see [58] and references therein) but without considering the supply chain as a whole.

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Since it is not possible to survey all the literature associated both with facility location and SCM, we will concentrate our review on articles published in the last decade 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 distract us from the typical SCM perspective. With this scope in mind, we identified approximately 120 articles that were published in the last decade, including a few papers that will appear in 2008. Further screening yielded 98 articles from 19 journals that address relevant aspects to our analysis. Of these, 56 were published in 2004 or later, 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 44 articles were identified). Other journals such as *Computers & Operations Research* (18 papers), *Interfaces* (six papers), *Transportation Research* (seven papers), and *Omega* and *International Journal of Production Economics* (each with six articles) have significantly contributed to this emerging research field.

The remainder of the paper is organized as follows: Section 2 focuses on the relation between facility location and SCM. Section 3 is devoted to reviewing facility location papers in strategic SCM. Optimization methods for solving facility location problems in a supply chain context are reviewed in Section 4 as well as practical applications of location models in SCM. The paper ends with some conclusions and possible directions for future research.

2. Facility location and SCM

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. [24,29,96]). 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 [88] and ReVelle et al. [97]. 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 [119]). 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.

Multi-period location problems have been proposed to approach situations in which parameters change over time in a predictable way (see [80] for a comprehensive list of references). 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.

Another important extension regards the inclusion of stochastic components in facility location models (see the recent survey by Snyder [115]). 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 [93] 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 practical location problems regards the existence of different types of facilities, each one of which playing a specific role (e.g., production, 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. Many papers can be found in the literature addressing this topic (see the recent survey by Sahin and Süral [100]). 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 [100] as well as Fig. 1).

Another aspect driven by real-life applications, and that has raised much attention, regards the necessity to cope with multi-commodity problems (see [58] and references therein).

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 such as 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 SCM, three planning levels are usually distinguished depending on the time horizon: strategic, tactical and operational (see [9,131]). Simchi-Levi et al. [114] state that "the strategic level deals

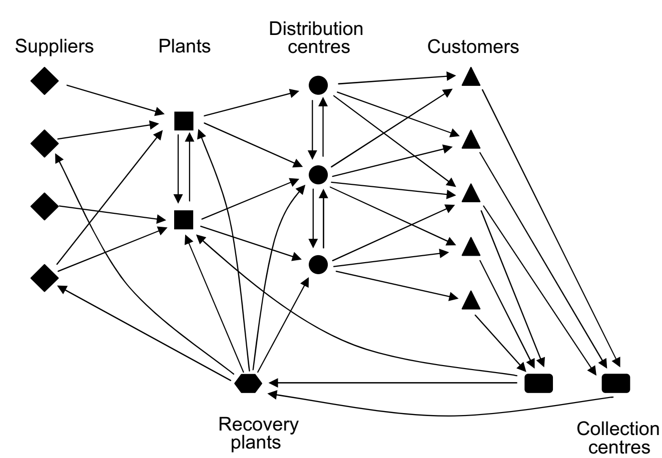

Fig. 1. A generic supply chain network.

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 (see also [40,103,106]). In general, a network design project starts with the identification of potentially interesting sites for new facilities and 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.

The terms *network design* and *supply chain network design* (SCND) are sometimes employed as synonyms of strategic supply chain planning (see [3,18,75,113]). 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. Accordingly, sophisticated facility location models may be necessary to determine the best supply chain configuration.

In the last 10 years, growing attention has also been given to reverse logistics, which refers to activities dedicated to the collection and/or recovery of product returns within SCM (see [26,31,62]). The early articles by Barros et al. [8], Fleischmann et al. [39] and Jayaraman et al. [52] encouraged much of the subsequent research in this recent field. Three aspects can be mentioned to justify reverse activities (see [120,135]): economic aspects (the possibility of recapturing value of used products), government directives (e.g., the European Union WEEE Directive [36]) and consumer pressure (e.g., return of defective products). Reverse logistics activities are often supported by specific facilities. These can be of two different main types: collection centres (i.e., facilities where customers hand in used products) and recovery/remanufacturing facilities (i.e., facilities where returned products are refurbished/remanufactured). 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).

Fig. 1 depicts a generic supply chain network that includes both forward and reverse activities. In addition to different types of facilities, the possible flow of material is shown in the figure. In contrast to classical location problems, flows between facilities of the same layer are prevalent in many supply chains. These flows are usually necessary for material balancing or inventory consolidation.

From the above 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 (see, e.g. [122]). However, this approach may 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 [32,41]).

Finally, the interested reader is referred to some important reviews where facility location issues in the context of SCND are discussed: Bhatnagar and Sohal [10] (on the impact of location factors, uncertainty and manufacturing practices in supply chain competitiveness), Daskin et al. [23], Min and Zhou [83], and Owen and Daskin [93].

In the next section we list several important issues that enable a facility location model to become compatible with SCND requirements, and survey the existing literature with respect to these features.

3. Strategic supply chain planning

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.

3.1. Network structure and basic 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. [28,44,133,136]).

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 [80] 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 2, 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.

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)

			Single-period		Multi-period	
			Deterministic	Stochastic	Deterministic	Stochastic
Single layer	Single location layer	Single commodity	[6,7,22,72,79,109,118,123,126,134,138]	[17,42,67,69,108,110,117]	[12,13,27,76,84]	
		Multiple commodities	[16,61,74,82,129]		[38,47,127]	
2 Layers	Single location layer	Single commodity	[2,15,30,33,34,37,57,77,78,98,104,111,135]	[25,48,65,86,87,112,128]		[1]
		Multiple commodities	[11,52,56,132,137]		[14]	
	2 Location layers	Single commodity	[44,53,63,64,70,73,85]			
		Multiple commodities	[5,50,51,55,60,95,121]	[43]	[45,46,120,133]	
⩾3 Layers	Single location layer	Single commodity	[92]			
		Multiple commodities	[28]			
	2 Location layers	Single commodity	[3,8,71,125]			
		Multiple commodities	[49,66]	[68,99]	[59]	
	⩾ 3 Location layers	Single commodity			[4,124]	
		Multiple commodities	[20,94,101,136,139]	[102,103]	[80]	

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 be drawn from Table 1 refers to the large number of deterministic models when compared with stochastic ones (approximately 80% against 20%). As pointed out by Sabri and Beamon [99], 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. Different sources of uncertainty can be found in the literature presented in Table 1, namely customer demands, exchange rates, travel times, amount of returns in reverse logistics, supply lead times, transportation costs, and holding costs.

In their review of hierarchical location models, Sahin and Süral [100] claim that facility location problems have been mostly studied for single-level systems. Regarding this aspect, some conclusions can also be drawn from Table 1. Almost 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 deliveries). These aspects were considered in [4,8,14,15,20,34,37,44,63,80,124,133]. Another important characteristic of many supply chain networks regards intra-layer flows. Aghezzaf [1], Carlsson and Rönnqvist [15], Cordeau et al. [20], Melo et al. [80], Troncoso and Garrido [124], Vila et al. [133], and Wouda et al. [137] introduced explicitly this feature into their models. One characteristic that has also had significant coverage in the literature refers to multiple commodities. Around 41% of the papers presented in Table 1 include this aspect.

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. This is the case of a p-median type of constraint [56,57,63,121,134], and a lower and/or an upper limit to the number of facilities to open/close [3,45,46,50–53,84,85,94,137].

3.2. 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. Table 2 classifies the literature according to some typical supply chain decisions namely, capacity, inventory, procurement, production, routing, and the choice of transportation modes.

It should be noted that 37 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.

In their recent survey dedicated to capacity expansion, Julka et al. [54] discuss multi-factor capacity expansion models for manufacturing plants. The possibility of expanding capacity is considered by Aghezzaf [1], Fleischmann et al. [38], Hugo and Pistikopoulos [47], Ko and Evans [59], Schultmann et al. [104], Srivastava [120], and Troncoso and Garrido [124]. With the exception of Schultmann et al. [104], these articles combine capacity expansion with multi-period location decisions. Some authors confine capacity decisions to one specific layer. This is the case of van Ommeren et al. [128], where capacity is to be decided only for the upper layer facilities, and of Aghezzaf [1] where capacity expansion is allowed in the upper layer facilities. In contrast, Lowe et al. [69] model the capacity reduction case. The simultaneous consideration of capacity expansion and reduction is studied by Levén and Segerstedt [64], Melachrinoudis and Min [76], Melo et al. [80], and Vila et al. [133]. Melachrinoudis et al. [78] 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 [80,127,128,133].

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 [28], Karabakal et al. [55], Mazzola and Neebe [74], Ulstein et al. [127], and Verter and Dasci [129]. Vila et al. [133] consider the choice of the facilities' layout as a decision to be made.

As emphasized by Shu et al. [112] and Daskin et al. [25], 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

Table 2
Supply chain decisions in addition to the typical location–allocation decisions

Article	Capacity	Inventory	Procurement	Production	Routing	Transportation modes
Aghezzaf [1]	✓	✓				
Aksen and Altinkemer [2]					✓	
Ambrosino and Scutellà [4]		✓			✓	
Amiri [5]	✓					
Avittathur et al. [6]		✓				
Barahona and Jensen [7]		✓				
Carlsson and Rönnqvist [15]						✓
Chakravarty [16]				✓		
Chan et al. [17]					✓	
Cordeau et al. [20]			✓	✓		✓
Daskin et al. [25]		✓				
Dogan and Goetschalckx [28]		✓		✓		
Erlebacher and Meller [33]		✓				
Eskigun et al. [34]						✓
Fleischmann et al. [38]	✓			✓		
Guillén et al. [43]	✓	✓		✓		
Hinojosa et al. [46]		✓	✓			
Hugo and Pistikopoulos [47]	✓			✓		
Hwang [48]					✓	
Jang et al. [49]		✓	✓	✓		
Jayaraman and Pirkul [50]				✓		
Jayaraman et al. [52]		✓		✓		
Ko and Evans [59]	✓					
Kouvelis and Rosenblatt [60]				✓		
Levén and Segerstedt [64]	✓	✓				
Lieckens and Vandaele [65]	✓	✓				
Lin et al. [66]		✓				
Lowe et al. [69]	✓			✓		
Ma and Davidrajuh [71]		✓			✓	
Melachrinoudis and Min [76]	✓					
Melachrinoudis and Min [77]				✓		
Melachrinoudis et al. [78]	✓			✓		
Melo et al. [80]	✓	✓	✓	✓		
Min and Melachrinoudis [82]		✓				
Min et al. [84]		✓				
Miranda and Garrido [86,87]		✓				
Nozick and Turnquist [92]		✓				
Pirkul and Jayaraman [95]				✓		
Romeijn et al. [98]		✓				
Sabri and Beamon [99]				✓		
Schultmann et al. [104]	✓					
Shen and Qi [108]		✓				
Shen [109]		✓				
Shen et al. [110]		✓				
Shu et al. [112]		✓				
Snyder et al. [117]		✓				
Sourirajan et al. [118]		✓				
Srivastava [120]	✓					
Syam [121]		✓				
Teo and Shu [123]		✓	✓			
Tuzun and Burke [126]					✓	
Ulstein et al. [127]	✓					
van Ommeren et al. [128]	✓	✓				
Verter and Dasci [129]				✓		
Vila et al. [133]	✓	✓		✓		
Wang et al. [135]		✓				
Wilhelm et al. [136]		✓	✓	✓		✓
Wouda et al. [137]				✓		
Wu et al. [138]					✓	
Yan et al. [139]			✓	✓		

inventory planning, this type of decision is mostly focused on exactly one layer, namely the one referring to stocking points. Nevertheless, a few models have been proposed in which inventory decisions are included in several layers [49,80,121,128,133]. However, full coordination of replenishment activities in different layers, which is a relevant aspect in SCM, has only been attempted by Romeijn et al. [98] and Teo and Shu [123].

In Table 2 only four papers feature the choice of transportation modes as a decision to be made. These articles can be divided into those that allow several transportation modes to be chosen for the same link/arc in the network [20,136] and those that only allow one transportation mode in each link (the remaining references). 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 (see, e.g. [15]).

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 only exception being the article by Ma and Davidrajuh [71]). Due to the multi-layer structure of a supply chain network, some articles study the routing problem associated with more than one layer [4,48]. The surveyed literature can also be divided into those papers that assume a homogeneous vehicle fleet [2,71] and those that consider vehicles of different types/capacities [4,17,48,126,138]. Another important aspect regards the possibility of having a customer serviced by more than one vehicle [2,17]. Finally, apart from the paper by Ma and Davidrajuh [71], 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 [20,49,136,139]] and those that consider procurement of finished products from an outside supplier [46,80,123].

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.

3.3. Reverse logistics

The literature dedicated to reverse logistics 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*.

The integration of reverse and forward networks leads to more complex SCND problems. For instance, the number of facility layers is increased by the layers associated with recovery facilities as shown in Fig. 1. Table 3 summarizes the surveyed literature 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.

Lu and Bostel [70] consider a layer of disposal facilities that receive returned products which cannot be recovered. In [72], the reverse flows are moved directly to plants for re-use in production. Similarly, in the model studied by Lee and Dong [63] return products are treated in the same facilities that support direct activities. In [52], location decisions are made only for facilities supporting "forward" activities. In [135], 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. The reverse flows in the context of the growing importance of post-sale services are given particular emphasis by Du and Evans [30] and Wang et al. [135].

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 classical forward networks.

3.4. 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. An early literature review on analytical models relevant to facility location decisions for a global company is by Verter and Dincer [130]. Cohen and Mallik [19] 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 [75] 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. The second category comprises financing and taxation incentives offered by governments to attract facility investments in certain countries or regions. The last category refers to investment expenditures which are usually limited by the total available budget. This aspect is

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

Article	Network structure	Specific facilities supporting reverse activities	
		Layers	Location decisions
Barros et al. [8]	Recovery	Collection, rework	Collection, rework
Du and Evans [30]	Recovery	Collection, rework	Rework
Jayaraman et al. [52]	Closed-loop	Collection	–
Jayaraman et al. [53]	Recovery	Collection, rework	Collection, rework
Ko and Evans [59]	Closed-loop	Collection	Collection
Lee and Dong [63]	Closed-loop	–	–
Lieckens and Vandaele [65]	Recovery	Rework	Rework
Listeş [67]	Closed-loop	Rework	Rework
Listeş and Dekker [68]	Recovery	Collection, rework	Collection, rework
Lu and Bostel [70]	Closed-loop	Collection, rework, disposal	Collection, rework
Marín and Pelegrin [72]	Closed-loop	–	–
Min et al. [84]	Recovery	Collection, rework	Collection
Min et al. [85]	Recovery	Collection, rework	Collection, rework
Pati et al. [94]	Recovery	Collection, rework	Collection, rework
Salema et al. [101]	Closed-loop	Rework	Rework
Salema et al. [102]	Closed-loop	Rework	Rework
Schultmann et al. [104]	Recovery	Collection, rework	Collection
Wang et al. [135]	Closed-loop	Collection	Collection

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

Article	Financial aspects			Risk management			Other aspects		
	Int. factors	Incentives	Budget const.	Robustness	Reliability	Risk pooling	Relocation	BOM	Multi-period factors
Aghezzaf [1]				✓					
Avittathur et al. [6]	✓								
Canel and Khumawala [12,13]	✓	✓							
Carlsson and Rönnqvist [15]							✓		
Chakravarty [16]	✓		✓						
Cordeau et al. [20]								✓	
Daskin et al. [25]						✓			
Dogan and Goetschalckx [28]									✓
Erlebacher and Meller [33]						✓			
Fleischmann et al. [38]			✓					✓	
Goetschalckx et al. [41]	✓							✓	
Goh et al. [42]	✓				✓				✓
Gunnarsson et al. [44]									✓
Jang et al. [49]								✓	
Kouvelis and Rosenblatt [60]	✓	✓	✓					✓	✓
Lowe et al. [69]	✓						✓		
Melachrinoudis and Min [76]		✓	✓				✓		
Melachrinoudis and Min [77]							✓		
Melachrinoudis et al. [78]		✓					✓		
Melo et al. [80]			✓				✓		
Min and Melachrinoudis [82]		✓					✓		
Miranda and Garrido [86]						✓			
Pati et al. [94]			✓						
Shen et al. [110]						✓			
Shu et al. [112]						✓			
Snyder et al. [117]						✓			
Teo and Shu [123]									✓
Vidal and Goetschalckx [132]	✓							✓	
Vila et al. [133]	✓							✓	✓
Wang et al. [134]			✓						
Wilhelm et al. [136]	✓							✓	✓
Wouda et al. [137]								✓	
Yan et al. [139]								✓	

modelled by budget constraints for opening and closing facilities. When the planning horizon includes multiple periods, 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 several facility location models have been developed taking stochastic parameters into account (recall the discussion in Section 3.1), the issue of robustness in SCND has not received much attention as shown in Table 4. Snyder [115] discusses the meaning of the term *robustness*, describes various robustness measures in a pure facility location context, and reviews the existing literature.

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 [116] 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 [116] 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 [25,33,86,112]).

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 first articles on multi-period location problems were published, did new models appear to handle this situation. They consider gradual capacity transfers from existing locations to new sites during a multi-period horizon and under variable capacity moving costs (see [76,80]). In particular, Melo et al. [80] 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. The explicit integration of bills of materials 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 3.1 that although this approach may yield a sub-optimal network configuration, it has been adopted 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.

4. Supply chain optimization and applications

We complete our review of the literature on facility location models in an SCM environment by presenting additional information regarding the papers listed in Table 1. We analyze the type of supply chain performance measures used, the methodology followed to solve the problems, and applications of facility location models to strategic supply chain planning.

Fig. 2 depicts the type of objective function that measures supply chain performance. The majority of the papers feature a cost minimization objective. Moreover, this objective 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 as shown in Fig. 2. This is rather surprising since most business activities are profit-oriented. Two different categories of profit maximization can be found in the literature: (i) maximization of revenues minus costs, and (ii) after-tax profit maximization. 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.

The last and smallest group of articles in Fig. 2 refers to models with multiple and conflicting objectives. 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 can be defined such as the cycle time, which is the time required to transport returned products from collection centres to repair facilities and the time necessary to repair the faulty products. Environmental measures have also been considered.

Fig. 3 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. [20] 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 has been identified. In this way, large computation times can be avoided. 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*.

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 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 [88]) due to the presence of two

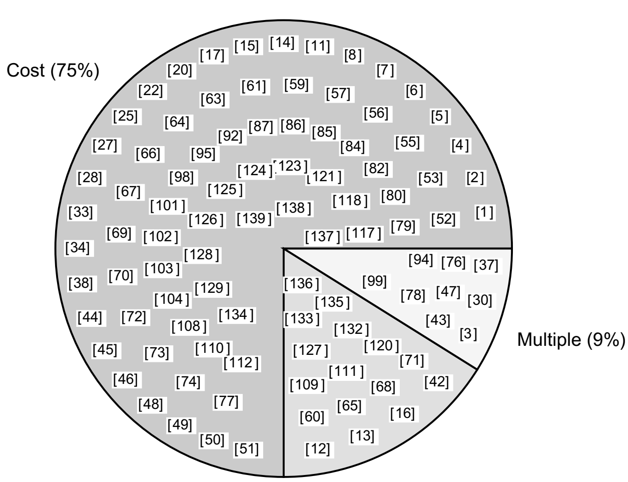

Fig. 2. Supply chain performance measures.

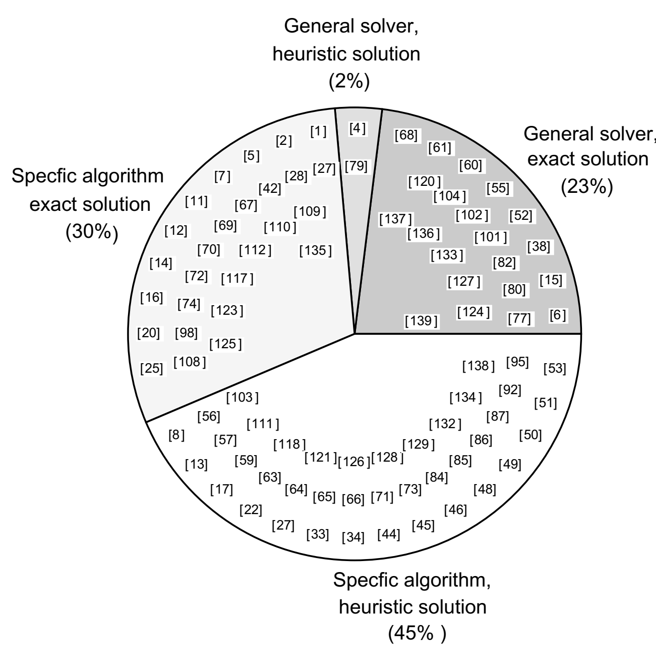

Fig. 3. Solution approaches for single-objective problems.

types of inherently different decisions: 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. Decomposition techniques were used by Cordeau et al. [20], Dogan and Goetschalckx [28] and Santoso et al. [103]. 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.

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 Fig. 3 in *Specific algorithm, heuristic solution*. Lagrangian relaxation, linear programming based heuristics and metaheuristics are among the most popular techniques.

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 or when goal programming is used. The ϵ-constraint method, which also combines the different objectives into a single one, has also been attempted.

Finally, we present some papers which explicitly address the application of facility location models to strategic supply chain planning. The articles listed in Table 5 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 a study using 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, 68% of the articles report on case studies, while the remaining 32% 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 addition to the articles listed in Table 5, we also refer to Bender et al. [9] and Melo et al. [81]. In the former work, the link between location planning and Geographic Information Systems is described. 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 [81], an application-oriented modelling framework is presented for strategic planning in SCM and a heuristic procedure is proposed for tackling a comprehensive model.

In spite of the papers presented in Table 5, there are still many potential areas for facility location models within the SCM context that have not been addressed so far. Shah [105], 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 (i) the disclosure of company data is not allowed; (ii) 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; (iii) difficulty of managers in using quantitative models for strategic decision support (see [107]). In fact, there is no tradition in developing and applying quantitative methods for strategic planning yet; (iv) difficulty in collecting data or even no data is available; (v) when data is available, preparation and aggregation tasks are rather time-consuming.

Table 5
Applications of facility location in a supply chain context

Industry	Context	Article
Automotive	Case study	Fleischmann et al. [38]
		Karabakal et al. [55]
	Industrial context	Nozick and Turnquist [92]
Chemicals	Case study	Canel and Khumawala [12,13]
		Jayaraman and Ross [51]
	Industrial context	Lowe et al. [69]
Food	Case study	Levén and Segerstedt [64]
		Tüshaus and Wittmann [125]
		Wouda et al. [137]
	Industrial context	Avittathur et al. [6]
Forestry	Case study	Carlsson and Rönnqvist [15]
		Gunnarsson et al. [44]
		Troncoso and Garrido [124]
	Industrial context	Vila et al. [133]
Hardware	Case study	Laval et al. [61]
	Industrial context	Sheu [111]
		Wilhelm et al. [136]
		Yan et al. [139]
Military	Case study	Chan et al. [17]
		Farahani and Asgari [37]
Sand	Case study	Barros et al. [8]
		Listeş and Dekker [68]
Other	Case study	Altiparmak et al. [3]
		Camm et al. [11]
		Dogan and Goetschalckx [28]
		Farahani and Asgari [37]
		Melachrinoudis and Min [76,77]
		Melachrinoudis et al. [78]
		Nickel et al. [91]
		Ulstein et al. [127]
	Industrial context	Pati et al. [94]
		Salema et al. [101,102]
		Schultmann et al. [104]
		Wang et al. [135]

5. Conclusions and directions for further research

In this paper we reviewed the most recent 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 dedicated separate sections to the relation between facility location and SCM, facility location models within SCM, and 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 3.2). 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 a few papers attempt 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. [136]. Clearly, more research is needed on this aspect, whose relevance 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 [111] who focused on maximizing the potential return on facility investment. Moreover, substantial investments lead to a period of time without profit. Companies may wish 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 [107]). 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 [89] 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, a rich and varied group of available solution techniques can be observed. This aspect along 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 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.

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