An integrated model for designing and optimising an international logistics network

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Abstract

Supply-chain configuration has recently gained increasing attention both from the practitioner's perspective and as a research area. This paper proposes an integrated model for designing and optimising international logistics networks. It consists of a mixed integer linear programming model and a data-mapping section (i.e. methodological guidelines for gathering and processing the data necessary to set up the model). It has been specifically developed for solving the configuration problem for supply chains characterised by a complexity level typical of real-life global logistics networks. Although this topic is well understood and well elaborated at a technical level in the extant literature, it still presents obstacles in practice especially in terms of dealing with real-life complexity, service-level constraints and data mapping. Thus, we developed our integrated approach with the aim to fill these gaps. We designed our model for dealing with multiple-layer, single location-layer, multiple-commodity and time-constrained logistics networks, to be implemented in a single period time horizon and in a deterministic environment. The proposed approach represents an innovative contribution to the existing body of scientific knowledge and facilitates the data gathering and processing activities, which are largely recognised as complex and time-consuming processes for the management of logistics activities.

1. Introduction

The recent evolutions of the world economy and of the competitive environment, such as the rise of global sourcing and the recent turmoil of the economic climate, compel companies to confront a series of challenges (Christopher 2007 Christopher, M., 2007. New directions in logistics. *In*: Waters, D., eds. *Global logistics: new directions in supply chain management*, Kogan Page). Among these, one of the most relevant is represented by an ever-growing pressure on service level along with a reduction in the price of goods and services (Cheong *et al*. 2007 Cheong, M, Bhatnagar, R and Graves, S. 2007. Logistics network design with supplier consolidation hubs and multiple shipment options. *Journal of Industrial and Management Optimization*, 3(1): 51–69. , , Jammernegg and Reiner 2007 Jammernegg, W and Reiner, G. 2007. Performance improvement of supply chain processes by coordinated inventory and capacity management. *International Journal of Production Economics*, 108(1/2): 183–190. ,). In this context, supply-chain configuration and coordination have become an important focus of competitive advantage for international companies. As defined by Porter (1986 Porter, ME. 1986. Changing patterns of international competition. *California Management Review*, 28(2): 9–40. , , [CSA]), configuration is the choice about the location and scale of some activities such as logistics (i.e. where in the world each activity included in the value chain is performed and in how many places), while coordination refers to 'how like activities performed in different countries are coordinated with each other'. Indeed, the configuration of the supply chain (i.e. the definition of its topological features such as the numbers of layers in the chain, the number of nodes in each layer, the distance between the nodes, the sourcing policies: Simchi-Levi *et al*. 2001 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2001. *Designing and managing the supply chain*, New York: McGraw-Hill.) has great importance for international competing companies (Ballou 2005 Ballou, RH. 2005. *Business logistics management*, Upper Saddle River, NJ: Prentice-Hall.). 'A company may be able to save millions of dollars in logistics costs and simultaneously improve service levels by redesigning its distribution network' (Teo and Shu 2004 Teo, CP and Shu., J. 2004. Warehouse-retailer network design problem. *Operations Research*, 52(3): 396–408. ,). As a matter of fact, the topological features of the supply chain have a considerable impact on supply-chain performance (Sezen 2008 Sezen, B. 2008. Relative effect of design, integration and information sharing on supply chain performance. *Supply Chain Management: an International Journal*, 13(3): 233–240. , , Pero *et al*. 2010 Pero, M. 2010. An exploratory study of the relation between supply chain topological features and supply chain performance. *International Journal of Production Economics*, 123(2): 266–278. ,). Beamon (1999 Beamon, BM. 1999. Measuring supply chain performances. *International Journal of Operations and Production Management*, 19(3): 275–292. ,) states that supply-chain performance mainly relates to costs and customer responsiveness. In particular, costs are connected to inventory and operating issues (manufacturing and distribution), while the latter is related to stock-out (or backlog) occurrence and probability of occurrence (e.g. lead time, stock-out probability and fill rate) (Beamon 1999 Beamon, BM. 1999. Measuring supply chain performances. *International Journal of Operations and Production Management*, 19(3): 275–292. , , Simchi-Levi *et al*. 2001 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2001. *Designing and managing the supply chain*, New York: McGraw-Hill. , Vachon and Klassen 2008 Vachon, S and Klassen, RD. 2008. Environmental management and manufacturing performance: the role of collaboration in the supply chain. *International Journal of Production Economics*, 111(2): 299–315. ,). However, maximising supply-chain performance entails the solution of a series of trade-offs (Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.). For instance, by reducing the number of nodes in the supply chain, it is possible to reduce inventory costs, owing to the decrease in safety stock according to the ‘square root law of inventory’. On the other hand, if we consider an increase in the number of nodes at the retailer stage, it is possible to offer better customer responsiveness. The nodes of the distribution network will be located closer to the end markets, and in this way the delivery time required by customers will be matched with the actual company delivery lead time.

In the last few years, many companies started to reconfigure their supply-chain networks from time to time to retain their competitive edge (Goetschalckx and Fleischmann 2005 Goetschalckx, M and Fleischmann, B. 2005. *Strategic network planning and advanced planning*, New York: Springer.). Pirelli Tyre, a multinational automotive tyre manufacturer, in 2009 was challenged to enhance the cost-efficiency of its supply chain, with the aim to gain competitive advantage in an industry characterised by a growing pressure on cost control and strict service-level requirements. By optimising its supply-chain configuration in terms of optimal location of its distribution centres, the company was able to minimise supply-chain costs while satisfying service-level requirements in different scenarios. Another example regards the car manufacturer BMW: in 2006, by exploiting the optimisation of its supply chain, it improved its long-term load planning for the production of cars, which is an essential phase in BMW's strategic-planning process (Fleischmann *et al*. 2006 Fleischmann, B, Ferber, S and Henrich, P. 2006. Strategic planning of BMW's global production network. *Interfaces*, 36(3): 194–208. ,). In the forestry industry, in 2005, Sodra Cell AB, a Swedish timber and pulp production company tackled the need for increasing its supply-chain performance by means of an optimisation regarding the existing production network and the activation of new distribution structures. Sodra Cell AB implemented an ongoing decision-support tool to decide terminal location and make distribution by vessels more integrated and efficient (Carlsson and Ronnqvist 2005 Carlsson, D and Ronnqvist, M. 2005. Supply chain management in forestry – case studies at Sodra cell AB. *European Journal of Operational Research*, 163(3): 589–616. ,). The real-life examples provided here confirm statements by Teo and Shu (2004 Teo, CP and Shu., J. 2004. Warehouse-retailer network design problem. *Operations Research*, 52(3): 396–408. ,), whereby multinationals are increasingly faced with strategic decisions regarding the configuration of their supply chain and logistics network (Chauhan *et al*. 2004 Chauhan, SS, Rakesh, N and Proth, JM. 2004. Strategic capacity planning in supply chain design for a new market opportunity. *International Journal of Production Research*, 42(11): 2197–2206. , , Meixell and Gargeya 2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550. , Chopra and Meindl 2007 Chopra, S and Meindl, P. 2007. *Supply chain management: Strategy, planning and operations*, Upper Saddle River: Prentice-Hall.).

Thus, companies have to confront great challenges in the decision-making process for configuring their supply chain. These are exacerbated if we consider that optimal decisions must be taken by solving constrained optimisation problems with strong inter-relationships between problem variables. In contexts where resources are tightly constrained, obtaining the optimal configuration is a noteworthy challenge.

Therefore, a need for effective decision-support tools has risen. These tools should make it possible to configure/re-configure logistics networks for maximising supply-chain performances easily, more accurately and more frequently and to solve the aforementioned trade-offs (Melachrinoudis and Min 2007 Melachrinoudis, E and Min, H. 2007. Redesigning a warehouse network. *European Journal of Operational Research*, 176(1): 210–229. , , Melo *et al*. 2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,). There exists a large body of literature on decision-support tools and optimisation models for supply-chain configuration. The problem has been addressed by a series of studies based on genetic/heuristic methods, simulation methods, and, as foremost approach, linear programming (Meixell and Gargeya 2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550. , Chopra and Meindl 2007 Chopra, S and Meindl, P. 2007. *Supply chain management: Strategy, planning and operations*, Upper Saddle River: Prentice-Hall.). The success of linear programming is due to the fact that, despite some well-known drawbacks, it allows solver tools to be easily developed, thus enabling realistic and precise solutions for the network configuration problems to be obtained, thanks also to widely available and reliable software packages (Schoen 2002 Schoen, F. 2002. "Two-phase methods for global optimization". In *Handbook of global optimization – Volume 2*, Edited by: Pardalos, P.M. and Romejin, H.E. 151–175. Dordrecht: Kluwer Academic Publishers. , Sharma 2006 Sharma, JK. 2006. *Linear programming: theory and applications*, New York: Macmillan.).

However, despite the large availability of scientific contributions focused on the addressed topic, the complexity of real-life supply-chain problems has not been considered in the extant literature. The objective of the current study is to propose a logistics network configuration model based on linear programming able to address and manage the complexity of a factual supply chain (i.e. characterised by a relevant number of nodes and by a series of constraints). Moreover, we aim to provide methodological guidelines for obtaining and processing the data and information necessary to set up the model, since data mapping and processing is considered a very relevant, difficult and time-consuming activity (Carlsson and Ronnqvist 2005 Carlsson, D and Ronnqvist, M. 2005. Supply chain management in forestry – case studies at Sodra cell AB. *European Journal of Operational Research*, 163(3): 589–616. ,).

The remainder of the paper is organised as follows: Section 2 is devoted to a review of the literature focusing on linear programming applications to supply-chain configuration. In Section 3, we describe our proposed logistics networks configuration model based on linear programming. Here, the corresponding data-mapping procedure is also presented. Finally, Section 4 recounts some concluding remarks and insights on potential future research on the topic.

2. Background of the study

This section presents a literature review on linear programming applied to the supply-chain configuration issue. Our analysis reviewed more than 170 papers, selected by means of the Systematic Literature Review approach by Tranfield *et al*. (2003 Tranfield, D, Denyer, D and Smart, P. 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, 14(3): 207–222. ,), which allows an evidenced-informed approach to identifying, selecting, and analysing secondary data. To conduct the search, a number of key words were identified in the areas of supply-chain management, supply-chain design, supply-chain configuration, logistics networks, optimisation models, and linear programming. They were further refined until the list of terms was deemed sufficient, also by integrating the Systematic Literature Review technique with the approach and the criteria developed by David and Han (2004 David, RJ and Han, S-K. 2004. A systematic assessment of the empirical support for transaction cost economics. *Strategic Management Journal*, 25(1): 39–58. ,) and subsequently exploited by Newbert (2007 Newbert, SL. 2007. Empirical research on the resource-based view of the firm: an assessment and suggestions for future research. *Strategic Management Journal*, 28(2): 121–146. ,). According to the adopted approaches, the literature search was performed on the most relevant online databases for the topic under study (ABI/Inform, Science Direct, EBSCO) looking for journal articles published in scholarly journals and for books and book chapters. We ensured that the contributions contained any of the pre-defined research terms. The results of the search were then further reviewed by reading the article title, the abstract, and, if necessary, the full paper. In this way, we managed to exclude a number of papers which were not sufficiently close to our research criteria.

The review of the literature was performed with the aim to understand the current state of the art concerning supply-chain configuration and to provide us with a guide for deciding which features should characterise our model. To do this, we organised the analysis according to the taxonomical approach proposed by Melo *et al*. (2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,). The authors classified the analysed papers according to the following dimensions: objective and decision variables of the optimisation models, number of considered supply-chain layers and stages, span of the time horizon, number of considered commodities, kind of considered data, and applications to real-life cases. Building upon this framework, we included two additional dimensions, i.e. modelling of the service-level constraint and presence of the data-mapping section, which were deemed particularly relevant for the supply-chain configuration issue, as highlighted by Cheong *et al*. (2007 Cheong, M, Bhatnagar, R and Graves, S. 2007. Logistics network design with supplier consolidation hubs and multiple shipment options. *Journal of Industrial and Management Optimization*, 3(1): 51–69. ,), Jammernegg and Reiner (2007 Jammernegg, W and Reiner, G. 2007. Performance improvement of supply chain processes by coordinated inventory and capacity management. *International Journal of Production Economics*, 108(1/2): 183–190. ,), and Carlsson and Ronnqvist (2005 Carlsson, D and Ronnqvist, M. 2005. Supply chain management in forestry – case studies at Sodra cell AB. *European Journal of Operational Research*, 163(3): 589–616. ,).

Matching the implications arising from each section of the analysis with our research objectives, we derived the specifications to be considered in developing the model.

In Figure 1, we include a summarising chart centred on the concepts of what has been modelled and how it was modelled so far in the state of the art. Then, for brevity, we report some highlights for the most relevant contributions only, analysed according to the above-mentioned dimensions. For each of the dimensions, we describe the implications of the literature analysis which led us to develop our optimisation model.

Figure 1. Summarising chart of what was modelled and how it was modelled (key features of the supply-chain design models).

2.1 Definition of the logistics network configuration problem

In a logistics network configuration problem, a series of strategic decisions (i.e. decisions involving major capital investments and with long-term effects) are generally considered. They are essentially represented by the definition of the optimal number, location and size of warehouses and/or plants, and the definition of the optimal sourcing strategy for each node and of the best distribution channels (Chopra 2003 Chopra, S. 2003. Designing the distribution network in a supply chain. *Transportation Research Part E: Logistics and Transportation Review*, 39(2): 123–140. , , [CSA], Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.).

In other words, the objective of the logistics network configuration problem is to find a minimal-cost configuration of the logistics network able to satisfy customers' orders. In order to reach this goal, a linear programming-based network configuration method should be composed of a mapping section, based on ready-to-implement data, and an optimisation model able to provide the optimal network configuration (Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.).

2.2 Objectives of the configuration models and decision variables

Coherently with the results obtained by Meixell and Gargeya (2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550.) and Melo *et al*. (2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,), we found that the main objective of the reviewed configuration models is total logistics cost minimisation (75.6%), with 17.2% of the contributions focused on maximising the company's profit and 7.2% of the reviewed articles characterised by a multi-objective function (i.e. multiple and conflicting objectives, which, in addition to economic factors, also consider measures based on resource utilisation and customer responsiveness; Melo *et al*. 2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,). As long as cost minimisation is regarded, the reviewed models consider transportation costs (97.1%), warehousing costs (67.1%), production costs (58.8%), sourcing costs (31.2%), inventory costs (29.4%), and international supply-chain costs such as currency exchange costs, duties, and taxation (17.1%).

In our study, we found that logistics network design problems have address decision variables such as the potential sites to be activated (97.6%). Of these papers, 84.9% consider warehouses or distribution centres as potential sites to be activated. Our analysis showed that the mere allocation of production and distribution has been considered in 78.2% of the papers. It is possible to find models (e.g. Sridharan 1995 Sridharan, R. 1995. The capacitated plant location problem. *European Journal of Operational Research*, 87(2): 203–213. , , Talluri and Baker 2002 Talluri, S and Baker, RC. 2002. A multi-phase mathematical programming approach for effective supply chain design. *European Journal of Operational Research*, 141(6): 544–558. , ReVelle and Eiselt 2005 Teo, CP and Shu., J. 2004. Warehouse-retailer network design problem. *Operations Research*, 52(3): 396–408. ,) proposing an iterative process where first the facility location problem is addressed, and second the transportation problem is addressed. Meixell and Gargeya (2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550.) affirm that contributions over time have been extending their focus from distribution to manufacturing: when the latter is considered, the decision variables are represented by the product mix to be allocated to plants (15.9% of contributions), and the models are based on analysis of the bill of materials, as shown by Paquet *et al*. (2008 Paquet, M, Martel, A and Montreuil, B. 2008. A manufacturing network design model based on processor and worker capabilities. *International Journal of Production Research*, 46(7): 2009–2030. ,), without selecting different production plant alternatives. In other cases (60.6% of the reviewed contributions) the allocation of sourcing flows from suppliers is considered. Moreover, 29.4% of the reviewed models include considerations on inventory costs and transportation time when global supply chains are optimised.

From this analysis, we learned that, coherently with the issues raised in the introduction and with our aims, it is possible to focus on minimising costs for optimising the logistics network relying on a strong literature support. As the objectives of the configuration models are regarded, the literature indicates that warehousing, transportation, and distribution represent the most investigated elements, while the choices regarding activation of production plants are only seldom considered, since they are generally connected to labour issues and to high required capital investments. This implies that, even if the allocation of production is still viable, plants are generally not modified in terms of location.

With respect to the objective of the optimisation model, we decided to focus on cost minimisation, while as regards the decision variables to include in our model, we decided to consider distribution allocation, by setting the quantities to be shipped from plants to customers through a network of selectable intermediate logistics nodes (i.e. distribution centres).

2.3 Considered layers and supply-chain stages

As far as the supply-chain layers are concerned, two different alternatives are available: single-layer and multiple-layer options. The two alternatives regard both the number of layers constituting the supply chain and the number of layers where the decision variables are included, named ‘location layers’. In their analysis, Melo *et al*. (2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,) affirm that when a single location layer is considered, the problem generally deals with the optimisation of secondary distribution.

Examining the different levels of hierarchical location, 91% of the reviewed articles focus on problems dealing with single location layers only. However, some relevant works extend this limitation: Fleischmann *et al*. (2006 Fleischmann, B, Ferber, S and Henrich, P. 2006. Strategic planning of BMW's global production network. *Interfaces*, 36(3): 194–208. ,) developed a model for the car manufacturer BMW to optimise both the production and distribution layers in a multi-stage supply chain. In the same industry, Karabakal *et al*. (2000 Karabakal, N, Gunal, A and Ritchie, W. 2000. Supply-chain analysis at Volkswagen of America. *Interfaces*, 30(1): 46–55.) optimised the American Volkswagen's distribution network through the location of new warehouses and plants. Gunnarsson *et al*. (2004 Gunnarsson, H, Ronnqvist, M and Lundgren, JT. 2004. Supply chain modelling of forest fuel. *European Journal of Operational Research*, 158(1): 103–123. ,) developed a two-location layer model to convert waste products from the forestry industry into bio-fuel, considering alternative sites for timber collection, for timber processing and heating terminals. In Meixell and Gargeya (2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550.) and Melo *et al*. (2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,), when international and global supply chains are considered, it is usual to find single decision layers in multi-layer supply chains. In fact, it is common practice that in those contexts, the optimisation regards the international logistics network, without considering the last mile local distribution, commonly delegated to a third-party provider on a local scale (Wood *et al*. 2002 Wood, DF. 2002. *International logistics*, Boston: AMACOM.). For these reasons, and given the growing importance of global logistics networks in supply-chain management research, we based our choice on multi-layer contexts with a single location layer.

2.4 Number of commodities involved in the optimisation problem

It is interesting to note that only 29.6% of the models included in the reviewed literature investigated a multiple-commodity context. This is probably due to the complexity of considering more than one single commodity in the optimisation problem at the same time. This complexity has been addressed in the literature by a series of simplifications and assumptions made to subdivide the overall optimisation problem into sub-problems. For example, Avittathur *et al*. (2005 Avittathur, B, Shah, J and Gupta, OK. 2005. Distribution centre location modelling for differential sales tax structure. *European Journal of Operational Research*, 162(3): 191–205.) integrated location and inventory decisions in a multi-commodity problem. Jayaraman and Ross (2003 Jayaraman, V and Ross., A. 2003. A simulated annealing methodology to distribution network design and management. *European Journal of Operational Research*, 144(5): 629–645.) developed a tool for supporting decisions regarding the location of new stores and the allocation of the required resources to respond to growing customer demand for multiple commodities. Arntzen *et al*. (1995 Arntzen, BC. 1995. Global supply chain management at Digital Equipment Corporation. *Interfaces*, 25(1): 69–93. ,) developed a multi-period, multi-commodity mixed integer linear programming (MILP) model to optimise the global supply chain of Digital Equipment Corporation. Similarly Manzini and Gebennini (2008 Manzini, R and Gebennini, E. 2008. Optimization models for the dynamic facility location and allocation problem. *International Journal of Production Research*, 46(8): 2061–2086. ,) introduced a model to design and manage multi-commodity location allocation problems. Camm *et al*. (1997 Camm, JD. 1997. Blending OR/MS, judgment, and GIS: Restructuring P&G's supply chain. *Interfaces*, 27(2): 128–142.) proposed a model for optimising Procter & Gamble's US production plant network, considering the presence of a number of different products, decomposing the overall supply-chain problem into sub-problems: a distribution-location problem and a product-sourcing problem (one for each product category). From our analysis, it transpired that the challenge the scientific community is currently confronting is to consider multi-commodity problems, since they enable the development of more realistic, although more complex, models. Thus, we decided to focus on multi-commodity problems.

2.5 Span of the time horizon

Another relevant characteristic to be considered is represented by the time horizon: the literature shows that 85.2% of the papers analysed are aimed at configuring a logistics network considering a single-period horizon (Melo *et al*. 2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,). A multi-period approach was presented by Ballou (2005 Ballou, RH. 2005. *Business logistics management*, Upper

Saddle River, NJ: Prentice-Hall.), who proposed a logistics network configuration model where the values of some topological variables change over time in a predictable way. Canel and Khumawala (2001 Canel, C and Khumawala, BM. 2001. International facilities location: A heuristic procedure for the dynamic uncapacitated problem. *International Journal of Production Research*, 39(30): 3975–4000. ,) focused on site location problems, placing special emphasis on the financial issues in a multi-period planning horizon, while Manzini and Gebennini (2008 Manzini, R and Gebennini, E. 2008. Optimization models for the dynamic facility location and allocation problem. *International Journal of Production Research*, 46(8): 2061–2086. ,) developed a model for managing a multi-period location-allocation problem, in a multi-stage and multi-commodity context. The literature provides other significant examples of models developed in various industries (e.g. plastics – Altiparmak *et al*. (2006 Altiparmak, F. 2006. A genetic algorithm approach for multiobjective optimization of supply chain networks. *Computers & Industrial Engineering*, 51(1): 197–216. ,); mining of silicon metals – Ulstein *et al*. (2006 Ulstein, NL. 2006. Elkem uses optimization in redesigning its supply chain. *Interfaces*, 36(3): 314–325.)), which include a multi-period approach to select the location of new sites, on the basis of specific investments and operating costs. A paper by Fleischmann *et al*. (2006 Fleischmann, B, Ferber, S and Henrich, P. 2006. Strategic planning of BMW's global production network. *Interfaces*, 36(3): 194–208. ,) represented another example of a multi-period approach: the proposed model is able to run a configuration problem with a planning horizon longer than one year and divided into monthly time buckets. Deepening the analysis of the reviewed contributions, we found that multi-period approaches are developed for operating contexts where the environmental and endogenous variables are very likely to change frequently over time (e.g. seasonal demand, variable production and warehousing capacity). Additionally, the reviewed literature shows that for commodities characterised by a low degree of seasonality and non-time-dependent production-distribution systems, a single-period approach can be an appropriate method for developing an optimisation model. With respect to the objectives of our research, since we do not intend to focus our analysis specifically on seasonal commodities or time-variable production-distribution systems, we decided to address a single-period model.

2.6 Kind of considered data

Literature shows that 92.2% of the reviewed papers have been focusing on deterministic models for configuring a logistics network. This is a reasonable approach when it is possible to assume that all of the data and future events regarding the problem are known with a sufficient degree of certainty. However, when unpredictable fluctuations of the values of some model variables have to be considered, an important extension is represented by the inclusion of stochastic components in the configuration model. Owen and Daskin (1998 Owen, SH and Daskin, MS. 1998. Strategic facility location: A review. *European Journal of Operational Research*, 111(4): 423–447.) state that often there is some uncertainty in determining the costs and future demand. In order to face environmental variance, procedures focused on stochastic programming have been drawn (Santoso 2002 Santoso, T., 2002. *A comprehensive model and efficient solution algorithm for the design of global supply chains under uncertainty*. Thesis (PhD). Georgia Institute of Technology , Alonso-Ayuso *et al*. 2003 Alonso-Ayuso, A. 2003. An approach for strategic supply chain planning under uncertainty based on stochastic 0–1 programming. *Journal of Global Optimization*, 26(1): 97–124. ,), or stochastic variables have been included in order to model uncertainty in the operation of a supply chain (Blackhurst *et al*. 2004 Blackhurst, J, Wu, T and O’Grady, P. 2004. Network-based approach to modelling uncertainty in a supply chain. *International Journal of Production Research*, 42(8): 1639–1658. ,). Nevertheless, it is important to underline that the reviewed literature suggests that for dealing with non-deterministic contexts, simulation tools can be considered more suitable for time-dependent contexts rather than MILP, since simulation is able to consider dynamic and stochastic issues but unable to provide optimised solutions (Law and Kelton 1997 Law, AM and Kelton, WD. 1997. *Simulation modeling and analysis*, New York: McGraw-Hill Higher Education. , Cigolini and Rossi 2006 Cigolini, R and Rossi, T. 2006. A note on supply risk and inventory outsourcing. *Production Planning and Control*, 17(4): 424–437. , , Chopra and Meindl 2007 Chopra, S and Meindl, P. 2007. *Supply chain management: Strategy, planning and operations*, Upper Saddle River: Prentice-Hall.). Thus, a simulation could be used to test the static outcomes of the MILP models derived from single-period approaches (e.g. 1 year) where the stochastic effect of variables can be compensated along time. Considering our aims, we decided to focus on models dealing with deterministic data: in this way, we better exploit MILP.

2.7 Modelling of the service-level constraint

Another important feature to be considered is how the service-level constraint is modelled. A model that is able to deal with real-life contexts should consider this issue in a realistic and comprehensive way. Almost all the reviewed contributions consider the service level as a constraint to fulfil customers' demand. This is evidently an essential constraint, but key factors such as the delivery lead time or the shipping frequency are neglected. Only three contributions add further elements to consider service level. Korpela and Lehmusvaara (1999 Korpela, J and Lehmusvaara, A. 1999. A customer oriented approach to warehouse network evaluation and design. *International Journal of Production Economics*, 59(2): 135–146.) propose a model based on the Analytical Hierarchy Process, which provides the inputs for selecting alternative service providers in the MILP logistics network design model, to ensure that the network achieves the requested performance (e.g. in terms of delivery lead time). Yan *et al*. (2003 Yan, H, Yu, Z and Cheng, TCE. 2003. A strategic model for supply chain design with logical constraints: formulation and solution. *Computers & Operations Research*, 30(14): 2135–2155. ,) model the service-level constraint as a percentage of the overall demand met, assuming a deterministic customer demand. Melachrinoudis and Min (2007 Melachrinoudis, E and Min, H. 2007. Redesigning a warehouse network. *European Journal of Operational Research*, 176(1): 210–229. ,) consider the negative influence of warehouse centralisation on lead times, as an equation of service level. This influence is considered with a constraint that forces each consolidated facility to meet customers' demand within 10 h of truck driving time. Even if the reviewed literature supports the relevance of the service-level constraint, only the cited contributions are able to consider the mentioned key factors, thus confirming the necessity to develop models able to include the service level as a key constraint. For this reason, we decided to propose an optimisation model able to fill this gap.

2.8 Applications to real-life cases and supply chains

Considering now the application of the described models to the deployment of network configuration problems, it is possible to cluster the revised scientific contributions according to two different groups (Melo *et al*. 2009 Melo, MT, Nickel, S and Saldanha-da-Gama, F. 2009. Facility location and supply chain management – A review. *European Journal of Operational Research*, 196(2): 401–412. ,):

- case studies, which refer to real-life applications, even if they might not have been practically implemented;

industrial contexts, which refer to virtual contexts for specific industries.

The number of revised papers presenting an application of the models they propose is fairly limited (28 papers out of 170, equal to approximately 16%). Twenty papers (70%) out of 28 found that applications can be included in the case study group, while the remainder were to be ascribed to the industrial context group. However, out of the 20 identified case studies, only eight are able to take into consideration the complexity of a real-life supply chain, since they are built on strong assumptions and simplifications.

2.9 Presence of the data-mapping section

The relevance of the data-mapping section has been acknowledged in the reviewed literature (Melachrinoudis and Min 2000 Melachrinoudis, E and Min, H. 2000. 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): 1–15. , , Carlsson and Ronnqvist 2005 Carlsson, D and Ronnqvist, M. 2005. Supply chain management in forestry – case studies at Sodra cell AB. *European Journal of Operational Research*, 163(3): 589–616. , , Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.). Our analysis showed that among the non-applied models, none of them are accompanied by a data-mapping section, and none of the industrial context papers propose a data-mapping section. Out of the case studies, we found only three examples of extensive data mapping. In particular, we found papers dealing with the selection of the most suitable configuration option among the feasible ones, taking into account a series of scenarios (Farahani and Asgari 2007 Farahani, RZ and Asgari, N. 2007. Combination of MCDM and covering techniques in a hierarchical model for facility location: A case study. *European Journal of Operational Research*, 176(3): 1839–1858. ,), or papers trying to reduce data complexity by means of data aggregation (Wouda *et al*. 2002 Wouda, FHE. 2002. An application of mixed-integer linear programming models on the redesign of the supply network of Nutricia Dairy & Drinks Group in Hungary. *OR Spectrum*, 24(4): 449–465. ,) or data clustering for products, customers, and delivery zones (Ulstein *et al*. 2006 Ulstein, NL. 2006. Elkem uses optimization in redesigning its supply chain. *Interfaces*, 36(3): 314–325.). The analysed literature strongly supports the necessity to rely on methodological guidelines for managing the considerable amount of data necessary to run optimisation models. However, we found that the literature is particularly wanting of examples of developed data-mapping sections for supporting the operationalisation of the supply chain and logistics network configuration models: thus, we raise the claim to fill this gap.

3. Proposed method

The logistics network configuration model we propose in this paper, built considering all the directions identified in the previous sections, is based on mixed integer linear programming (MILP) and is completed by a data-mapping section (Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.).

3.1 Logistics network configuration model

The typology of logistics network we are addressing comprises the following:

- a series of product-focused un-capacitated production plants (defined as P_p), which manufacture products characterised by some different features (e.g. technical specifications);
- a series of regional distribution warehouses (defined as RDW $_h$);
- a series of delivery points (such as wholesalers or outlets) which serve final customers.

The delivery points are characterised by demand features which are strictly related to the products manufactured by the different plants. Delivery points are served by RDW $_h$ according to a single sourcing policy. Considering that a real-life distribution system of a multinational company could have over 20,000 accounts, there is a need to perform an aggregation of the delivery points in macro-groups or clusters (Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.), defined in this work as Aggregated Delivery Points (ADP $_j$). Then, we assume that the shipments from P_p to RDW $_h$ are performed by means of full truck loads (FTL), while the secondary distribution from RDW $_h$ to ADP $_j$ is generally performed by means of less-than-truck-load services (LTL). Figure 2 depicts the typology of logistics network we address.

Figure 2. Description of the considered logistics network.

3.1.1 Input data

The developed model needs the following data as input variables:

- the set of P_p originating the logistics flows, with their geographical location (i.e. latitude and longitude), the manufactured type of product, the load capacity characterising a full truck load shipment originating from them, and the corresponding primary distribution costs for reaching the different RDW $_h$;
- the set of potential RDW $_h$, with their geographical location, maximum floor space size, inventory turnover ratio, secondary distribution costs for shipping one unit of product to the different ADP $_j$, unit housing cost, unit handling cost, and throughput capacity;
- the set of ADP $_j$ to be served, with their geographical location (for calculating the distance between each potential P_p and each ADP $_j$), their demand profile (in terms of amount of products annually required), and, finally, the required service level and product mix.

3.1.2 Decision variables

Given the above listed input data, the model is aimed at minimising the overall logistics and distribution costs (primary and secondary distribution costs and warehousing costs), fulfilling a required service level, by defining the values of two types of Boolean decision variables:

- the first allows for selecting which RDW $_h$ out of the set of potential location must be activated;
- the second allows for determining which RDW $_h$, if activated, must serve which ADP $_j$.

With reference to the logistics network nodes, only the activation of the RDW $_h$ is a decision variable of the model, since the sets of P_p and of ADP $_j$ are considered as given. As far as the linkages between the nodes of the network are considered, only those connecting RDW $_h$ and ADP $_j$ are considered decision variables, since the linkages between P_p and RDW $_h$ are determined by the product mix required by each ADP $_j$ (as a matter of fact, P_p denotes product-focused production plants). Finally, the quantity of products shipped from a RDW $_h$ to an ADP $_j$ is not a decision variable, owing to the single sourcing policy adopted.

3.1.3 Objective function

The model's objective function, representing the minimisation of the annual overall logistics cost, is shown in Equation (1):

$$\min \left(\begin{array}{l} \sum_{h=1}^{H} \sum_{j=1}^{J} cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{H} \sum_{j=1}^{J} \frac{cw_h \cdot k_{h,j}}{ITR_h} \cdot \frac{D_j}{S_j} \\ \quad + \sum_{h=1}^{H} \sum_{j=1}^{J} ch_h \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{H} \sum_{p=1}^{P} cp_{p,h} \cdot \frac{\sum_{j=1}^{J} m_{p,j} \cdot k_{h,j} \cdot D_j}{LC_p} \end{array} \right) \tag{1}$$

In this equation, the input data are represented by:

- $cs_{h,j}$, the secondary distribution cost for shipping one unit of product along one unit of distance (i.e. according to the commonly adopted transportation rates, this is the cost for shipping 1 kg of product for 1 km) from RDW $_h$ to ADP $_j$ (€/kg km).
- $d_{h,j}$, the distance between RDW $_h$ and ADP $_j$ (km). It is derived, as shown in Section 3.2, from the RDW $_h$ and ADP $_j$ geographical locations.
- D_j , the annual demand of ADP $_j$. For consistency with the secondary distribution cost, D_j must be expressed in kilograms per year (kg/year).
- cw_h , the unit housing cost, i.e. the yearly cost per square metre in each RDW $_h$ (€/m^2 year).
- S_j , the average space utilisation index connected to ADP $_j$, indicating how many kilograms of products requested by ADP $_j$ can be stocked within a square metre (kg/m^2). This value almost exclusively depends on the required products' space utilisation index (essentially deriving from the product density and from the physical configuration of each stock-keeping unit), since in the present study we are considering a set of similar and equivalent warehouses (potential and activated).
- ITR $_h$, the average yearly inventory turnover ratio characterising the products requested by ADP $_j$ (1/year). The ITR $_h$ can be considered as a standard average value for the new potential RDW $_h$ while for the existing RDW $_h$ the actual values apply.
- ch_h , the unit handling cost, i.e. the cost for handling one kilogram of product in RDW $_h$ (€/kg).

$cp_{p,h}$, the primary distribution cost for a full truck load shipment from P_p to RDW $_h$ (€/FTL shipment).

$m_{p,j}$, the percentage of D_j fulfilled by means of products supplied by P_p . It is worth noting that, as mentioned above, in our model we consider a logistics network where each plant is product-focused, and each ADP $_j$ is demanding a range of different products. Consequently, we modelled this feature considering that the demand of each ADP $_j$ must be fulfilled by each P_p according to a certain percentage.

LC_p , the average full truck load capacity (expressed in kilograms of product) for a FTL shipment leaving from P_p (kg/FTL shipment).

In Equation (1), the only decision variable is represented by:

$k_{h,j}$, the Boolean decision variable, which allows defining whether ADP $_j$ is served by RDW $_h$ ($k_{h,j} = 1$) or not ($k_{h,j} = 0$).

No costs for activating a generic RDW $_h$ are taken into account in the objective function, since we consider that warehouses nowadays are commonly outsourced to logistics service providers. Thus, both the current and potential RDW $_h$ in the model correspond in real life to the facilities of logistics service providers, which are already active and do not require significant switching costs for including (or excluding) them in the optimised network configuration.

The objective function presented in this section can be generalised and modified in order to consider different types of products: the demand of ADP $_j$ for the different products manufactured by the production plants P_p can be included and the hypotheses according to which the space utilisation index and the yearly inventory turnover ratio are not depending on the specific product removed. For such a generalisation, see Appendix 1.

3.1.4 Constraints

The constraints of the proposed MILP model are given by the following equations:

$$\sum_{h=1}^{H} k_{h,j} = 1 \quad \forall j \tag{2}$$

$$k_{h,j} \leq I_{h,j} \cdot k_h \quad \forall h,j \tag{3}$$

$$\sum_{h=1}^{H} k_{h,j} = bin \quad \forall h,j \tag{4}$$

$$\sum_{h=1}^{H} k_h = bin \quad \forall h \tag{5}$$

$$\sum_{j=1}^{J} k_{h,j} \cdot \frac{D_j}{S_j \cdot ITR_h} > 4,000 \quad \forall h \tag{6}$$

Equation (2) is the constraint representing the single sourcing policy: each ADP $_j$ can be served by a single RDW $_h$ only. Therefore, only one connection linkage between a certain ADP $_j$ and all the potential RDW $_h$ can be activated.

Equation (3) represents the constraint concerning the service-level requirement. The connection linkage between a certain RDW $_h$ and a certain ADP $_j$ exists (i.e. the decision variable $k_{h,j}$ is equal to 1) only if that activated RDW $_h$ allows goods to be delivered to that ADP $_j$ within a given time. This last condition is modelled by means of the Boolean variable $I_{h,j}$ whose value is set equal to 1 if it is possible to serve ADP $_j$ from RDW $_h$ within the required delivery lead time and 0 otherwise. In particular, the allocation of binary values to the variables $I_{h,j}$ leads to the definition of an (h × j) origin–destination matrix (Table 1) where the RDW $_h$ and the ADP $_j$ are matched.

Table 1. Example of a potential origin–destination matrix for the definition of the service-level constraint.

CSVDisplay Table

Finally, Equations (4) and (5) constrain the decision variables $k_{h,j}$ and k_h respectively to be Boolean variables, while Equation (6) represents the constraint connected to the minimum size of a generic RDW $_h$ to be activated. We decided to set the minimum size equal to 4,000 m^2, since this represents the typical minimum plot size present in the contractual agreements with logistics service providers.

3.2 Data mapping and information processing

In this section, we provide a series of methodological guidelines for obtaining and processing the data necessary to set up and run the model.

3.2.1 Aggregation of customers' demand

A real-life global logistics network usually includes more than 20,000 delivery points. This implies an overwhelming complexity in dealing with such a large number of nodes. With reference to the definition of ADP $_j$, some geographical aggregation drivers are suggested by the literature. Since most Geographical Information Systems (GIS) assign NUTS codes (Nomenclature des Unités Territoriales Statistiques, Nomenclature of Territorial Units for Statistics, proposed by Eurostat in 1988) to each territory, we assumed that this coding should be considered for aggregating the actual delivery points into the ADP $_j$ of the model. Three different levels of aggregation are present in the NUTS codes, based on the number of inhabitants per aggregated cluster. We suggest using the most disaggregated codes (NUTS3) for aggregating the delivery points into ADP $_j$. Then, for each NUTS3 area the centre of gravity is determined by geographically referencing, using the ArcGIS™ software package, the demand profile data of the delivery points included in the corresponding geographical cluster. The latitude and longitude of the centre of gravity are representative of the geographical position of the ADP $_j$ used in the model, and in this way it is possible to reduce the complexity of the geographical system without impairing the internal validity of the model.

Concerning the ADP $_j$ demand, according to the described geographical aggregation and clustering methodology, the aggregate demand of the ADP $_j$ (D_j) is obtained according to Equation (7):

$$D_j = \sum_{k=K'}^{\tilde{K}} d_k \quad \forall j \qquad (7)$$

where d_k is the annual demand of the kth real delivery point included into the generic ADP $_j$, and K' and

$\bar{K}$
are the indexes of the generic customers within a generic ADP $_j$.

3.2.2 Product mix

The product mix is represented into the model by $m_{p,j}$: this value represents the percentage of products that a generic ADP $_j$ requires from each P_p . In order to derive $m_{p,j}$, it is necessary to consider the mix of products manufactured by the specific P_p and required by the single delivery point k ($m_{p,k}$). This is a piece of information that can be gathered from the company's accounting sheets. In particular, $m_{p,j}$ can be derived according to Equation (8):

$$m_{p,j} = \sum_{k=K'}^{\bar{K}} \frac{m_{p,k} \cdot d_k}{D_j} \quad \forall j \quad \forall p \tag{8}$$

where:

$m_{p,k}$ is the percentage of the delivery point demand (d_k) represented by the product manufactured by P_p and

D_j is the ADP $_j$ demand calculated according to Equation (7).

3.2.3 Unit secondary distribution cost

Since the *to-be* configuration of the logistics network could result in new linkages between RDW $_h$ and ADP $_j$ compared with the *as-is* configuration, it is necessary to derive, for each RDW $_h$, the secondary distribution unit cost ($cs_{h,j}$) as a function of the distance travelled to reach the ADP $_j$. Such a function is needed, since it is generally not possible to apply the cost values present in the transport accounting reports for assessing the overall secondary distribution cost, if the transport leg set changes from a configuration to another. As a matter of fact, such reports referring to a certain origin typically include cost values (expressed in Euros per kilogram) related to the shipped volumes subdivided into pre-defined weight ranges and to the possible destinations. The above-mentioned cost function, with reference to a particular RDW $_h$, can be obtained from both the transportation accounting reports and the quantities of product (in kilograms) yearly shipped (per weight range and per destination included in the transportation accounting sheet). Moving from these data, per destination a single €/kg rate, weighted on the basis of the shipped volume for each weight range, is calculated. Then, by dividing such rates by the distances between the corresponding destinations and the considered RDW $_h$, a series of €/kg km rates is obtained. Finally, by representing the obtained rates on a graph depending on the distance and through a regression analysis, the best-fitting curve interpolating these data is drawn. Of course, this calculation guideline should be taken into account for all those distribution contexts where a secondary distribution unit cost based on pre-defined weight and distance ranges applies. It is then necessary to calculate, with reference to the considered RDW $_h$, the distance for reaching each connected ADP $_j$ ($d_{h,j}$), given by the Euclidean distance between RDW $_h$ and ADP $_j$ multiplied by the 'circuity factor' of the geographical territory to which RDW $_h$ and ADP $_j$ belong (Ballou *et al*. 2002 Ballou, RH, Rahardja, H and Sakai, N. 2002. Selected country circuity factors for road travel distance estimation. *Transportation Research Part A: Policy and Practice*, 36(9): 843–848. , , [CSA]). By selecting the function ordinate corresponding to the abscissa given by the previously calculated distance between RDW $_h$ and ADP $_j$, the €/kg km rate to be applied is obtained. By multiplying this rate by the same distance, the unit secondary distribution cost corresponding to the connection between the considered RDW $_h$ and ADP $_j$ is derived.

3.2.4 Warehousing and handling costs

Concerning the unit warehousing cost (cw_h), a benchmarking activity, aimed at gathering the most significant cost values, can be performed with logistics real-estate companies, which are able to provide the €/m^2 year cost for renting a logistics facility in a given location. Since the unit housing cost is expressed in €/m^2 year, it is necessary to convert the kilograms of products flowing yearly through each RDW $_h$ into the required warehousing floor space to be included in the model objective function. It is necessary to consider that in similar warehouses the space utilisation index and the inventory turnover ratio are functions of the features of the stored products. Additionally the products stored in a specific RDW $_h$ depend on the ADP $_j$ served by this specific RDW $_h$. Consequently, the conversion of kilograms of products into warehouse floor space can be performed by dividing the demand of each ADP $_j$ served by the considered RDW $_h$ by the space utilisation (S_j) and the inventory turnover ratio (ITR $_j$) characterising the products required by each ADP $_j$. The values of S_j and ITR $_j$ can be respectively approximated by the space utilisation and the inventory turnover ratio of the RDW $_h$ which, in the as-is logistics network configuration, serves the considered ADP $_j$.

As far as the handling cost (ch_h) is concerned, its value can be obtained from logistics service providers, in terms of unit rate for the handling of inbound and outbound flows (€/kg).

3.2.5 Service-level requirement

With reference to the service-level requirement, the potential origin–destination matrix shown in Table 1 must be derived. In particular, for each RDW $_h$ one must verify which ADP $_j$ can be reached by truck in a required delivery time. To perform such a check, it is necessary to draw an isochronal zone, i.e. to draw the boundaries of the area accessible in a certain delivery time from each RDW $_h$, and to verify which ADP $_j$ lie completely within the isochronal zone. To perform this task, software packages such as Microsoft MapPoint™ can be used. These packages are able to consider average driving speeds coherently with the typologies of roads and other factors such as the driving stops imposed by regulations (e.g. driving times, stops for customs clearance).

4. Concluding remarks

In this paper, we addressed one of the most important and topical issues in supply-chain research: supply-chain configuration and optimisation (Teo and Shu 2004 Teo, CP and Shu., J. 2004. Warehouse-retailer network design problem. *Operations Research*, 52(3): 396–408. , , Meixell and Gargeya 2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550. , Chopra and Meindl 2007 Chopra, S and Meindl, P. 2007. *Supply chain management: Strategy, planning and operations*, Upper Saddle River: Prentice-Hall.). In particular, we focused on linear programming models, the most widespread modelling tool for designing logistics networks (Meixell and Gargeya 2005 Meixell, M and Gargeya, V. 2005. Global supply chain design: a literature review and critique. *Transportation Research – part E*, 41(6): 531–550. , Chopra and Meindl 2007 Chopra, S and Meindl, P. 2007. *Supply chain management: Strategy, planning and operations*, Upper Saddle River: Prentice-Hall.).

In detail, after having performed an extensive review of the literature, which allowed assessing the existing logistics network configuration models, we proposed a taxonomy for classifying the scientific literature according to seven classification dimensions. We found the current state of the art particularly wanting of exhaustive configuration models, i.e. models dealing with real-life complexity and including both service-level constraints and data-mapping sections, whose relevance is widely acknowledged by the literature (Melachrinoudis and Min 2000 Melachrinoudis, E and Min, H. 2000. 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): 1–15. , , Simchi-Levi *et al*. 2005 Simchi-Levi, D, Kaminski, P and Simchi-Levi, E. 2005. *Designing and managing the supply chain: concepts, strategies and case studies*, 2nd, New York: McGraw-Hill.). On the basis of the outcomes of our literature analysis, we decided to focus on the development of a MILP model with a data-mapping section for configuring multiple-layer, single location-layer, multiple-commodity, and time-constrained logistics networks considering a single period time horizon and a deterministic environment.

We believe that the proposed model could be profitably applied by supply-chain and logistics managers for optimising real-life supply chains characterised by similar features compared with those considered. Moreover, the data-mapping section provided could represent a useful guideline that can be successfully used by practitioners to gather and handle the high volume of data necessary for the model operationalisation. This would also give companies the opportunity for rationalising the body of available information and for identifying the missing data to be further gathered. Moreover, the input data for the model could be exploited as a managerial cockpit: for instance, the set of secondary distribution unit cost functions could be considered as a tool for monitoring and assessing the transportation rates applied by the logistics service providers hired by the company. Again, as a managerial tool, the proposed integrated approach to the design of the logistics network could be exploited to evaluate the alignment of the strategic fit between the logistics network configuration and the changing logistics business conditions. This could be achieved by means of periodical runs of the optimisation model along with the data-mapping process. In this case, it would also be necessary to consider the implications connected to the logistics network configuration changes, in terms of strategic and long-term actions.

It should be noted that all the logistics network optimisation techniques are decision-support tools aimed at assisting logistics managers in the decision-making process, which entails the concurrent evaluation of different context variables. For example, if the business objectives encompass the evaluation of the traditional trade-off between service level and logistics costs, it would be suitable to evaluate, together with the sales and marketing department, the marginal utility of an overall reduction in the service level and the connected cost and benefits implications. This could help to align the outcomes of the optimisation process with the objectives of the overall company.

We believe that our proposed integrated approach (the optimisation model and the exhaustive data-mapping and processing section) could be a useful tool for companies. This is confirmed by its factual application to a real-life example, regarding the redesign of the European Pirelli Tyre logistics network. We refer the interested reader to Creazza *et al*. (2011), where this application has been thoroughly described. In particular, the implementation of the proposed model in the Pirelli Tyre supply chain (characterised by more than 40,000 nodes) led the company to define a new optimised logistics network configuration, which allowed for a reduction in the overall logistics cost by 7%.

Of course, the proposed model presents a limitation, since it can be applied only to selected fields, as mentioned above. To overcome this limitation, our aim is to carry out research considering a multi-location layer MILP model for addressing production-distribution networks.

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Appendix 1

When the ADP $_j$ demands of different products as well as product-dependent space utilisation index and yearly inventory turnover ratio are considered, the objective function depicted by Equation (1) changes according to Equation (9):

$$\min \left(\begin{array}{l} \sum_{h=1}^{H} \sum_{j=1}^{J} cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{H} \sum_{j=1}^{J} \sum_{p=1}^{P} \frac{cw_h \cdot k_{h,j}}{ITR_{h,p}} \cdot \frac{D_{j,p}}{S_{h,p}} \\ + \sum_{h=1}^{H} \sum_{j=1}^{J} \sum_{p=1}^{P} ch_{h,p} \cdot k_{h,j} \cdot D_{j,p} + \sum_{h=1}^{H} \sum_{p=1}^{P} \frac{\sum_{j=1}^{J} cp_{p,h} \cdot k_{h,j} \cdot D_{j,p}}{LC_p \cdot PS_p} \end{array} \right) \tag{9}$$

In Equation (9), different from Equation (1):

$D_{j,p}$ is the ADP $_j$ annual demand of product 'p', i.e. of the product manufactured by the production plant P_p. $D_{j,p}$ is expressed in kilograms per year (kg/year) and is linked to the annual demand of ADP $_j$ (D_j) by Equation (10):

$$D_j = \sum_{p=1}^{P} D_{j,p} \tag{10}$$

$S_{h,p}$ is the space utilisation index, which indicates how many kilograms of product 'p' can be stocked within a square metre (kg/m^2) into the RDW $_h$. In this case the hypothesis which allowed to consider the concept of equivalent warehouses (see Section 3.1.3) is removed, and as a consequence, the space utilisation depends not only on the product stocked but also on the warehousing facilities of each RDW $_h$.

ITR $_{h,p}$ is the yearly inventory turnover ratio characterising the product 'p' in RDW $_h$ (1/year).

$ch_{h,p}$ is the unit handling cost, i.e. the cost for handling one kilogram of product 'p' in RDW $_h$ (€/kg). We consider the hypothesis according to which the characteristics of the product handled, e.g. volume and shape, can influence the unit handling cost.

PS_p is a percentage value representing the utilisation of the full truck load capacity, which is a function of the shipped product and, in particular, of its unit volume.

It is worth noting that the first term of Equation (9) is the same as that in Equation (1). In fact, the unit secondary distribution cost depends on the distance covered and the shipped weight (see Section 3.2.4), and not on the shipped product. Therefore, Equation (11), owing to Equation (10), can be verified:

$$\sum_{h=1}^{H} \sum_{j=1}^{J} \sum_{p=1}^{P} cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_{j,p} = \sum_{h=1}^{H} \sum_{j=1}^{J} cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot \sum_{p=1}^{P} D_{j,p} = \sum_{h=1}^{H} \sum_{j=1}^{J} cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j \tag{11}$$

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