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An integrated model for designing and optimising an international logistics network

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Supply chain configuration has recently gained an increasing attention both from the practitioners' 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. In details, 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 it facilitates the data gathering and processing activities, which are largely recognised as complex and time consuming processes for the management of logistics activities.

Keywords: supply chain configuration, linear programming, data mapping section, service level constraint

An integrated model for designing and optimising an international logistics network

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Keywords: supply chain configuration, linear programming, data mapping section, service level constraint

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). Among these, one of the most relevant is represented by an ever-growing pressure on service level along with a reduction of the price of goods and services (Cheong et al., 2007; Jammernegg and Reiner, 2007). In this context, supply chain configuration and coordination have become an important focus of competitive advantage for international companies. As defined by Porter (1986), 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

1
2
3 like activities performed in different countries are coordinated with each other”.

4
5 **Indeed**, the configuration of the supply chain (i.e. the definition of its topological
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7
8 features such as the numbers of layers in the chain, the number of nodes in each layer,
9
10 the distance between the nodes, the sourcing policies – Simchi Levi et al., 2001) has a
11
12 great importance for international competing companies (Ballou, 2005). **“A company**
13
14 **may be able to save millions of dollars in logistics costs and simultaneously improve**
15
16 **service levels by redesigning its distribution network”** (Teo and Shu, 2004). As a
17
18 matter of fact, the topological features of the supply chain have a considerable impact
19
20 on supply chain performance (Pero et al., 2010; Sezen, 2008). Beamon (1999) states
21
22 that supply chain performance mainly relates to costs and customer responsiveness. In
23
24 particular, **costs** are connected to inventory and operating **issues** (manufacturing and
25
26 distribution), while the latter is related to stock-out (or backlog) occurrence and
27
28 probability of occurrence (e.g. lead time, stock-out probability and fill rate) (Vachon
29
30 and Klassen, 2008; Simchi-Levi et al., 2001; Beamon, 1999). **However, maximising**
31
32 **supply chain performance entails the solution of a series of trade-offs (Simchi-Levi et**
33
34 **al., 2005).** For instance, by reducing the number of nodes in the supply chain, it is
35
36 possible to reduce inventory costs, due to the decrease of safety stock according to the
37
38 “square root law of inventory”. On the other hand, if we consider an increase of the
39
40 number of nodes at the retailer stage, it is possible **to offer** better customer
41
42 responsiveness. The nodes of the distribution network **will be** located closer to the end
43
44 markets and in this way the delivery time required by customers **will be matched** with
45
46 the actual company delivery lead time.
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55 **In the last few many companies started to reconfigure their** supply chain
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57 networks from time to time to retain their competitive edge (Goetschalckx and
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59 Fleischmann, 2005). Pirelli Tyre, a multinational automotive tyre manufacturer, in
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3 2009 was challenged in enhancing the cost-efficiency of its supply chain, with the aim
4 to gain competitive advantage in an industry characterised by a growing pressure on
5 cost control and strict service level requirements. By optimising its supply chain
6 configuration in terms of optimal location of its distribution centres, the company was
7 able to minimise supply chain costs while satisfying service level requirements in
8 different scenarios. Another example regards the car manufacturer BMW, which in
9 2006 by exploiting the optimisation of its supply chain improved its long-term load
10 planning for the production of cars, which is an essential phase in BMW's strategic-
11 planning process (Fleischmann et al., 2006). In the forestry industry Sodra Cell AB, a
12 Swedish timber and pulp production company, in 2005 tackled the need for increasing
13 its supply chain performance by means of an optimisation regarding the existing
14 production network and the activation of new distribution structures. Sodra Cell AB
15 implemented an ongoing decision support tool to decide terminal location and make
16 distribution by vessels more integrated and efficient (Carlsson and Ronnqvist, 2005).
17 The provided real-life examples confirm what stated by Teo and Shu (2004),
18 according to which multinationals are more and more faced with strategic decisions
19 regarding the configuration of their supply chain and logistics network (Chauhan et
20 al., 2004; Meixell and Gargeya, 2005; Chopra and Meindl, 2007).

21
22 Thus, companies have to confront great challenges in the decisions making
23 process for configuring their supply chain. These are exacerbated if we consider that
24 optimal decisions must be taken by solving constrained optimisation problems with
25 strong interrelationships between problem variables. In contexts where resources are
26 tightly constrained, obtaining the optimal configuration is a noteworthy challenge.

27
28 Therefore, the need for effective decision support tools has risen. These tools
29 should allow to easily, more accurately and more frequently configure/re-configure
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3 logistics networks for maximising supply chain performances and solve the
4
5 mentioned trade-offs (Melachrinoudis and Min, 2007; Melo et al., 2009). There exists
6
7 a large body of literature on decision support tools and optimisation models for supply
8
9 chain configuration. The problem has been addressed by a series of studies based on
10
11 genetic/heuristic methods, simulation methods and, as foremost approach, linear
12
13 programming (Meixell and Gargeya, 2005; Chopra and Meindl, 2007). The success of
14
15 linear programming is due to the fact that, despite some well-known drawbacks, it
16
17 allows for developing solver tools in an easy way, which enable realistic and precise
18
19 solutions for the network configuration problems to be obtained, thanks also to widely
20
21 available and reliable software packages (Sharma, 2006; Schoen, 2002).
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27 However, despite the large availability of scientific contributions focused on
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29 the addressed topic, the complexity of real-life supply chain problems has not been
30
31 considered in the extant literature. The objective of the current study is to propose a
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33 logistics network configuration model based on linear programming able to confront
34
35 and manage the complexity of a factual supply chain (i.e. characterised by a relevant
36
37 number of nodes and by a series of constraints). Moreover, we aim to provide
38
39 methodological guidelines for obtaining and processing the data and information
40
41 necessary to set-up the model, since data mapping and processing is considered a very
42
43 relevant, difficult and time-consuming activity (Carlsson and Ronnqvist, 2005).
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48 The remainder of the paper is organised as follows: section 2 is devoted to
49
50 review the literature focused on linear programming applications to supply chain
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52 configuration. In section 3, we describe our proposed logistics networks configuration
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54 model based on linear programming. Here, the corresponding data mapping procedure
55
56 is also presented. Finally, section 4 recounts some concluding remarks and insights on
57
58 potential future research on the topic.
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60

2. Background of the study

This section presents a literature review on linear programming applied to 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) 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, 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) and subsequently exploited by Newbert (2007). According to the adopted approaches, the literature search was performed on the most relevant on line 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. For doing this, we organised the analysis according to the taxonomical approach proposed by Melo et al. (2009). 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

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2
3 considered commodities, kind of considered data, applications to real-life cases.
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5 Building upon this framework, we included two additional dimensions, i.e. modelling
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7 of the service level constraint and presence of the data mapping section, which were
8
9 deemed particularly relevant for the supply chain configuration issue, as highlighted
10
11 by Cheong et al. (2007), Jammernegg and Reiner (2007) and Carlsson and Ronnqvist
12
13 (2005).
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16
17 Matching the implications arising from each section of the analysis with our
18
19 research objectives, we derived the specifications to be considered in developing the
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21 model.
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24
25 In figure 1 we include a summarising chart centred on the concepts of what
26
27 has been modelled and how it was modelled so far in the state of the art. Following,
28
29 due to brevity reasons, we report some highlights for the most relevant contributions
30
31 only, analysed according to the abovementioned dimensions. For each of the
32
33 dimensions we describe the implications of the literature analysis which led us in the
34
35 development of our optimisation model.
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40 Figure 1. Summarising chart of what was modelled and how it was modelled (key
41 features of the supply chain design models)
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45 ***2.1 Definition of the logistics network configuration problem***

46 In a logistics network configuration problem, a series of strategic decisions (i.e.
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48 decisions involving major capital investments and with long term effects) are
49
50 generally considered. They are essentially represented by the definition of the optimal
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52 number, location and size of warehouses and/or plants and by the definition of the
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54 optimal sourcing strategy for each node and of the best distribution channels (Chopra,
55
56 2003; Simchi-Levi et al., 2005).
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3 In other words, the objective of the logistics network configuration problem is
4 to find a minimal-cost configuration of the logistics network able to satisfy customers'
5 orders. In order to reach this goal, a linear programming-based network configuration
6 method should be composed by a mapping section, based on ready-to-be-
7 implemented data, and by an optimisation model able to provide the optimal network
8 configuration (Simchi-Levi et al., 2005).
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21 **2.2 Objectives of the configuration models and decision variables**

22 Coherently with the results obtained by Meixell and Gargeya (2005) and Melo et al.
23 (2009), we found that the main objective of the reviewed configuration models is total
24 logistics cost minimisation (75,6%), with 17,2% of the contributions focused on
25 maximising the company's profit and 7,2% of the reviewed articles characterised by a
26 multi-objective function (i.e. multiple and conflicting objectives, which in addition to
27 economic factors consider also measures based on resource utilization and customer
28 responsiveness – Melo et al., 2009). As long as cost minimisation is regarded, the
29 reviewed models consider transportation costs (97,1%), warehousing costs (67,1%),
30 production costs (58,8%), sourcing costs (31,2%), inventory costs (29,4%) and
31 international supply chain costs such currency exchange costs, duties and taxation
32 (17,1%).
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48 In our study, we found that logistics network design problems have **address**
49 decision variables such as the potential sites to be activated (97,6%). 84,9% of these
50 papers **consider** warehouses or distribution centres as potential sites to be activated.
51 Then, our **analysis** showed that the **mere** allocation of production and distribution has
52 been considered in the 78,2% of the papers. It is possible to find models (e.g.
53 Sridharan, 1995; Talluri and Baker, 2002; ReVelle and Eiselt, 2005) proposing an
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3 iterative process where firstly the facility location **problem** is addressed and secondly
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5 the transportation **one is faced**. Meixell and Gargeya (2005) affirm that **contributions**
6
7 **over time** have been extending their focus from distribution to manufacturing: when
8
9 **the latter is** considered, the decision variables are represented by the product mix to be
10
11 allocated to plants (15,9% of the contributions) and the models are based on **analysis**
12
13 **of** the bill of materials, as shown by Paquet et al. (2008), without selecting different
14
15 production plant alternatives. In other cases (60,6% of the reviewed contributions) **the**
16
17 **allocation** of sourcing flows from suppliers **is** considered. Moreover, 29,4% of the
18
19 reviewed models include considerations on inventory costs and transportation time
20
21 when global supply chains are optimised.
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27 From this analysis we learned that, coherently with the issues raised in the
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29 introduction and **with** our aims, it is possible to focus on minimising costs for
30
31 optimising the logistics network relying on a strong literature support. As the
32
33 objectives of the configuration models are regarded, literature indicates that
34
35 warehousing, transportation **and distribution represent the** most investigated elements,
36
37 while the choices regarding activation of production plants are only seldom
38
39 considered since they are generally connected to labour issues and to high required
40
41 **capital** investments. This implies that, even if the allocation of production is still
42
43 viable, plants are generally not modified in terms of location.
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48 **With respect** to the objective of the optimisation model we decided to focus on
49
50 cost minimisation while as regards the decision variables to include in our model we
51
52 decided to consider distribution allocation, by setting the quantities to be shipped
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54 from plants to customers through a network of selectable intermediate logistics nodes
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56 (i.e. distribution centres).
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59
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2.3 Considered layers and supply chain stages

As far as the supply chain layers are considered, two different alternatives are available: single-layer and multiple-layer options. The two alternatives regard both the number of layers composing the supply chain and the number of layers where the decision variables are included, named “location layers”. In their analysis Melo et al. (2009) 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) 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) optimise the American Volkswagen’s distribution network through the location of new warehouses and plants. Gunnarsson et al. (2004) 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. As emerging from Melo et al. (2009) and Meixell and Gargeya (2005), 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 a 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). For these reasons, and giving the growing importance of global logistics networks in supply chain management research, we drove 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 notice that **only 29,6%** of the models included in the reviewed literature **investigates** 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 confronted in literature with a series of simplifications and assumptions made to subdivide the overall optimisation problem **into** sub-problems. For example, Avittathur et al. (2005) integrate location and inventory decisions in a multi-commodity problem. Jayaraman and Ross (2003) 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) 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) introduce a model to design and manage multi-commodity location allocation **problems**. **Camm et al. (1997)** propose 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 emerges 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:

literature shows that 85,2% of the **analysed** papers are aimed at configuring a logistics network considering a single-period horizon (Melo et al., 2009). A multi-period approach is presented by Ballou (2005) 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) focus on site location problems, giving special emphasis to the financial issues in a multi-period planning horizon, while Manzini and Gebennini (2008) developed a model for managing a multi-period location allocation problem, in a multi-stage and multi-commodity context. Literature provides other significant examples of models developed in various **industries** (e.g. plastics, by Altiparmak et al. (2006); mining of silicon metals, by Ulstein et al. (2006)), **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) represents another example of 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 frequently change 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 specifically focus our analysis on seasonal**

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3 commodities or time-variable production-distribution systems, we thus decided to
4
5 address a single-period model.
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10 11 *2.6 Kind of considered data*

12 Literature shows that 92,2% of the reviewed papers have been focusing on
13
14 deterministic models for configuring a logistics network. This is a reasonable
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16 approach when it is possible to assume that all of the data and future events regarding
17
18 the problem are known with a sufficient degree of certainty. However, when
19
20 unpredictable fluctuations of the values of some model variables have to be
21
22 considered, an important extension is represented by the inclusion of stochastic
23
24 components in the configuration model. Owen and Daskin (1998) state that often
25
26 there is uncertainty in determining the costs and future demand. In order to face
27
28 environmental variance, procedures focused on stochastic programming have been
29
30 drawn (Alonso-Ayuso et al., 2002; Santos, 2002) or stochastic variables have been
31
32 included in order to model uncertainty in the operation of a supply chain (Blackhurst
33
34 et al., 2004). Nevertheless, it is important to underline that the reviewed literature
35
36 suggests that for dealing with non-deterministic contexts, simulation tools can be
37
38 considered as more suitable for time dependent contexts rather than MILP since
39
40 simulation is able to consider dynamic and stochastic issues, although unable to
41
42 provide optimised solutions (Chopra and Meindl, 2007; Cigolini and Rossi, 2006;
43
44 Law and Kelton, 1997). Thus, simulation could be used to test the static outcomes of
45
46 the MILP models derived from single-period approaches (e.g. 1 year) where the
47
48 stochastic effect of variables can be compensated along time. Considering our aims,
49
50 we decided to focus on models dealing with deterministic data: in this way we better
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52 exploit MILP.
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2.7 Modelling of the service level constraint

Another important **feature** to be considered is how the service level constraint is modelled. A model able to deal with real-life contexts should consider this issue in a realistic and comprehensive way. Almost the totality of the reviewed contributions considers 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) 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) model the service level constraint as a percentage of the overall demand met, assuming a deterministic customer demand. Melachrinoudis and Min (2007) consider the negative influence of warehouse centralisation on lead times, as an expression of service level. This influence is considered with a constraint that forces each consolidated facility to meet customers' demand within 10 hours 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):

- 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%). 20 papers (70%) out of the 28 found applications can be included in the case study group, while the remainder are to be ascribed to the industrial contexts group. However, out of the 20 identified case studies, only 8 of them are able to keep 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 (Carlsson and Ronnqvist, 2005; Simchi-Levi et al., 2005; Melachrinoudis and Min, 2000). Our analysis showed that among the non-applied models, none of them is accompanied by a data mapping section and that none of the industrial context papers proposes 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 (Fahranı and Asgari, 2007), or papers trying to reduce data complexity by means of data aggregation (Wouda et al., 2002) or data clustering for products, customers and delivery zones (Ulstein et al., 2006). The

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3 analysed literature strongly supports the necessity to rely on methodological
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5 guidelines for managing the considerable amount of data necessary to run
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7 optimisation models. However, we found that literature is particularly wanting of
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9 examples of developed data mapping sections for supporting the operationalisation of
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11 the supply chain and logistics network configuration models: thus we raise the claim
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13 to fill this gap.
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21 **3. The proposed method**

22 The logistics network configuration model we propose in this paper, **built** considering
23
24 all the directions identified in the previous sections, is based on mixed integer linear
25
26 programming (MILP) and it is completed by a data mapping section (Simchi-Levi et
27
28 al., 2005).
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33 **3.1 The logistics network configuration model**

34 The **typology of** logistics network we are addressing is constituted by:

- 35
36 • a series of product-focused un-capacitated production plants (defined as P_p),
37
38 which manufacture products characterised by some different features (e.g.
39
40 technical specifications);
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42
- 43 • a series of regional distribution warehouses (defined as RDW_h);
44
45
- 46 • a series of delivery points (such as wholesalers or outlets) which serve final
47
48 customers.
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51 The delivery points are characterised by demand features which **are strictly related to**
52
53 the products manufactured by the different plants. **Delivery points** are served by
54
55 RDW_h according to a single sourcing policy. Considering that a real-life distribution
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57 system of a multinational company could have over than 20,000 accounts, there needs
58
59 to perform an aggregation of the delivery points in macro-groups or clusters (Simchi-
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Levi et al., 2005), 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 characterizing 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 one allows for selecting which RDW_h out of the set of potential location must be activated;
- the second one 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 variables 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

the ones connecting RDW_h and ADP_j are considered as 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 facts, P_p are product-focused production plants). Finally, the quantity of products shipped from a RDW_h to an ADP_j is not a decision variable, due to the adopted single sourcing policy.

3.1.3 The objective function

The model's objective function, representing the minimisation of the annual overall logistics cost, is shown by expression 1:

$$\min \left(\begin{aligned} & \sum_{h=1}^{24} \sum_{j=1}^J cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{24} \sum_{j=1}^J \frac{cw_h \cdot k_{h,j}}{ITR_h} \cdot \frac{D_j}{S_j} + \\ & + \sum_{h=1}^{24} \sum_{j=1}^J ch_h \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{24} \sum_{p=1}^6 cp_{p,h} \cdot \frac{\sum_{j=1}^J m_{p,j} \cdot k_{h,j} \cdot D_j}{LC_p} \end{aligned} \right) \quad (1)$$

In this expression 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 one kilogram of product for one kilometre) 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 meter in each RDW_h [€/m²·year];
- S_j , the average space utilisation index connected to ADP_j and indicates how many kilograms of products requested by ADP_j can be stocked within a square metre [kg/m²]. This value is almost exclusively depending on the required products' space utilisation index (essentially deriving from the product density and from the physical configuration of each stock keeping unit), since we are considering in the present study 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 to notice that, as abovementioned, 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 expression 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 are nowadays commonly outsourced to logistics service providers. Then, 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 The constraints

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

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

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

$$k_{h,j} = \text{bin} \quad \forall h, j \quad (4)$$

$$k_h = \text{bin} \quad \forall h \quad (5)$$

$$\sum_{j=1}^J k_{h,j} \cdot \frac{D_j}{S_j \cdot \text{ITR}_h} > 4,000 \quad \forall h \quad (6)$$

Expression 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.

Expression 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 a **[h x j] origin-destination matrix (see 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

Finally, expressions 4 and 5 constrain the decision variables $k_{h,j}$ and k_h respectively to be Boolean variables, while expression 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 square metres since this represents the typical

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3 minimum plot size present in the contractual agreements with logistics service
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5 providers.
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10 **3.2 Data mapping and information processing**

11 In this section we provide a series of methodological guidelines for obtaining and
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13 processing the data necessary to set-up and run the model.
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16 **3.2.1 The aggregation of customers' demand**

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

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

where d_k is the annual demand of the k -th real delivery point included into the generic ADP_j, and K' and \tilde{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 expression 8:

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

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.

3.2.4 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 to 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

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3 travelled distance to reach the ADP_j . Such a function is needed since it is generally
4 not possible to apply the cost values present in the transport accounting reports for
5 assessing the overall secondary distribution cost, if the transport leg set changes from
6 a configuration to another. As a matter of fact, such reports referring to a certain
7 origin typically include cost values (expressed in Euros per kilogram) related to the
8 shipped volumes subdivided into pre-defined weight ranges and to the possible
9 destinations. The above mentioned cost function, with reference to a particular RDW_h ,
10 can be obtained from both the transportation accounting reports and the quantities of
11 product (in kilograms) yearly shipped (per each weight range and per each destination
12 included in the transportation accounting sheet). Moving from these data, per each
13 destination a single €/kg rate, weighted on the basis of the shipped volume for each
14 weight range, is calculated. Then, by dividing such rates by the distances between the
15 corresponding destinations and the considered RDW_h , a series of €/kg·km rates is
16 obtained. Finally, by representing the obtained rates on a graph depending on the
17 distance and through a regression analysis, the best fitting curve interpolating these
18 data is drawn. Of course, this calculation guideline should be kept into account for all
19 those distribution contexts where a secondary distribution unit cost based on pre-
20 defined weight and distance ranges applies. It is then necessary to calculate, with
21 reference to the considered RDW_h , the distance for reaching each connected ADP_j
22 ($d_{h,j}$), given by the Euclidean distance between RDW_h and ADP_j multiplied by the
23 “circuitry factor” of the geographical territory which RDW_h and ADP_j belong to
24 (Ballou et al., 2002). By selecting the function ordinate corresponding to the abscissa
25 given by the previously calculated distance between RDW_h and ADP_j , the €/kg·km
26 rate to be applied is obtained. By multiplying this rate by the same distance the unit
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3 secondary distribution cost corresponding to the connection between the considered
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6 RDW_h and ADP_j is derived.
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9 3.2.4 Warehousing and handling costs

10 As far as the unit warehousing cost (c_{wh}) is regarded, a benchmarking activity, aimed
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12 at gathering the most significant cost values, can be performed with logistics real
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14 estate companies, which are able to provide the $\text{€}/\text{m}^2\cdot\text{year}$ cost for renting a logistics
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16 facility in a given location. Since the unit housing cost is expressed in $\text{€}/\text{m}^2\cdot\text{year}$, it is
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18 necessary to convert the kilograms of products yearly flowing through each RDW_h
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20 into the required warehousing floor space to be included in the model objective
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22 function. It is necessary to consider that in similar warehouses the space utilisation
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24 index and the inventory turnover ratio are function of the features of the stored
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26 products. Additionally the products stored in a specific RDW_h depend on the ADP_j
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28 served by this specific RDW_h . Consequently, the conversion of kilograms of products
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30 into warehouse floor space can be performed by dividing the demand of each ADP_j
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32 served by the considered RDW_h by the space utilisation (S_j) and the inventory
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34 turnover ratio (ITR_j) characterizing the products required by each ADP_j . The values of
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36 S_j and ITR_j can be respectively approximated by the space utilisation and the
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38 inventory turnover ratio of the RDW_h which in the as-is logistics network
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40 configuration serves the considered ADP_j .
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48 As far as the handling cost (c_{ch}) is concerned, its value can be obtained from
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50 logistics service providers, in terms of unit rate for the handling of inbound and
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52 outbound flows ($\text{€}/\text{kg}$).
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56 3.2.5 Service level requirement

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

21 22 23 **4. Concluding remarks**

24 In this paper we addressed one of the most important and topical issues in supply
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26 chain research: supply chain configuration and optimisation (Chopra and Meindl,
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28 2007; Meixell and Gargeya, 2005; Teo and Shu, 2004). In particular, we focused on
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30 linear programming models, the most widespread modelling tool for designing
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32 logistics networks (Chopra and Meindl, 2007; Meixell and Gargeya, 2005).

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35 In detail, after having performed an extensive review of the literature, which
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37 allowed assessing the existing logistics network configuration models, we proposed a
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39 taxonomy for classifying the scientific literature according to seven classification
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41 dimensions. We found the current state of the art particularly wanting of exhaustive
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43 configuration models, i.e. models dealing with real-life complexity and including both
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45 service level constraints and data mapping sections, whose relevance is widely
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47 acknowledged by the literature (Melachrinoudis and Min, 2000; Simchi-Levi et al.,
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49 2005). On the basis of the outcomes of our literature analysis, we decided to focus on
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51 the development of a MILP model with a data mapping section for configuring
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53 multiple-layer, single location-layer, multiple-commodity and time-constrained
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3 logistics networks **considering** a single period time horizon **and a deterministic**
4 **environment.**
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8 We believe that the proposed model could be profitably applied by supply
9 chain and logistics managers for optimising **real-life supply chains** characterised by
10 similar features compared to the considered ones. **Moreover, the provided data**
11 **mapping section could represent a useful guideline**, which can be successfully used by
12 practitioners to gather and handle the high volume of data necessary for the model
13 **operationalisation. This would also give companies** the opportunity for rationalising
14 the body of available information and for identifying the missing data to be further
15 gathered. Moreover, the input data for the model could be exploited as a managerial
16 cockpit: for instance, the **set of** secondary distribution unit cost functions could be
17 considered as a tool for monitoring and assessing the transportation rates applied by
18 the logistics service providers hired by the company. Again, as a managerial tool, the
19 proposed integrated approach to the design of the logistics network could be exploited
20 to evaluate the alignment of the strategic fit between the logistics network
21 configuration and the changing logistics business conditions. **This could be achieved**
22 **by means** of periodical runs of the optimisation model along with the data mapping
23 process. In this case, **there would need to consider also** the implications connected to
24 the logistics network configuration changes, **in terms of strategic and long-term**
25 **actions.**
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50 **It should be remarked** that all the logistics network optimisation techniques are
51 decision support tools aimed at assisting logistics managers in the decision making
52 process, which entails the concurrent **evaluation of different** context variables. For
53 example, if the **business** objectives encompass the evaluation of the traditional trade-
54 off between service level and logistics costs, **it would be suitable to evaluate, together**
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3 with the sales & marketing department, the marginal utility of an overall reduction of
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5 the service level and the connected cost and benefits implications. This could lead to
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7 align the outcomes of the optimisation process with the objectives of the overall
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9 company.
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12 We believe that our proposed integrated approach (the optimisation model and
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14 the exhaustive data mapping and processing section) could be a useful tool for
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16 companies. This is confirmed by its factual application to a real-life example,
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18 regarding the redesign of the European Pirelli Tyre logistics network. We refer the
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20 interested reader to XXX, where this application is thoroughly described. In
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22 particular, the implementation of the proposed model to the Pirelli Tyre supply chain
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24 (characterised by more than 40,000 nodes) led the company to define a new optimised
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26 logistics network configuration, which allowed for a reduction of the overall logistics
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28 cost by 7%.
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34 Of course, the proposed model presents a limitation, represented by the
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36 possibility to apply it to selected fields only, as abovementioned. To overcome this
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38 limit, our purpose is to develop a research considering a multi-location layer MILP
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40 model for addressing production-distribution networks.
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47
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49
50 the paper.
51

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31 Appendix 1

32 When the ADP_j demands of different products as well as product-dependent space
33 utilization index and yearly inventory turnover ratio are considered, the objective
34 function depicted by expression 1 changes according to expression 9.

$$35 \min \left(\begin{aligned} & \sum_{h=1}^H \sum_{j=1}^J c_{s_{h,j}} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j + \sum_{h=1}^H \sum_{j=1}^J \sum_{p=1}^P \frac{c_{w_h} \cdot k_{h,j} \cdot D_{j,p}}{ITR_{h,p} \cdot S_{h,p}} + \\ & + \sum_{h=1}^H \sum_{j=1}^J \sum_{p=1}^P c_{h,p} \cdot k_{h,j} \cdot D_{j,p} + \sum_{h=1}^H \sum_{p=1}^P \frac{\sum_{j=1}^J c_{p,p,h} \cdot k_{h,j} \cdot D_{j,p}}{LC_p \cdot PS_p} \end{aligned} \right) \quad (9)$$

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51 In expression 9, by difference from expression 1:

- 52 • D_{j,p} is the ADP_j annual demand of product 'p', i.e. of the product manufactured by
53 the production plant P_p. D_{j,p} is expressed in kilograms per year [kg/year] and it is
54 linked to the annual demand of ADP_j (D_j) by expression 10;

$$55 D_j = \sum_{p=1}^P D_{j,p} \quad (10)$$

- $S_{h,p}$ is the space utilization 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 ;
- $\text{ITR}_{h,p}$ 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 to notice that the first term of expression 9 is the same as expression 1. As a matter of fact, the unit secondary distribution cost depends on the distance covered and on the shipped weight (see section 3.2.4) and not on the shipped product. Therefore, the equality 11, due to expression 10, is verified:

$$\begin{aligned} \sum_{h=1}^H \sum_{j=1}^J \sum_{p=1}^P cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_{j,p} &= \sum_{h=1}^H \sum_{j=1}^J cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot \sum_{p=1}^P D_{j,p} = \\ &= \sum_{h=1}^H \sum_{j=1}^J cs_{h,j} \cdot d_{h,j} \cdot k_{h,j} \cdot D_j \end{aligned} \quad (11)$$

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

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	ADP_1	ADP_2	$ADP_{j...}$	ADP_j
RDW_1	0	1	...	1
RDW_2	1	0	...	1
$RDW_{h...}$
RDW_H	1	0	...	0

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

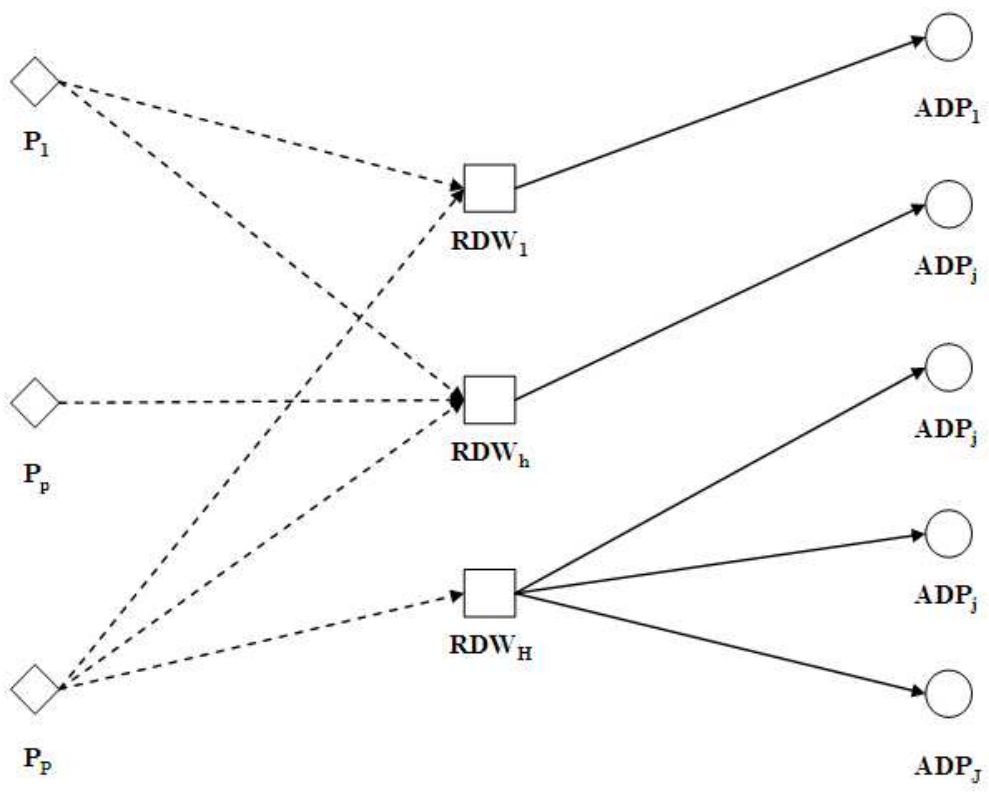
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Figure 2. Description of the considered logistics network

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