A strategic model for exact supply chain network design and its application to a global manufacturer

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Abstract

Motivated by the considerable value and competitive advantage resulting from supply chain efficiency, this paper presents a comprehensive model that captures significant strategic decisions involved in designing or re-designing high performance supply chains from the perspective of the manufacturer. The problem setting considers deterministic demand estimates by multiple clients, for multiple products, over the periods of a long term horizon. The strategic decisions involve selection of raw material suppliers, establishment or resizing of production facilities and/or selection of production subcontractors, establishment/resizing of distribution centers and/or subcontracting of the related activities, and selection of transportation modes and routes. The problem is formulated by a mixed integer linear programming (MILP) model. Its objective is to minimize the overall costs associated with procurement, production, inventory, warehousing, and transportation over the design horizon. Appropriate constraints model the complex relationships among the links of the supply chain. The proposed model has been applied to a large case study of a global manufacturing firm, providing valuable insights into the transformation of the firm's current supply chain network. The system has also been analyzed under variations of key parameters.

1 Introduction

The term "Supply Chain Management" (SCM) describes the relationship between logistics and other enterprise functions, such as procurement, production, distribution channel management and client service (Oliver and Webber, 1982). Responsiveness, cost, reliability, and responsibility are the main drivers of supply chains (Lee and Billington, 1995). Furthermore, globalization forces supply chains to be integrated and flexible, while the rapid growth of communication and information technologies offers significant opportunities and changes in supply chain structures, operations, and coordination (Thomas and Griffin, 1996).

Supply Chain Network Design (SCND) determines the structure of the supply chain and greatly influences performance (Chopra and Meindl, 2007; Klibi *et al*., 2010). Thus, SCND has received significant interest from both industry and academia. It has been recognized as a major improvement lever for businesses that strive to optimize their global networks relocating key functions (Ernst and Young 2013). SCND has been traditionally characterized as a strategic decision problem (Erengüç *et al*., 1999; Altiparmak *et al*., 2006; Chopra and Meindl, 2007), although recent approaches associate SCND with decisions ranging from the strategic to more tactical/ operational levels (Melo *et al*., 2009; Farahani *et al*., 2014). In terms of complexity, Production-Distribution (P-D) planning problems address the delicate balance among multiple issues, and have been recognized to be NP-hard (Thomas and Griffin, 1996), involving large numbers of entities and constraints (Pitty *et al*., 2008).

The research contributions and future directions for SCND have been captured in multiple literature surveys (Vidal and Goetschalckx, 1997; Owen and Daskin, 1998; Sarmiento and Nagi, 1999; Erengüç *et al*., 1999; Schmidt and Wilhelm, 2000;

Goetschalckx *et al*., 2002; Shah, 2005; Meixell and Gargeya, 2005; Melo *et al*., 2009; Papageorgiou, 2009; Klibi *et al*., 2010; Mula *et al*., 2010; Fahimnia *et al*., 2013a; Lambiase *et al*., 2013; Brandenburg *et al*., 2014; Farahani *et al*., 2014, Eskandarpour *et al*., 2015). Key research directions emerging from these surveys are overviewed below.

A major concern in SCND concerns the importance of activity integration from the supplier to the end customer (Gupta and Maranas, 2003), since this may greatly affect profitability (Guillén *et al*., 2005). Beamon (1998) identified two highly interacting processes in a supply chain: (a) production planning and inventory control, and (b) distribution and logistics, including warehousing and transportation. Production–distribution integration has attracted significant research efforts (Yan *et al*., 2003; Yılmaz and Çatay, 2006; Fahimnia *et al*., 2013b). Nevertheless multiple research challenges remain to be addressed in order to achieve integrated supply chain planning (Sarmiento and Nagi, 1999; Erengüç *et al*., 1999; Meixell and Gargeya, 2005; Melo *et al*., 2009; Nikolopoulou and Ierapetritou, 2012).

In addition to integration, and notwithstanding the vast body of literature devoted to SCND, we highlight those areas of emerging research that are related to the work in this paper. Starting from sourcing, supplier considerations are significant (Yan *et al*., 2003) and have been addressed by a few authors (Melo *et al*., 2009; Mula *et al*., 2010; Farahani *et al*., 2014) under simple assumptions (e.g. single planning time horizon, single product, and one type of manufacturing facility). Concerning the relationship of raw material supply and production, Vidal and Goetschalckx (1997) argue that consideration of the product Bill of Materials (BoM) is a significant issue since it provides information on the necessary coordination of these activities (see also Yan *et al*., 2003). Moving to production, Fahimnia *et al*. (2013b) acknowledge gaps

including the consideration of production cost at the work center level, and production outsourcing. The authors also point out gaps in downstream logistics functions, such as the consideration of third party logistics options, which reflects strong current trends (Meixell and Gargeya, 2005; Farahani *et al*., 2014). Aligned with globalization imperatives is also the inclusion of significant transportation decisions in SCND, such as transportation mode selection (Goetschalckx *et al*., 2002; Melo *et al*., 2009; Zakeri *et al*., 2015), and exploitation of economies of scale (e.g. Full Truck Load- FTL, block trains) (Mula *et al*., 2010).

An emerging "horizontal" area related to transportation and many other supply chain activities is sustainability and social responsibility. Several authors have recently highlighted the significance of these concerns in SCND, (Shah, 2005; Papageorgiou, 2009; Fahimnia *et al*., 2013a; Brandenburg *et al*., 2014; Farahani *et al*., 2014).

Concerning the planning horizon, several authors highlight the importance of considering multiple time periods in SCND models (Badri *et al*., 2013; Govindan *et al*., 2014; Mota *et al*., 2015; Zhang *et al*., 2016). For example, Zhang *et al*. (2016) argue that the multiplicity of time periods may address the intrinsic variation of end customer demand, while Badri *et al*. (2013) regard the multiplicity of periods to be essential in capturing realistic dynamic decisions into the related models.

The optimization models that incorporate the multiplicity of decisions discussed above are, obviously, of high complexity, especially when they are applied to practical cases. Eskandarpour *et al*. (2015) identified the limitations of solvers to address such realistic practical cases and to arrive to exact solutions within reasonable computational times.

In Table 1, we present literature on deterministic SCND addressing some of the important issues mentioned above. In terms of the objective function, most references of Table 1 pursue total cost minimization (11 out of 15). Profit maximization and multi-objective models have received less attention, although such concerns may be more relevant to practice. Regarding transportation, six out of 15 references of Table 1 consider multiple transportation paths i.e. direct transportation from manufacturer to customer and indirect transportation through a distribution center, and only three out of 15 have discussed transportation types/modes e.g. unimodal and multimodal transport. Limited attention has also been given to production decisions, plant capacity expansion, idle production time and production or warehousing subcontracting decisions, as also pointed out in the aforementioned literature surveys.

A characteristic example of a comprehensive SCND model is the one proposed by Martel (2005). It is a mixed integer programming model that maximizes the profit after tax and is solved by commercial solvers. The model describes a multi-echelon network in a multi-period context in which demand for multiple products varies per time period. Note that in multi-echelon problems, such as the one considered by Martel, appropriate constraints ensure the balance between inbound and outbound flows (Ghiani *et al.*, 2004). The critical issues of aggregate BoM structures and capacity are also taken into consideration. The model involves design decisions only at the beginning of the planning horizon, and considers operational decisions during multiple periods comprising this horizon. Although Martel (2005) refers to transportation economies of scale, the author assumes for simplicity that transportation costs are linear.

Table 1 Key features of SCND models in recent literature

	Obj. Function	Model breadth								Production Decisions						Distribution Decisions				
	Min Cost Max Profit Multiple Obj.	Multiple periods	Multiple products	Multiple suppliers	Multiple plants	Multiple DCs	Multiple customers	Multiple transportation types/ modes	Multiple transportation paths	BoM	Plant establishment decisions	Capacity decisions per department	Plant workforce decisions	Plant idle capacity considerations	Plant outsourcing decisions	DC establishment decisions	DC capacity decisions	DC workforce decisions	DC idle capacity considerations	DC outsourcing decisions
Yan *et al*., 2003	MC		•	•	•	•	•			•										
Kanyalkar and Adil, 2005	MC	•	•	•	•		•			•										
Martel, 2005	MP	•	•	•	•	•	•		•	•	•	•		•	•	•	•		•	•
Melo *et al*., 2006	MC	•	•	•	•	•	•		•		•					•	•			
Yılmaz and Çatay, 2006	MC	•		•	•	•														
Park *et al*., 2007	MC	•	•	•	•	•														
Thanh *et al*., 2008	MC	•	•	•	•	•	•		•	•	•					•	•			•
Bard and Nananukul, 2009	MC	•					•													
Hamedi *et al*., 2009	MC	•		•	•	•	•		•											
Manzini and Bindi, 2009	MC	•			•	•	•	•												
Cintron *et al*., 2010	MO				•	•	•	•	•											
Bashiri *et al*., 2012	MP	•	•	•	•	•	•			•	•					•	•			•
Fahimnia *et al*., 2012	MC	•	•		•	•	•		•						•					
Badri *et al*., 2013	MP	•	•	•	•	•	•			•	•	•				•	•			•
Fahimnia *et al*., 2013b	MC	•	•	•	•	•	•			•										
Sadrnia *et al*., 2013	MO			•	•	•	•	•		•										
Govindan *et al*., 2014	MO	•			•	•	•	•	•			•								
Mota *et al*., 2015	MO	•	•	•	•	•	•	•	•	•										
Zakeri *et al*., 2015	MC	•	•		•	•	•	•	•											
Zhang *et al*. 2016	MC		•	•	•	•	•			•										
The proposed model	MC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

The current paper proposes a mixed integer linear programming (MILP) model that incorporates all important SCN characteristics presented in Table 1 in an attempt to support strongly integrated decision making. Thus our contribution arises from addressing the identified gaps in the literature, in two major areas.

The first concerns the completeness of the model, which captures multiple (a) time periods, (b) products, (c) facilities, i.e. manufacturing plants and distribution centers, (d) players, i.e. customers, and suppliers, (e) transportation types and modes and multimodal transport, and (f) transportation paths. The model also captures critical aspects of manufacturing, such as product Bill of Materials (BoMs) and production macro-routings along with the associated set up and production times. These aspects strongly affect the SCN architecture.

The second contribution area concerns the comprehensive set of SCN design (or re-design) decisions supported by the proposed model. For each time period of the planning horizon these decisions concern: (a) establishing, expanding or closing facilities (production departments in plants, or distribution centers), (b) allocating production to these plants, and inventory to the distribution centers, (c) subcontracting operations (production or logistics), (d) adjusting the workforce size, (e) selecting transportation modes and routes. All these decisions are made in an integrated manner, fully recognizing their interrelated nature.

An additional contribution of the current work is in line with the view of Eskandarpour *et al*., (2015) that "SCND is the meeting point of the academic facility location problem and the real-life SCND problem". Specifically, we applied the proposed model to a large practical case of a global manufacturer of commercial refrigerators in order to re-design the company’s SCN. Despite the high complexity of

this case, exact solutions are obtained by a commercial solver, and the resulting optimal network is compared to the current network of the manufacturer. Furthermore, we analyzed the resulting network with respect to key factors, such as the geographical distribution of suppliers, plants and DCs, the main SC costs, and the modal split of transportation. The findings of this analysis can be an effective tool for industry practitioners, supporting their strategic SCND decisions in obtaining robust architectures that may be robust in potential changes in key SC parameters.

The remainder of this paper is organized as follows: Section 2 defines the problem and discusses the related assumptions. Section 3 presents the integrated optimization model. The ability of the model to address successfully complex, integrated cases is validated by applying it to the major practical case presented in Section 4. Analysis of the impact of variations on key SCN characteristics is also included in this Section. Finally, conclusions and future research opportunities are discussed in Section 5.

2 Problem description and justification

Consider the problem faced by a manufacturing firm in designing (or transforming) its SCN over a certain, typically long, planning horizon. The network comprises suppliers, manufacturing plants, distribution centers and customers as well as transportation links (see Fig. 1). The firm aims to satisfy forecasted (deterministic) demand for its products, while minimizing associated costs. The problem parameters and related decisions are discussed below.

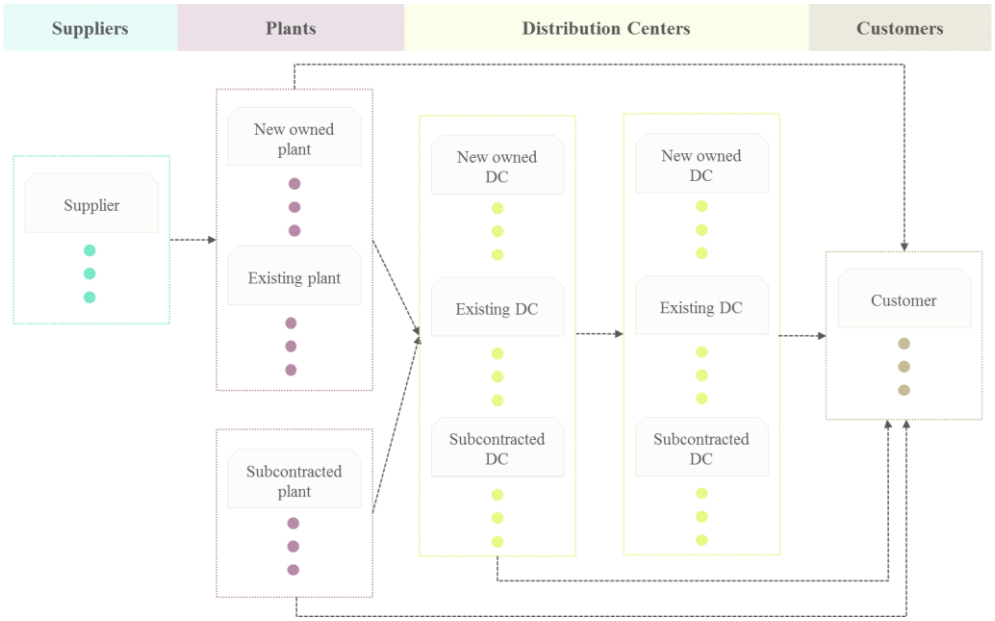


Figure 1 Graphical representation of a typical SCN

Products and Bill of Materials

At this strategic level, products are aggregated into families, each comprising products with the same manufacturing characteristics. Each product family is characterized by an aggregate Bill of Materials (BoM), which specifies the raw material types (or raw material families) required to produce it, as well as the related quantities. For example, consider a family of open commercial refrigerators. This may comprise products, such as 300 lt and 500 lt open refrigerators, which are produced using like raw materials, and production processes.

The items of the (aggregate) BoM of each product family may be procured from one or more suppliers at the specified quantities.

Manufacturing plants and production routings

The products comprising the product families are manufactured either by new (owned by the firm) plants, existing (owned by the firm) plants, or by subcontractors. Note that hereafter we will use the term owned plants for both new and existing plants owned by the firm.

Each owned plant may produce certain product families depending on the manufacturing departments available in the plant. Each product family is manufactured following a certain macro-routing, which specifies the sequence of macro-operations, each performed in a manufacturing department of the plant's shop floor. The macro-routing also specifies the related set up and run times (per macro-operation/department). Note that a manufacturing department is an aggregation of production resources with similar manufacturing characteristics. Continuing the refrigerator manufacturing example, the assembly department assembles the final refrigerator using a set of departmental resources. The macro-routing for the refrigerator product family mentioned above may also include the metal, glass, plastic and paint departments.

The capacity of each department in an existing owned manufacturing plant is given, and may be expanded at an investment cost. Investment costs are also considered for the establishment of new owned plants, and are related to the type and size (capacity) of their constituent departments. In the proposed framework, the investment cost (establishment cost for a new plant and expansion cost for an existing plant) is accounted for by considering the depreciation cost corresponding to each period of the problem. This allows the model to treat the option of establishing new plants or expanding existing ones, without considering the entire investment cost within the problem's time horizon, and (indirectly) allowing any new investments to hold an appropriate value at the end of this horizon.

Furthermore, each manufacturing department in a firm's owned plant employs a certain number of direct labor staff that is adjusted according to production needs. Thus, we distinguish the department's equipment capacity from the department's

labor capacity. The former concerns the availability of the department in equipment time per period, and the latter concerns the availability of department staff in labor time per period. If a department is not utilized up to its capacity, then labor and equipment idle costs are considered. Note that the labor idle cost comes from the payroll costs of idle workers, while the equipment idle costs come from the opportunity costs of idle equipment.

Subcontractor plants may undertake the production of a number of product families, if this is preferable. For subcontractor plants, workforce size (and thus labor capacity), as well as equipment capacity are not considered.

Distribution channels and warehousing

Product families can be distributed through different channels. Channel type 1 is a direct channel that contains three stages between the shipper and the consignee, that is, the supplier, the manufacturer and the customer. Channel types 2 and 3 are indirect channels including intermediaries between manufacturer and end customer, such as one or two Distribution Centers (DCs).

Thus, a DCs (existing, new, or subcontracted) may receive products form manufacturing plants and from other distribution centers. As before we will use the term owned DCs for both new and existing DCs that are owned by the firm under consideration. We consider that owned DCs may store up to a maximum number of unit loads (e.g. pallets) of final products. This capacity may be expanded if necessary at an appropriate investment cost, which is defined through the depreciation cost per period of the time horizon. If a DC is not utilized up to its capacity, then idle costs are also considered (both labor idle cost and opportunity cost for empty warehousing

space). Note that the number of products carried in a unit load (e.g. pallet) is, in general, different per product family.

Workforce sizing is considered in the firm's owned DCs but not in third party ones, which provide warehousing services.

Transportation

Regarding transportation, there are no capacity considerations; supply matches demand. Transportation demand is quantified by unit loads (e.g. pallets) of a certain product/raw material family within a certain time period. Since the number of units of each product and raw material family per unit load (e.g. pallet) is given, the transportation cost between two nodes per transportation type may be defined either per unit load or per unit of product/ raw material family.

Product and raw material families can be transported by a variety of ways depending on the available types of transportation between the origin and destination. Specifically, transportation by truck includes two types; less than truck load (LTL) and full truck load (FTL) (Goetschalckx, 2011). Regarding rail services, the full train load (FTL) type is related to a shipper using all cars of a train (the number depends on the train type), while less than train load (LTL) is related to occupying one or more cars but not the entire train (Wieser *et al*., 2012). In sea transport, transportation types include full container load (FCL) or less than container load (LCL) (Van Eijs, 1994). Finally, a multimodal operation comprises a number of unimodal stages of transport, such as road, rail, sea or air. The initial and final legs in multimodal transportation are typically carried out by truck. The transportation types considered in the current model are provided in Table 2.

Table 2 Transportation types considered in the model

Types of transport	Truck	Rail	Sea

		LTL	FTL	LTL	FTL	LCL	FCL
Unimodal	Type 1 (T_L)	•					
	Type 2 (T_F)		•				
	Type 3 (R_L)			•			
	Type 4 (R_F)				•		
Multimodal	Type 5 (T_L&R_L)	•		•			
	Type 6 (T_F&R_L)		•	•			
	Type 7 (T_F&R_F)		•		•		
	Type 8 (T_L&S_L)	•				•	
	Type 9 (T_F&S_L)		•			•	
	Type 10 (T_F&S_F)		•				•
	Type 11 (R_L&S_L)			•		•	
	Type 12 (R_L&S_F)			•			•
	Type 13 (R_F&S_F)				•		•
	Type 14 (T_L&R_L&S_L)	•		•		•	
	Type 15 (T_F&R_L&S_L)		•	•		•	
	Type 16 (T_F&R_L&S_F)		•	•			•
	Type 17 (T_F&R_F&S_F)		•		•		•

Customer demand

We consider product family demand per time period and per customer. Customers may include retail outlets, retailer distribution centers, wholesalers, etc. No late deliveries are allowed.

Key SC design decisions

The decisions to be made in an integrated manner to design (or transform) the SCN, while satisfying fully the forecasted demand, include the following per time period of the planning horizon:

(a) Which existing plants and DCs should be used and at what level? Note that in the case of manufacturing plants, the level of utilization is considered at the department level per plant. Furthermore, expansion of a department's capacity for an existing plant is possible at an appropriate cost. So is the expansion of an existing DC.

(b) Where to establish new manufacturing plants and of what capacity per department?

(c) Where to establish new DC and of what capacity?

(d) What is the appropriate number of employees of a department in an owned plant or of an owned DC?

(e) Which supplier should be selected (among alternative ones)?

(f) Which are the appropriate manufacturing/ logistics subcontractors to collaborate with, and to what extent?

(g) Which transportation modes should be utilized, including intermodal transport, and at what level?

(h) Which transportation routes should be followed?

3 Problem formulation and validation

In Section 3.1 we propose a mathematical model that optimizes support making the above decisions in order to optimize cost, using the entities and relationships described in Section 2. Due to the complexity of the proposed model, a series of validation tests have been performed as described in Section 3.2.

3.1 Problem formulation

The SCN is represented by a typical oriented multigraph, $G = (N, A)$, where N is the set of nodes and A is the set of arcs between these nodes. The sets, parameters, and decision variables of the proposed model are defined below.

Sets

▪ **Sets of nodes**	
Suppliers	S: Set of possible suppliers

Plants	$\widetilde{M}$: Set of existing owned plants
	$\widehat{M}$: Set of possible new owned plants
	$\breve{M}$: Set of possible subcontractor plants
	$M = \widetilde{M} \cup \widehat{M} \cup \breve{M}$
Plant department types	W: Set of possible types of departments in an owned plant
Distribution centers	$\widetilde{D}$: Set of existing owned distribution centers
	$\widehat{D}$: Set of possible new owned distribution centers
	$\breve{D}$: Set of possible subcontractor distribution centers
	$D = \widetilde{D} \cup \widehat{D} \cup \breve{D}$
Customers	C: Set of customers
Set of nodes	$N = M \cup D \cup C$

- **Other sets**

Products/ Raw materials	F: Set of product families; each family comprises products with similar manufacturing characteristics
	Θ: Set of raw material families; each family comprises raw materials with similar characteristics
	Θ^f: Set of raw material families related to product family $f \in F$. $\Theta^f \subseteq \Theta$
Time periods	$T = \{1,2, \dots, \tilde{t}\}$: Set of time periods.
Transportation types	R: Set of types of transportation types
	R_i: Set of types of transportation types available at node $i \in N$, $R_i \subseteq$ R

- **Sets of arcs**

Arc set	$A = \{(i,j) \mid i \in S, j \in \widehat{M} \cup \widetilde{M}\} \cup \{(i,j) \mid i \in M, j \in D \cup C\} \cup \{(i,j) \mid i \in D, j \in D \cup C \setminus \{i\}\}$
	$\bar{A} = \{(i,j,r) \mid (i,j) \in A, r \in R_i \cap R_j\}$ where $r \in R_i \cap R_j$ are the transportation types serving origin i and destination j

Parameters

Definition: The term *working time units per period* is used to define: (a) the labor input of staff per time period (i.e. an employee is available x hours per quarter of a year), and (b) the capacity of a department per time period (i.e. a department is available y hours per quarter of a year). This definition applies to many parameters below.

▪ **Costs**	
Supplier costs	κ_i^{θ}: Procurement cost per unit of raw material family $\theta \in \Theta$ related to supplier $i \in S$
Manufacturing costs	γ_i^{w}: Depreciation cost per unit of capacity per period (expressed in working time units, e.g. working hours) related to department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$
	σ_i^{f}: Set up cost for product family $f \in F$ when this is manufactured in owned plant $i \in \widehat{M} \cup \widetilde{M}$. The set up cost is the product of the direct labor cost rate multiplied by the cumulative set up time of a representative product in family f. This cost may be also enhanced by the appropriate overhead costs depending on the accounting practices followed
	β_i^{f}: Production cost (associated with run time) for product family $f \in F$ when it is manufactured in owned plant $i \in \widehat{M} \cup \widetilde{M}$. The production cost is the product of the direct labor cost rate by the cumulative production/run time of a representative product in family f. Again, this cost may be enhanced by the appropriate overhead costs
	λ_i^{w}: Idle equipment cost per unit of capacity per period (expressed in working time units, e.g. working hours) of department $w \in W$ in owned plant $i \in \widehat{M} \cup \widetilde{M}$
	u_i: Idle labor cost per unit of capacity per period (expressed in working time units, e.g. working hours) of department $w \in W$ in owned plant $i \in \widehat{M} \cup \widetilde{M}$
	f_i: Severance cost per dismissed employee associated with owned plant $i \in \widehat{M} \cup \widetilde{M}$
	h_i: Recruitment cost per new hire associated with owned plant $i \in \widehat{M} \cup \widetilde{M}$
	v_i^{f}: Subcontracting cost per unit of product family $f \in F$ for subcontractor

	plant $i \in \breve{M}$
Distribution costs	$\bar{\gamma}_i$: Depreciation cost per unit of storage (expressed in units of area e.g. m^2) and time period of owned distribution center $i \in \hat{D} \cup \tilde{D}$
	v_i^f: Inventory cost per unit of product family $f \in F$ and time period related to owned distribution center $i \in \hat{D} \cup \tilde{D}$
	$\bar{\lambda}_i$: Idle unit cost per unit of capacity (expressed in units of area e.g. m^2) and time period of owned distribution center $i \in \hat{D} \cup \tilde{D}$
	$\bar{u}_i$: Idle labor cost per unit of capacity (expressed in units of area e.g. m^2) and time period of owned distribution center $i \in \hat{D} \cup \tilde{D}$
	$\bar{f}_i$: Severance cost per dismissed employee associated with owned distribution center $i \in \hat{D} \cup \tilde{D}$
	$\bar{h}_i$: Recruitment cost per new hire associated with owned distribution center $i \in \hat{D} \cup \tilde{D}$
	$\bar{v}_i^f$: Subcontracted warehousing cost per unit of product family $f \in F$ and time period related to subcontracted distribution center $i \in \breve{D}$
Transportation costs	$\tau_{ijr}^f, \{((i,j),r) \mid (i,j) \in \bar{A}, i \in M \cup D, r \in R_i \cap R_j, f \in F\}$: Transportation cost per unit of product family $f \in F$ from node i to node j by transportation type r
	$\mu_{ijr}^{\theta}, \{((i,j),r) \mid (i,j) \in \bar{A}, i \in S, r \in R_i \cap R_j, \theta \in \Theta\}$: Transportation cost per unit of raw material family $\theta \in \Theta$ from node i to node j by transportation type r
▪ **Capacities**	
Supplier capacity	$a_i^{\theta t}$: Maximum number of raw material units of family $\theta \in \Theta$ provided by supplier $i \in S$ in time period $t \in T$
Manufacturing capacity	$\hat{\delta}_i^w$: Initial capacity in working time units per period of department $w \in W$ related to owned plant $i \in \hat{M} \cup \tilde{M}$ at the beginning of the time horizon. In case of a new plant $i \in \hat{M}$, this parameter equals to zero
	$\hat{c}_i^{ft}$: Maximum number of products of family $f \in F$ provided by subcontractor $i \in \breve{M}$ in time period $t \in T$
	H: Number of working time units an employee is available to work per time

	period
Distribution capacity	$\hat{\rho}_i$: Initial capacity of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ (expressed in units of area e.g. m^2) at the beginning of the time horizon. In case of a new owned distribution center, $i \in \widehat{D}$, this parameter equals to zero
	$\hat{q}_i^t$: Available capacity of subcontractor distribution center $i \in \check{D}$ (expressed in units of area e.g. m^2) at time period $t \in T$
	E: Number of employees required per unit of capacity (expressed in units of area e.g. m^2)of a distribution center

- **Time**

Manufacturing time	U_f^w: Production time in working time units required to process a unit of product family $f \in F$ in department $w \in W$
	Y_f^w: Set up time in working time units per time period required to process product family $\in F$ in department $w \in W$. Note that at this strategic level if a department will process a certain product family within a certain period, then the number of set ups within this period is considered to be fixed (e.g. z set ups per quarter of a year) based on current department practice. Thus, Y_f^w is the total set up time per period for this fixed number of set ups

- **Products**

Customer demand	d_i^{ft}: Number of products of family $f \in F$ required by customer $i \in C$, at time period $t \in T$
BoM	Q_f^θ: Quantity (in units of measure) of raw material family $\theta \in \Theta^f$ required to produce one unit of product family $f \in F$
Level of safety stock	S_f: Level of safety stock of product family $f \in F$ as a percentage of the total demand. It depends on the inventory management policy applied by the company, and is used in the strategic model as input in order to size the appropriate warehousing needs. Note also that in the strategic model it is useful to determine the inventory held at the end of each period to serve the needs of the next period.
Unit load	K^f: Number of products of family $f \in F$ that can be carried in a unit load (e.g. m^2)

	Λ^{θ}: Number of raw materials of family $\theta \in \Theta$ that can be carried in a unit load
Transport lower bound	l_r: Lower bound in number of unit loads (e.g. m^2) per transportation type $r \in R$ per time period. Below this lower bound it is not considered financially viable to use the related transportation type
Decision variables	
Manufacturing facilities	φ_i^t: Binary variable that is equal to 1 if new owned plant $i \in \widehat{M}$ is established at time period $t \in T$ (if so this plant remains available thereafter); otherwise φ_i^t is equal to zero
	δ_i^{wt}: Expansion of production capacity (in working time units per period) of department $w \in W$ related to owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$ (Department capacity either remains invariable or increases)
	ε_i^{wt}: Total production capacity (initial and expanded) in working time units of department $w \in W$ related to owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$
	ψ_i^{ft}: Binary variable that is equal to 1 if owned plant $i \in \widehat{M} \cup \widetilde{M}$ manufactures product family $f \in F$ at time period $t \in T$; otherwise it is equal to zero
	ζ_i^{ft}: Quantity of product family $f \in F$ that each plant $i \in M$ manufactures at time period $t \in T$
	θ_i^{wt}: Number of labor staff in department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$. We also define parameter $\theta_i^{w0} = \left\lceil \frac{\hat{\delta}_i^w}{H} \right\rceil$, to represent the initial workforce at department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$
	ι_i^{wt}: Number of dismissed employees related to department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at the beginning of time period $t \in T$
	η_i^{wt}: Number of hired employees related to department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at the beginning of time period $t \in T$
	ξ'^{wt}_i: Labor idle capacity in working time units of department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$
	ξ_i^{wt}: Equipment idle capacity in working time units of plant department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$

Distribution facilities	$\bar{\varphi}_i^t$: Binary variable that is equal to 1 if new owned distribution center $i \in \widehat{D}$ is established at time period $t \in T$ (if so this DC remains available thereafter); otherwise it is equal to zero
	$\bar{\delta}_i^t$: Expansion of storage capacity (expressed in units of area e.g. m^2) related to owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$ (DC capacity either remains invariable or increases)
	$\bar{\varepsilon}_i^t$: Total storage capacity (existing and extension expressed in units of area e.g. m^2) related to owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$
	$\bar{\psi}_i^t$: Binary variable that is equal to 1 if owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ is operational at time period $t \in T$; otherwise is equal to zero
	π_i^{ft}: Inventory of product family $f \in F$ that distribution center $i \in D$ holds at time period $t \in$ T. We also define $\pi_i^{f0} = 0, i \in D, f \in F$ to be the initial inventory in distribution center $i \in D$ for product family $f \in F$
	$\bar{\theta}_i^t$: Number of employees of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$. We also define parameter $\bar{\theta}_i^0 = \hat{\rho}_i \cdot E, i \in \widehat{D} \cup \widetilde{D}$ to be the initial workforce number at owned new or existing distribution center $i \in D$
	$\bar{\iota}_i^t$: Number of dismissed employees of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at the beginning of time period $t \in T$
	$\bar{\eta}_i^t$: Number of hired employees of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at the beginning of the time period $t \in T$
	$\overline{\xi'}_i^t$: Labor idle capacity (expressed in units of area e.g. m^2) of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$ – note that the idle capacity in terms of staff members is $\overline{\xi'}_i^t$/E
	$\bar{\xi}_i^t$: Facility idle capacity (expressed in units of area e.g. m^2) of owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$
Transportation types	y_{ijr}^t: Binary variable that is equal to 1 if transportation type *r* is operated along arc $(i, j) \in A$ at time period $t \in T$
	χ_{ijr}^{ft}: Quantity of products of family $f \in F$ being transferred by transportation type

	r through arc $\{(i,j) \in A \mid i \in M \cup D\}$ at time period $t \in T$
	$\omega_{ijr}^{\theta t}$: Quantity of raw material family $\theta \in \Theta$ being transferred by transportation type r through arc is $\{(i,j) \in A \mid i \in S\}$ at time period $t \in T$

The mathematical formulation of the proposed SCND model is presented below.

Objective function (1) minimizes total investment and operational costs, over the entire time horizon. Total cost comprises the following parts: (a) cost of depreciation related to owned plants ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{w\in W}\sum_{t\in T}\gamma_i^w\cdot\varepsilon_i^{wt}$), (b) cost of depreciation related to owned distribution centers ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{t\in T}\bar{\gamma}_i\cdot\bar{\varepsilon}_i^t$), (c) procurement cost of raw materials ($\sum_{\{(i,j,r)\in\bar{A}\mid i\in S\}}\sum_{\theta\in\Theta}\sum_{t\in T}\kappa_i^\theta\cdot\omega_{ijr}^{\theta t}$), (d) set up costs in owned plants ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{f\in F}\sum_{t\in T}\sigma_i^f\cdot\psi_i^{ft}$), (e) production (run time) costs in owned plants ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{f\in F}\sum_{t\in T}\beta_i^f\cdot\zeta_i^{ft}$), (f) severance ($\sum_{\epsilon\hat{M}\cup\tilde{M}}\sum_{w\in W}\sum_{t\in T}f_i\cdot\iota_i^{wt}$) and (g) recruitment ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{f\in F}\sum_{t\in T}h_i\cdot\eta_i^{wt}$) costs related to employees of owned plants, (h) labor ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{f\in F}\sum_{t\in T}\upsilon_i\cdot\xi'^{wt}_i$) and, (i) equipment ($\sum_{i\in\hat{M}\cup\tilde{M}}\sum_{w\in W}\sum_{t\in T}\lambda_i^w\cdot\xi_i^{wt}$) idle capacity costs related to owned plants, (j) subcontracting manufacturing cost ($\sum_{i\in\check{M}}\sum_{f\in F}\sum_{t\in T}\upsilon_i^f\cdot\zeta_i^{ft}$), (k) inventory cost in owned distribution centers ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{f\in F}\sum_{t\in T}\nu_i^f\cdot\pi_i^{ft}$), (l) severance ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{t\in T}\bar{f}_i\cdot\bar{\iota}_i^t$) and (m) recruitment ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{t\in T}\bar{h}_i\cdot\bar{\eta}_i^t$) costs related to employees of owned distribution centers, (n) labor ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{t\in T}\bar{\upsilon}_i\cdot\bar{\xi}'^t_i$) and (o) facility ($\sum_{i\in\hat{D}\cup\tilde{D}}\sum_{t\in T}\bar{\lambda}_i\cdot\bar{\xi}_i^t$) idle capacity costs related to owned distribution centers, (p) subcontracting warehousing cost ($\sum_{i\in\check{D}}\sum_{f\in F}\sum_{t\in T}\bar{\upsilon}_i^f\cdot\pi_i^{ft}$), (q) transportation cost of final products ($\sum_{\{(i,j,r)\in\bar{A}\mid i\in M\cup D\}}\sum_{f\in F}\sum_{t\in T}\tau_{ijr}^f\cdot\chi_{ijr}^{ft}$), (r) transportation cost of raw materials ($\sum_{\{(i,j,r)\in\bar{A}\mid i\in S\}}\sum_{\theta\in\Theta}\sum_{t\in T}\mu_{ijr}^\theta\cdot\omega_{ijr}^{\theta t}$); i.e.:

$$
\begin{aligned}
min \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{w\in W}\sum_{t\in T}\gamma_i^w\cdot\varepsilon_i^{wt} + \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{t\in T}\bar{\gamma}_i\cdot\bar{\varepsilon}_i^t + \sum_{\{(i,j,r)\in\bar{A}|i\in S\}}\sum_{\theta\in\Theta}\sum_{t\in T}\kappa_i^\theta\cdot\omega_{ijr}^{\theta t} \\
+ \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{f\in F}\sum_{t\in T}\sigma_i^f\cdot\psi_i^{ft} + \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{f\in F}\sum_{t\in T}\beta_i^f\cdot\zeta_i^{ft} + \sum_{\in\widehat{M}\cup\widetilde{M}}\sum_{w\in W}\sum_{t\in T}f_i\cdot\iota_i^{wt} \\
+ \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{w\in W}\sum_{t\in T}h_i\cdot\eta_i^{wt} + \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{w\in W}\sum_{t\in T}v_i\cdot\xi'^{wt}_i + \sum_{i\in\widehat{M}\cup\widetilde{M}}\sum_{w\in W}\sum_{t\in T}\lambda_i^w\cdot\xi_i^{wt} \\
+ \sum_{i\in\widehat{M}}\sum_{f\in F}\sum_{t\in T}v_i^f\cdot\zeta_i^{ft} + \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{f\in F}\sum_{t\in T}\nu_i^f\cdot\pi_i^{ft} + \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{t\in T}\bar{f}_i\cdot\bar{\iota}_i^t \\
+ \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{t\in T}\bar{h}_i\cdot\bar{\eta}_i^t + \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{t\in T}\bar{v}_i\cdot\bar{\xi}'^t_i + \sum_{i\in\bar{D}\cup\tilde{D}}\sum_{t\in T}\bar{\lambda}_i\cdot\bar{\xi}_i^t + \sum_{i\in\bar{D}}\sum_{f\in F}\sum_{t\in T}\bar{v}_i^f\cdot\pi_i^{ft} \\
+ \sum_{\{(i,j,r)\in\bar{A}|i\in M\cup D\}}\sum_{f\in F}\sum_{t\in T}\tau_{ijr}^f\cdot\chi_{ijr}^{ft} + \sum_{\{(i,j,r)\in\bar{A}|i\in S\}}\sum_{\theta\in\Theta}\sum_{t\in T}\mu_{ijr}^\theta\cdot\omega_{ijr}^{\theta t}
\end{aligned}
\tag{1}
$$

The constraints of the proposed model are presented in groups as follows:

Supplier capacity

Constraints (2) ensure that the procurement of raw material family $\theta \in \Theta$ from supplier $i \in S$ at time period $t \in T$ cannot exceed the supplier's capacity during the same period.

$$
\sum_{(j,r)|(i,j,r)\in\bar{A}} \omega_{ijr}^{\theta t} \le a_i^{\theta t}, \quad i \in S, \theta \in \Theta, t \in T \tag{2}
$$

Material requirements

Constraints (3) ensure that the quantity $\omega_{ijr}^{\theta t}$ of raw material family $\theta \in \Theta^f$ shipped from all suppliers to owned plant $j \in \widehat{M} \cup \widetilde{M}$ by any transportation type $r \in R$ equals the quantity required to manufacture the final products of product family $f \in F$ in plant j, during time period $t \in T$. The JIT procurement assumption is in effect here.

$$\sum_{(i,r)|(i,j,r)\in\bar{A}} \omega_{ijr}^{\theta t} = \sum_{f\in F|(\theta\in\Theta f)} Q_f^{\theta} \cdot \zeta_j^{ft},\ j \in \widehat{M} \cup \widetilde{M}, \theta \in \Theta, t \in T \qquad (3)$$

Demand

Constraints (4) ensure that the cumulative production of product family $f \in F$ by all plants $i \in M$ until time period $t \in T$ must be equal to or greater than the cumulative demand for this product family by all customer nodes $j \in C$ until the same period.

$$\sum_{i\in M}\sum_{b=1}^{t} \zeta_i^{fb} \geq \sum_{j\in C}\sum_{b=1}^{t} d_j^{fb},\ f \in F, t \in T \qquad (4)$$

Demand and continuity

Constraints (5) ensure no early shipping; that is, the quantity of product family $f \in F$ shipped to each $j \in C$ from every node $i|(i,j) \in A$ by any transportation type $r \in R$ equals to the related demand of node $j \in C$, at each time period $t \in T$. Constraints (6) ensure shipping upon production (to a distribution center or a customer); that is, at each time period $t \in T$ the product quantity of family $f \in F$ shipped from an owned plant $i \in \widehat{M} \cup \widetilde{M}$ equals to the product quantity of $f \in F$ that owned plant $i \in \widehat{M} \cup \widetilde{M}$ produced.

$$\sum_{(i,r)|(i,j,r)\in\bar{A}} \chi_{ijr}^{ft} = d_j^{ft},\ j \in C, f \in F, t \in T \qquad (5)$$

$$\zeta_i^{ft} = \sum_{(j,r)|(i,j,r)\in\bar{A}} \chi_{ijr}^{ft},\ i \in \widehat{M} \cup \widetilde{M}, f \in F, t \in T \qquad (6)$$

Plants and plant capacities

Constraints (7) ensure new owned plant $i \in \widehat{M}$ can be established at the candidate location at most once. Constraints (8) ensure that each plant operates on or after its time of establishment. Constraints (9) define the total production capacity of plant's department $w \in W$ related to owned plant $i \in \widehat{M} \cup \widetilde{M}$ in working time units at time period $t \in T$.

$$\sum_{t \in T} \varphi_i^t \leq 1\,,\ i \in \widehat{M} \tag{7}$$

$$\sum_{b=1}^{t} \varphi_i^b \geq \psi_i^{ft},\ i \in \widehat{M}, f \in F, t \in T \tag{8}$$

$$\varepsilon_i^{wt} = \sum_{b=1}^{t} \delta_i^{wt} + \hat{\delta}_i^w,\ i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \tag{9}$$

Production and production time

Constraints (10) ensure that any production requires set up, assuming that B≫1. Constraints (11) ensure that required set up and production time in department $w \in W$ of owned plant $i \in \widehat{M} \cup \widetilde{M}$ at time period $t \in T$ cannot exceed this department's capacity at the same period. Constraints (12) define the department's idle capacity.

$$\zeta_i^{ft} \leq B \cdot \psi_i^{ft},\ i \in \widehat{M} \cup \widetilde{M}, f \in F, t \in T \tag{10}$$

$$\sum_{f \in F} (U_f^w \cdot \zeta_i^{ft} + Y_f^w \cdot \psi_i^{ft}) \leq \varepsilon_i^{wt},\ i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \tag{11}$$

$$\varepsilon_i^{wt} - \sum_{f \in F} (U_f^w \cdot \zeta_i^{ft} + Y_f^w \cdot \psi_i^{ft}) = \xi_i^{wt},\ i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \tag{12}$$

Workforce

Constraints (13) define the variation of the workforce level in each department of an owned plant. Constraints (14) define the labor idle capacity (always non negative) that is related to department $w \in W$ of new owned plant $i \in \widehat{M}$ at time period $t \in T$.

$$\theta_i^{wt} = \theta_i^{wt-1} - \iota_i^{wt} + \eta_i^{wt},\ i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \tag{13}$$

$$H \cdot \theta_i^{wt} - \sum_{f \in F} (U_f^w \cdot \zeta_i^{ft} + Y_f^w \cdot \psi_i^{ft}) = \xi'^{wt}_i,\ i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \tag{14}$$

Subcontracting production

Constraints (15) ensure that outsourced production of product family $f \in F$ at time period $t \in T$ cannot exceed the subcontracting plant's capacity at the same period. Constraints (16) ensure that cumulative production related to each subcontractor plant $i \in \check{M}$ until time period $t \in T$ must not exceed the cumulative quantity of product family $f \in F$ shipped from plant $i \in \check{M}$ until this time period.

$$\zeta_i^{ft} \leq \hat{c}_i^{ft},\ i \in \check{M}, f \in F, t \in T \tag{15}$$

$$\sum_{b=1}^{t} \zeta_i^{fb} \geq \sum_{(j,r)|(i,j,r) \in \bar{A}} \sum_{b=1}^{t} \chi_{ijr}^{fb},\ i \in \check{M}, f \in F, t \in T \tag{16}$$

Inventory levels and continuity

Constraints (17) guarantee the safety stock for each product family $f \in F$ at each time period $t \in T$. Constraints (18) define the variation of inventory related to each distribution center $i \in D$ for product family $f \in F$ at time period $t \in T$.

$$\sum_{i \in D} \pi_i^{ft} \geq S_f \cdot \sum_{j \in C} d_j^{ft},\ f \in F, t \in T \tag{17}$$

$$\pi_i^{f(t-1)} + \sum_{(k,r)|(k,i,r)\in\bar{A}} \chi_{kir}^{ft} - \sum_{(j,r)|(i,j,r)\in\bar{A}} \chi_{ijr}^{ft} = \pi_i^{ft},\ i \in D, f \in F, t \in T \quad (18)$$

Warehousing

Constraints (19) ensure that a new distribution center $i \in \widehat{D}$ can be established at the candidate location at most once. Constraints (20) and (21) ensure that this DC operates on and after the time of its establishment. Constraints (21) define the warehousing operations (store or ship products) related to each owned distribution center $i \in \widehat{D} \cup \widetilde{D}$. Constraints (22) define the total capacity (existing and extension) in unit loads related to owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$. Constraints (23) ensure that the total inventory in unit loads related to owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$ cannot exceed its total capacity at the same period. Constraints (24) define the warehouse idle capacity (always non negative) related to owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$. Constraints (25) define the variation of workforce at each owned distribution center. Constraints (26) define the labor idle capacity in unit loads (always non negative) related to each owned distribution center $i \in \widehat{D} \cup \widetilde{D}$ at time period $t \in T$. Constraints (27) ensure that inventory level at each subcontractor distribution center $i \in \check{D}$ at time period $t \in T$ cannot exceed its capacity at the same period.

$$\sum_{t \in T} \bar{\varphi}_i^t \leq 1, \; i \in \widehat{D} \tag{19}$$

$$\sum_{b=1}^{t} \bar{\varphi}_i^t \geq \bar{\psi}_i^t, \; i \in \widehat{D}, t \in T \tag{20}$$

$$\sum_{(j,r)|(i,j,r) \in \bar{A}} \sum_{f \in F} (\chi_{ijr}^{ft} + \pi_i^{ft}) \leq B \cdot \bar{\psi}_i^t, \; i \in \widehat{D} \cup \widetilde{D}, f \in F, t \in T \tag{21}$$

$$\bar{\varepsilon}_i^t = \sum_{b=1}^{t} \bar{\delta}_i^t + \hat{\rho}_i,\ i \in \hat{D} \cup \tilde{D}, t \in T \tag{22}$$

$$\sum_{f \in F} \frac{\pi_i^{ft}}{K^f} \leq \bar{\varepsilon}_i^t,\ i \in \hat{D} \cup \tilde{D}, t \in T \tag{23}$$

$$\bar{\varepsilon}_i^t - \sum_{f \in F} \frac{\pi_i^{ft}}{K^f} = \bar{\xi}_i^t,\ i \in \hat{D} \cup \tilde{D}, f \in F, t \in T \tag{24}$$

$$\bar{\theta}_i^t = \bar{\theta}_i^{t-1} - \bar{\iota}_i^t + \bar{\eta}_i^t,\ i \in \hat{D} \cup \tilde{D},\ t \in T \tag{25}$$

$$\frac{1}{E} \cdot \bar{\theta}_i^t - \sum_{f \in F} \frac{\pi_i^{ft}}{K^f} = \bar{\xi'}_i^t,\ i \in \hat{D} \cup \tilde{D}, t \in T \tag{26}$$

$$\sum_{f \in F} \frac{\pi_i^{ft}}{K^f} \leq \hat{q}_i^t,\ i \in \check{D}, f \in F, t \in T \tag{27}$$

Transportation

The following sets of constraints are used to select the transport type(s) to be used among suppliers, plants, DCs, and customers. The selection depends on the volumes of raw materials or products to be transported and the economies of scale related to each transportation type. This is achieved through decision variable y_{ijr}^t, which takes the value of 1 if type r is used (and 0 otherwise). If $y_{ijr}^t = 1$, then the entire load $\sum_{f \in F} \frac{1}{K^f} \cdot \chi_{ijr}^{ft}$ (or $\sum_{\theta \in \Theta} \frac{1}{\Lambda^\theta} \cdot \omega_{ijr}^{\theta t}$ for raw materials) is transported by transportation type r between nodes i and j. Specifically, constraints (28) and (29) guarantee compliance with the lower bound per transportation type $r \in R$ at time period $t \in T$. The parameters K^f and Λ^θ are conversion factors of quantities to unit loads. Constraints

(30) and (31) allow the use of transportation type $r \in R$. Note that typically more than one shipment takes place between nodes i and j within the same period. The typical number of shipments per time period should be considered when setting the above lower bounds.

$$\sum_{f \in F} \frac{1}{K^f} \cdot \chi_{ijr}^{ft} \geq l_r \cdot y_{ijr}^t, \ (i,j,r) \in \bar{A}, r \in R, t \in T \quad (28)$$

$$\sum_{\theta \in \Theta} \frac{1}{\Lambda^\theta} \cdot \omega_{ijr}^{\theta t} \geq l_r \cdot y_{ijr}^t, \ i \in S, (i,j,r) \in \bar{A}, r \in R, t \in T \quad (29)$$

$$\sum_{f \in F} \frac{1}{K^f} \cdot \chi_{ijr}^{ft} \leq B \cdot y_{ijr}^t, \ (i,j,r) \in \bar{A}, r \in R, t \in T \quad (30)$$

$$\sum_{\theta \in \Theta} \frac{1}{\Lambda^\theta} \cdot \omega_{ijr}^{\theta t} \leq B \cdot y_{ijr}^t, \ (i,j,r) \in \bar{A}, r \in R, t \in T \quad (31)$$

Ranges of Decision Variables

Constraints (32–36) require the related decision variables to be binary. Constraints (37–42) define that all variables relating to labor force $\theta_i^{wt}, \iota_i^{wt}, \eta_i^{wt}, \bar{\theta}_i^t, \bar{\iota}_i^t, \bar{\eta}_i^t, \xi'^{wt}_i, \bar{\xi}_i^t$ belong to the set of non-negative integers. Constraints (43–54) restrict all other decision variables from taking non-negative values.

$$\varphi_i^t \in \{0,1\}, i \in \widehat{M}, t \in T \quad (32)$$

$$\bar{\varphi}_i^t \in \{0,1\}, \ i \in \widehat{D}, \ t \in T \quad (33)$$

$$\psi_i^{ft} \in \{0,1\}, i \in \widehat{M} \cup \widetilde{M}, f \in F, t \in T \quad (34)$$

$$\bar{\psi}_i^t \in \{0,1\}, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (35)$$

$$y_{ijr}^{t} \in \{0,1\}, (i,j,r) \in \bar{A}, t \in T \quad (36)$$

$$\theta_i^{wt} \in \mathbb{N}_0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (37)$$

$$\iota_i^{wt} \in \mathbb{N}_0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (38)$$

$$\eta_i^{wt} \in \mathbb{N}_0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (39)$$

$$\bar{\theta}_i^{t} \in \mathbb{N}_0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (40)$$

$$\bar{\iota}_i^{t} \in \mathbb{N}_0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (41)$$

$$\bar{\eta}_i^{t} \in \mathbb{N}_0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (42)$$

$$\zeta_i^{ft} \geq 0, i \in M, f \in F, t \in T \quad (43)$$

$$\delta_i^{wt} \geq 0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (44)$$

$$\varepsilon_i^{wt} \geq 0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (45)$$

$$\xi_i^{wt} \geq 0, i \in \widehat{M} \cup \widetilde{M}, t \in T \quad (46)$$

$$\xi'^{wt}_i \geq 0, i \in \widehat{M} \cup \widetilde{M}, w \in W, t \in T \quad (47)$$

$$\pi_i^{ft} \geq 0, i \in D, f \in F, t \in \mathrm{T} \quad (48)$$

$$\bar{\delta}_i^{\,t} \geq 0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (49)$$

$$\bar{\varepsilon}_i^{t} \geq 0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (50)$$

$$\bar{\xi}_i^{t} \geq 0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (51)$$

$$\overline{\xi}_i^t \geq 0, i \in \widehat{D} \cup \widetilde{D}, t \in T \quad (52)$$

$$\chi_{ijr}^{ft} \geq 0, \{(i,j,r) \in \bar{A} | \in M \cup D\}, f \in F, t \in T \quad (53)$$

$$\omega_{ijr}^{\theta t} \geq 0, \{(i,j,r) \in \bar{A} \, | i \in S\}, \theta \in \Theta, t \in T \quad (54)$$

3.2 Model Validation

The proposed model was implemented in Mathwork's Matlab 2014b and was solved by the Gurobi optimizer 6.6.0 (Gurobi Optimization Inc., 2014) for Windows 64bit. Model validation and experimental runs used an Intel Core i7 PC with 3.4 GHz processor and 8GB RAM. In order to validate the proposed model and its implementation, we first applied it to a number of focused, relatively simple, cases. These cases progressively tested parts of the model, i.e.:

- the optimal selection of **suppliers**, of **production** facilities among new and existing plants, as well as of production subcontractors during multiple periods
- the optimal selection of **distribution** facilities among new and existing DCs as well as warehousing subcontractors during multiple periods
- the optimal selection of **transportation** types during multiple periods.

In these tests, the problem parameters were set so that the solutions were known in advance. The expected solutions were obtained by the model in all cases. All cases and the corresponding validation test results are presented in Arampantzi and Minis (2016b).

Furthermore, we validated our model with published results of the production/distribution model of Park *et al*. (2007), which addressed some of the aspects of our proposed model (see Case 11 in Arampantzi and Minis, 2016b). This

test case involves 10 suppliers, 10 plants, 10 DCs, 10 products and 10 periods. Table 3 exhibits the average results from 100 repeated experiments. The results indicate that the proposed model may obtain comparable but slightly better average solutions within reasonable time (less than 0.26 sec).

Table 3 Results of applying the proposed model to the most complex problem in Park *et al*. (2007)

	Cost[1]	**Time (sec.)**
The proposed MILP model	6,021,500	0.26
Genetic chromosome algorithm (Park *et al*., 2007)	6,209,590	465
Difference	3%	× 1788 faster[2]

[1] Average of 100 runs [2]Different systems were used

4 Case study

To investigate the applicability and effectiveness of the proposed model, we considered a large case study of an existing global manufacturer of commercial refrigerators. The company owns eight (existing) plants located in Europe, Asia, and the US. Its supply chain network comprises 850 suppliers and 350 customers globally.

All data for the case study were obtained from publicly available sources, mainly from stock exchange reports. Some detailed manufacturing parameters were obtained from the literature (e.g. Braglia *et al.*, 2006). Specifically, from the literature we used information on raw material families, plant departments, set up and production times, the required ratios of employees in DCs, etc. The actual information used and the related assumptions are further described in Arampantzi and Minis (2016a).

The objective of the case study was to re-design (transform) the company's supply chain network over a planning horizon of five years in order to minimize overall supply chain costs, satisfying an assumed demand forecast. To generate this forecast for the first period (year) of the 5-year horizon, we distributed the known total actual

sales among countries in proportion to their GDP, only for those countries in which customers are located. If more than one customer is located in the same country, the estimated sales volume of this country was distributed equally among these customers. For the remaining years of the time horizon, we assumed an annual increase in sales by 1.4% in Europe, 2.9% in the US and by 5.5% in Asia (Global Economic Outlook, 2015).

For this case study the MILP model of Section 3.1 included 25,915 variables and 29,442 constraints; the run time to optimality is approximately 180 sec.

4.1 Importance of re-designing the current supply chain network

In this section, we first analyze the current (*as* is) supply chain network of the manufacturer under consideration. The analysis is also used to calibrate the model of Section 3. Subsequently, the current design is transformed (*to-be*) to optimize the supply chain costs. In both cases we solve the MILP model of (1) to (54) under appropriate conditions as described below.

4.1.1 *As-is* design and model calibration

In addition to the publicly available information, further assumptions were needed in order to set up the existing SCN of the firm under study. These assumptions are overviewed below (and are provided in detail in Arampantzi and Minis, 2016a).

Network

For the SCN, we considered 35 major suppliers, all eight existing plants, the sole existing DC and only major customers, that is, 14 customers that generate 64 % of all sales. The total demand was distributed per customer as mentioned above. All model parameters were scaled proportionally to the above sales activity level.

Products and materials supply

Final products were classified according to the company's own product classification into four refrigerator families. Each product family is characterized by a known BoM. As per the company's classification, there are six raw material families, which are used in the above BoM. As per the published financial information, the costs of the raw materials amount to almost 70% of the respective product family cost. It is worth mentioning that we have assumed 15% lower procurement costs for suppliers in Asia (BCG, 2004).

Manufacturing

The typical manufacturing process comprises five steps: (a) metal, (b) glass, (c) plastic, (d) assembly, and (e) paint. Each of these steps is carried out in a dedicated plant department. We have assumed that department capacities are proportional to the number of department employees. The latter have been determined by the known labor staff in each existing plant and using staff distribution ratios among the departments. These ratios are proportional to the manufacturing time requirements per department (see Arampantzi and Minis, 2016a). No plant expansion has been considered in the *as-is* design.

Each product family is characterized by a macro-routing with appropriate set-up and run times related to the above manufacturing steps. The corresponding times have been inspired by Braglia *et al.* (2006). Labor costs were obtained from various sources (incl. Institut der Deutschen Wirtschaft, 2010 and Global-production Inc., 2014). Concerning workforce mobility issues, we assume that the severance cost per employee equals to one half of a year's salary, and the hiring cost equals to the salary

of a three month period. Depreciation costs per period have been estimated by considering the company's actual depreciation costs per asset class.

Warehousing (and inventory)

We considered the existing major DC of the company and its known capacity. We also assumed that the minimum stock level for each product family equals to 15% of its annual demand. Warehousing costs were defined to include inventory, labor, human resource mobility and idle costs (facility and labor), as well as depreciation costs. Regarding outsourcing, we assumed that inventory keeping costs are 30% higher than total warehousing costs excluding workforce mobility costs.

Transportation assumptions

We assumed the typical unimodal and multimodal types of transport with appropriate lower limit parameters and transportation costs.

Figure 2 presents the company's SCN and the current (*as-is*) geographical distribution of the procurement, production, inventory and sales activities.

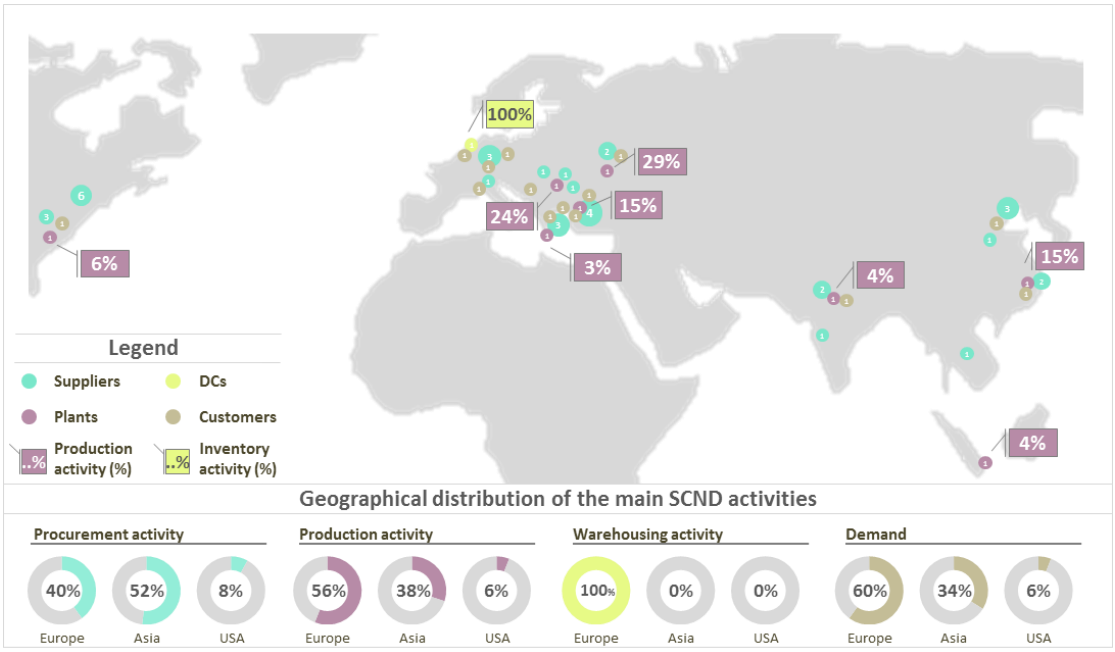


Figure 2 Illustration of the *as-is* SCND

In order to test the robustness of the above assumptions, as well as the model itself, we modeled the current situation by fixing the model's decision variables of Table 4. The values of the remaining decision variables, such as the transportation types and the available links, workforce-related variables, capacity-related variables, etc., which could not be derived from the publicly available data, were provided by the solution of the MILP model.

Table 4 Decision variables that were fixed to model the *as-is* design

Decision variable	Description
φ_i^t:	All equal to zero, since all plants of the current SCN are existing
ψ_i^{ft}:	Equal to 1 for all eight existing plants in all time periods
ζ_i^{ft}:	Equal to the known distributed production of the company
$\bar{\varphi}_i^t$:	Equal to zero since all DCs of the current SCN are existing
$\bar{\psi}_i^t$:	Equal to 1 for the sole existing major DC in all time periods
$\omega_{ijr}^{\theta t}$:	Equal to the known distributed procurement activity of the company per geographical region

Testing the assumptions and the model was performed by comparing the company's actual costs reported in its Financial Statements, with the costs for the initial reference year obtained from the proposed MILP model of the *as-is* design. As presented in

Table 5, the average % difference in costs is low, ranging from -2.9% to -11.8%. These differences in costs are attributed partially to the optimization opportunities offered by the "free" decision variables, i.e. the ones that were not fixed and were free to assume their optimal values. Furthermore, the procurement cost benefits stem from the reduced procurement cost assumptions assumed for Asia.

Table 5 Comparison of major SCND costs (*as-is* design): Actual (from the company's official financial statements) versus those obtained from the proposed MILP model – single year model

	Cost 2013 (€)		
SCND major activity	**actual data**	**model results**	**Difference (%)**
Production [a]	32,000,000	31,061,336	-2.9
Warehousing [b]	22,000,000	19,787,175	-10.1
Procurement	110,000,000	97,027,413	-11.8
Transportation	11,000,000	10,311,143	-6.3
Total	175,000,000	158,187,067	-9.6

[a] *includes fixed and variable production costs, human resource costs (hiring/ firing cost), idle equipment/ idle labor cost, and depreciation cost*

[b] *includes inventory cost, labor cost, human resource costs, idle equipment/ idle labor cost, and depreciation cost*

4.1.2 *To-be* design

For the *to-be* design, we used the same parameters as those in the *as-is* design concerning manufacturing, distribution, and transportation costs, product characteristics, manufacturing times, initial facility capacities etc. Over the 5 year horizon, the demand was increased as described in the introduction of this Section. Furthermore, we used the current supply chain network architecture (e.g. facility locations, customer locations, transportation types), providing however the possibility of adding one or more outsourcing warehouses (DCs) in the following three potential locations: (a) Netherlands-Amsterdam, (b) China-Hong Kong, (c) East Coast of USA-Pennsylvania; see also Arampantzi and Minis (2016a). No new plants were allowed to be established, while the capacities of existing plants could be enhanced. Thus, the initial condition (at year t=0) of the SCND is the current supply chain network of

Section 4.1.1. This may be transformed over the four subsequent years of the planning horizon.

The solution for the *to-be* design provided by the model is shown in Figure 3.

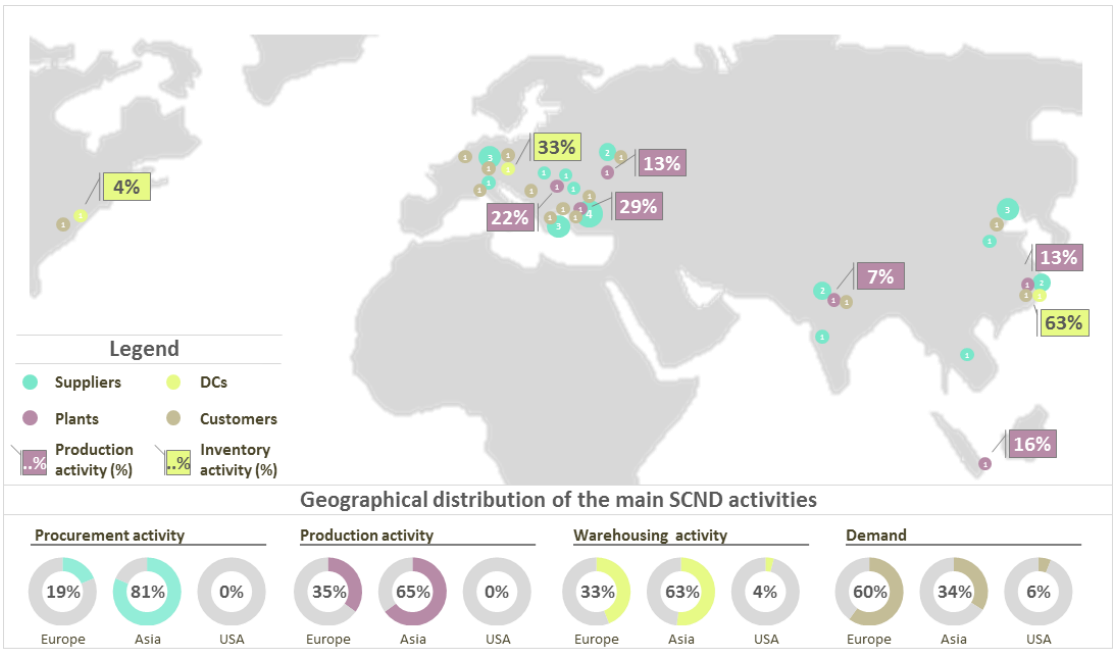


Figure 3 Illustration of the *to-be* SCND at the end of the planning horizon of five years

The significant changes between the proposed *to-be* design of Figure 3 and the *as-is* one of Figure 2 include the following:

- There is a significant increase of the SC activities in Asia.
- USA procurement and production have been eliminated, while 15% of the total inventory has been outsourced to a logistics provider in the East Coast (at one of the candidate locations).
- The total production in Europe has been decreased, while one plant in Greece is no longer used.

The main reasons behind the reallocation of SC activities to Asia are: (a) lower labor costs, (b) lower procurement costs (by 15%), and (c) more efficient utilization of the network enabled by the new outsourcing DCs.

Table 6 compares the major cost components of the *as-is* and the *to-be* designs in an average sense over the five year planning horizon. Note that the difference between values of Table 5 (model results column) and Table 6 (*as-is* design column) is due to the different time horizons assumed (single year in Table 5 vs. average values of five years in Table 6).

According to Table 6 the total cost has decreased by approximately 6% due to a significant reduction in all areas. The main reason behind the significant reduction of production and transportation costs is the reallocation of SC activities to Asia. Especially, the reduction of production cost is related to the lower labor costs in Asia's plants comparing with plants in EU. At the same time, the need to transport products from Asia increases the proportion of the cost effective sea transport mode, decreasing the total transportation cost. Furthermore, there is a significant reduction of inventory cost due to the selection of three (3) outsourcing DCs in addition to the existing one in Europe. These outsourcing options provide the advantage of a more efficient utilization of the network reducing the total inventory cost by 4.7%.

Note that the cost improvements of Table 6 may be partially due to the assumptions made on key model parameters. We believe, however, that even if those assumptions are substituted by the (publicly unavailable) actual values, significant cost savings could still be expected.

Table 6 Comparison of major SCND costs resulting from the *to-be* design of the proposed MILP model versus the *as-is* design

	Average cost of five years (€/year)		
SCND major activity	***as-is* design**	***to-be* design**	**Difference (%)**
Production [a]	31,535,932	28,761,223	-8.8
Warehousing [b]	22,092,702	21,051,450	-4.7
Procurement	102,908,329	97,883,715	-4.9
Transportation	11,443,317	10,197,060	-10.9
Total	167,980,280	157,893,448	-6.0

[a] *including production and set up cost (including labor cost), hiring/ firing cost, idle equipment/ idle labor cost, and depreciation cost*

[b] *includes (insourcing and outsourcing) inventory cost, labor cost, human resource costs, idle equipment/ idle labor cost, and depreciation cost*

4.2 Scenario analysis

In order to further study how various parameters affect the *to-be* design of the SCN and its performance, we varied certain model inputs and studied the related effects on the selected major SCN activities of Table 7 and the normalized cost.

Table 7 Major activities and total cost of SCN

SCND major activity	KPIs	Unit
Procurement	Distribution of procurement activity per continent	%
Production	Distribution of production activity per continent and per plant	%
Warehousing	Total warehousing cost [a]	€
	Total outsourced warehousing activity	%
Transportation	Split of total transportation per type (in product units per mode)	%
Normalized total cost	Total cost (as per Equation 1) per product unit	€

[a] *Note that hereafter we will use the term warehousing cost for all individual costs that are related to DCs such as insourcing and outsourcing inventory cost, labor cost, human resource costs, idle equipment/ idle labor cost, and depreciation cost*

The input parameters used in the scenario analysis were the following: (a) demand reduction in Asia, (b) demand reduction in EU, and (c) outsourcing inventory cost increase. Each parameter is varied independently, in an one-at-a-time fashion. The nominal values of the inputs are those of the *to-be* scenario of Section 4.1, and the parameter levels are provided in Table 8. For each experiment the values of the input parameters apply to all periods of the time horizon.

Table 8 Scenario parameters and their levels (w.r.t the *to-be* scenario)

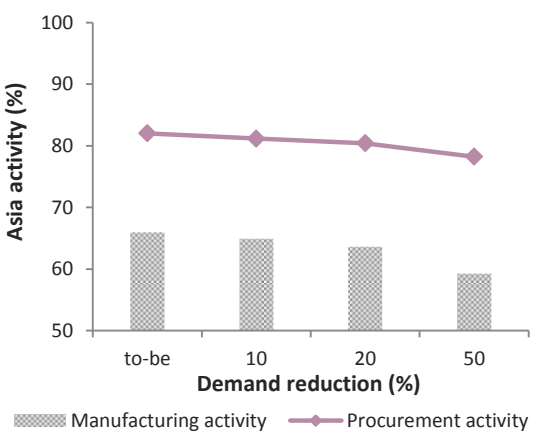
Parameters	Level 1	Level 2	Level 3
Asia's demand reduction	10% lower	20% lower	50% lower
EU's demand reduction	10% lower	20% lower	50% lower
Outsourcing inventory cost increase	40% higher [a]	50% higher [a]	60% higher [a]

[a] *higher than the insourcing inventory cost*

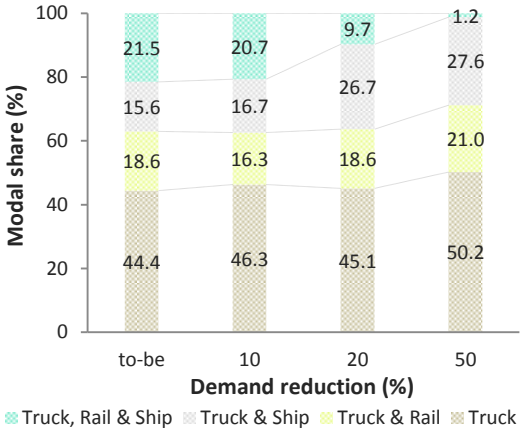
The results of the scenario analysis are given in the following figures.

Figure 4a presents the effect of reduction in Asia's demand, on Asia's procurement and manufacturing activities (as a percentage of global activities). Both procurement and manufacturing activities are insensitive to this reduction. Even for a substantial 50% demand drop, the manufacturing and procurement activities are reduced only by 10% and 5%, respectively. This may be attributed to the competitive Asia labor and

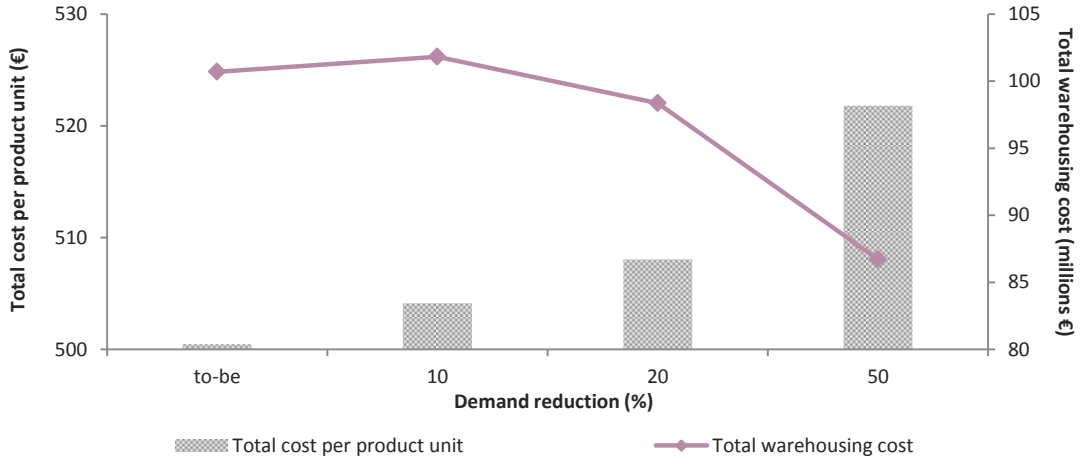
procurement costs which maintain Asia's manufacturing as a supplier of global markets. Regarding modal split, in Figure 4b we observe that the global share of combined transportation by truck, rail and ship decreases significantly. This is attributed to the considerable reduction of Indonesia's production activity and the related increase of Turkey's production. In our network, the Indonesia plant uses combined transportation by truck, rail and ship, while the Turkey plant uses mainly combined transportation by truck and the share of which increases in Figure 4b. Figure 4c shows that the total warehousing cost follows the drop in demand, as expected due to the safety stock assumptions, while the total cost per product unit increases by 4.3%. This is attributed to the increase in transport unit costs due to longer distances travelled and more expensive types of transportation used to serve EU customers from Asia's plants.



(a)



(b)



(c)

Figure 4 Impact Asia demand reduction on (a) Asia manufacturing and procurement activities, (b) global transport modal share, (c) total cost per product and total warehousing cost

Figure 5a shows the impact on EU manufacturing and procurement activities (as % of the global ones) when EU demand is reduced. The reduction of EU manufacturing activity follows the respective reduction of the EU demand. For instance, in case of 50% reduction in EU demand, a 62% reduction in EU manufacturing activity is observed. Similarly, the EU procurement activities are reduced by 66%, while EU warehousing by 34%. For the same case, in Figure 5b we observe that global transportation by ship increases by 23% (i.e. truck/rail/ship, truck/ship) due to the need to transport products from Asia. Regarding total warehousing cost in Figure 5c, similarly to the previous case, it follows the drop in demand due to the safety stock assumptions. In the Figure 5c we also observe that for 50% drop in EU demand the total cost per product unit increases by 4% due to longer distances travelled, and more expensive transportation types used to serve EU customers from Asia's plants.

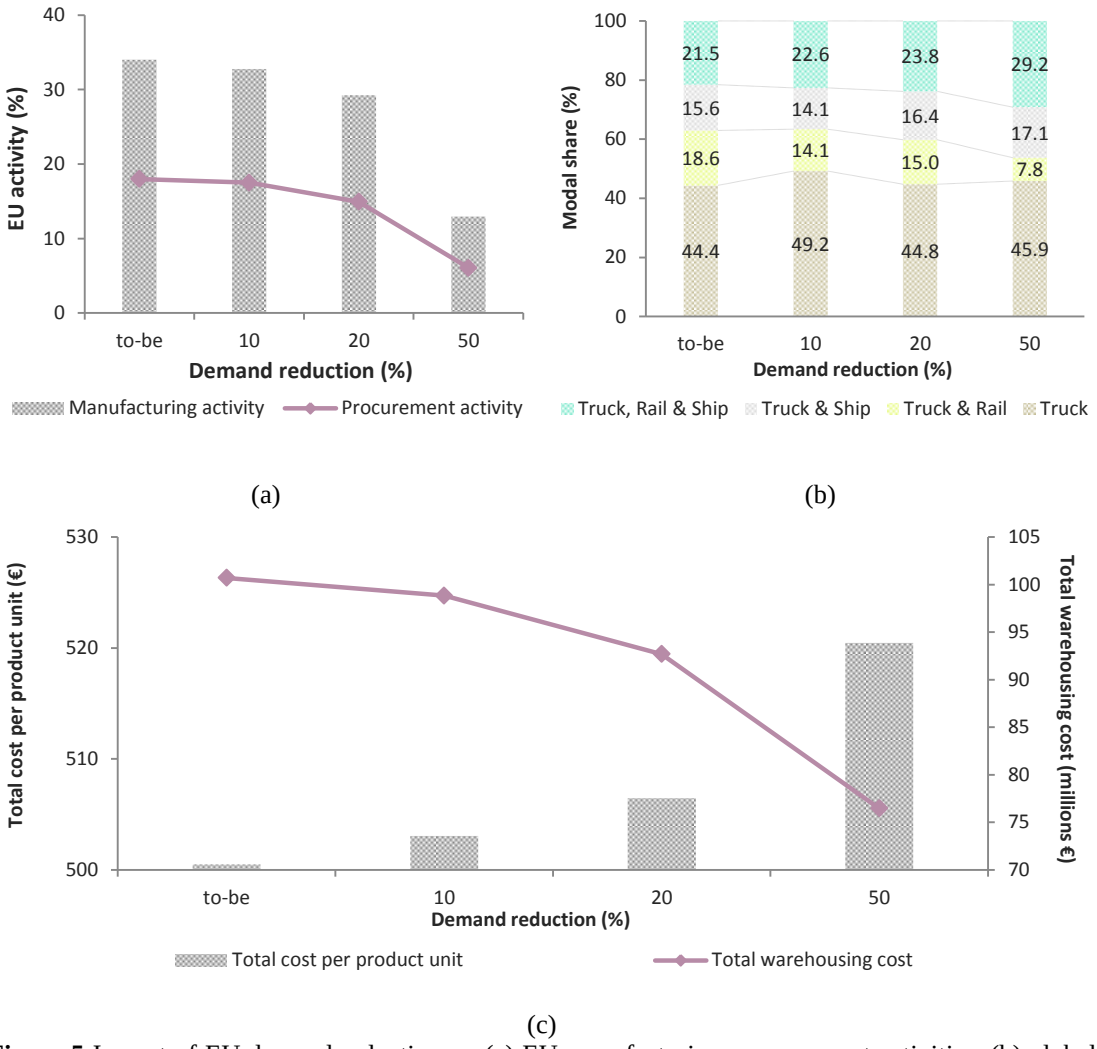


Figure 5 Impact of EU demand reduction on (a) EU manufacturing, procurement activities, (b) global transport modal share, (c) total cost per product and total warehousing cost

Figure 6 presents the impact on outsourcing inventory activity and total warehousing cost in case of increasing inventory outsourcing costs. It seems that even for a substantial 50% increase in outsourcing inventory cost, the outsourcing inventory activity is reduced only by 1% while the total warehousing cost is increased by 4%. These results indicate that, under the current values of the network's parameters, outsourcing inventory remains preferable even for higher outsourcing costs. The other SCN key outputs (i.e. procurement, production and transportation activities) have not been significantly affected by the change in outsourcing inventory cost.

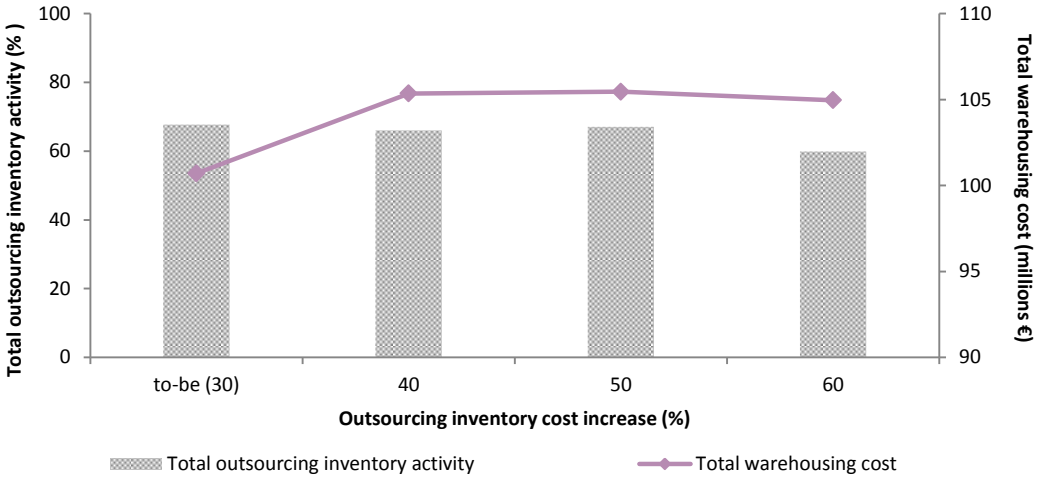


Figure 6 Impact on outsourcing inventory activity and total warehousing cost in case of increasing outsourcing inventory costs

From a practical perspective, these results may offer insights for crafting the company's supply chain strategy. For example, EU manufacturing activity is sensitive to a possible reduction in EU demand, while Asia manufacturing activity is more robust to changes in local demand. As already mentioned, the main reason behind this is the competitive Asia labor and procurement costs even though the transportation costs between Asia plants and EU customers are significantly higher. Thus, under the current system parameters, low-cost country sourcing and manufacturing emerges as a preferred strategy. Moreover, outsourcing warehousing emerges as a robust strategic choice for the company under study, even under significant outsourcing cost variations.

5 Conclusions

We proposed an integrated MILP model that incorporates many of the significant strategic (re)design decisions of Supply Chain Networks mentioned in the related literature. The model assumes deterministic customer demand by multiple clients for multiple products over multiple periods of a long term horizon. The strategic

decisions per time period involve: selection of raw material suppliers, establishment or resizing of production facilities and/or selection of production subcontractors, establishment/resizing of distribution centers and/or subcontracting the related activities, and selection of transportation modes. The objective is to minimize the overall costs associated with the aforementioned strategic decisions.

Extensive numerical experiments indicated that the proposed model may reach optimal solutions for instances of substantial size within reasonable computational times.

Using the proposed model in order to redesign the existing SCN of a global manufacturing firm, we were able to decrease total costs by 6%, under certain assumptions. In fact, excluding the rather inelastic procurement and inventory costs (at this strategic level), production and transportation costs were reduced by 8.8% and 10.9%, respectively. These results validate the ability of the proposed model to (re)design high performing supply chains.

The scenario analysis performed in the above large industrial case indicated that the proposed model can be applied as an effective tool for supporting strategic SCND decisions, and obtaining architectures that may withstand changes in key SC parameters.

Interesting directions for further research in this area include the consideration of environmental, social, and other sustainability concerns in the SCND process. The resulting changes w.r.t. a SCND based solely on cost may significantly enhance a firm’s competitive advantage.

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