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Impact of partial product outsourcing, transportation mode selection, and single-assignment requirements on the design of a multi-stage supply chain network

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Abstract

In this paper, we propose a novel mixed-integer linear programming model for a comprehensive multi-stage supply chain network design problem. Our model integrates location and capacity choices for plants and warehouses with supplier and transportation mode selection, and distribution of multiple products through the network. The aim is to identify the network configuration with least total cost subject to side constraints related to resource availability, technological conditions, and required customer service level. In addition to in-house production, end products may also be purchased from external sources and consolidated in warehouses. Therefore, our model identifies the best mix between in-house production and product outsourcing. To measure the impact of this strategy, we further present two additional formulations for alternative network design approaches that do not include partial product outsourcing. Several classes of valid inequalities tailored to the problems at hand are also proposed. We test our models on randomly generated instances and analyze the trade-offs achieved by integrating partial outsourcing into the design of a supply chain network against a pure in-house manufacturing strategy, and the extent to which it may not be economically attractive to provide full demand coverage.

Keywords: supply chain network design; facility location; supplier selection; in-house production; product outsourcing; transportation mode selection; single-assignment; mixed-integer linear programming

1 Introduction

In today's volatile global business environment, firms face a continuous need to review the configuration of their supply chain networks to respond to changing market conditions and maintain a competitive advantage. Supply chain network design (SCND) is a key lever in improving a firm's financial performance. A successful network design sets the conditions for reducing costs through ensuring operational efficiency of supply chain-related functions such as sourcing, production, and distribution. Typically, SCND determines the suppliers to be selected, the number, location and capacities of the facilities to be operated (e.g., plants, warehouses), and the distribution channels through which materials flow from suppliers to customers. Most SCND projects pursue the goal of minimizing total cost subject to side constraints related to resource availability, technological conditions, and required customer service level (Melo et al. [17]). As a rule, the cost to be minimized is associated with supply chain operations (e.g., sourcing, manufacturing, storage, consolidation, transportation) and the level of investment in establishing and equipping new facilities.

In this paper, we address a multi-stage network design problem involving suppliers, plants, warehouses, and customer zones. Decisions must be made regarding: (i) the location and capacity level of plants and warehouses to open; (ii) the choice of suppliers; (iii) the allocation of raw materials from suppliers to plants; (iv) the activity mix of each facility (i.e., the amount of products manufactured in a plant and the amount of products handled by a warehouse); (v) the selection of a transportation mode between each origin and destination in the network; (vi) the flows of raw materials and end products through the network; (vii) the assignment of each customer zone to a single facility; and (viii) the amount of product outsourcing. In particular, the last aspect has received little attention in the literature dedicated to SCND. External sourcing offers various benefits, including improved flexibility and shorter lead times, which makes this strategy interesting and economically feasible for many firms (Fredriksson et al. [11]). In our problem, outsourced products are consolidated into larger shipments in warehouses and further delivered to customer zones. The configuration of the supply chain network is expected to be affected by the combination of product outsourcing and in-house manufacturing. Depending on the level of product outsourcing, it may be possible to reduce the capital investment in the number, location, and size of in-house production facilities. This, in turn, will also influence decisions regarding the procurement of raw materials and the distribution of end products from plants to warehouses. According to Fredriksson et al. [11], products with relatively stable demand are more suited to be purchased from external sources, whereas in-house production provides the required flexibility to deal with variations in demand.

The contributions of the present work are summarized as follows: (1) We propose a new mathematical model for a SCND problem that has a significantly greater scope compared with the existing literature. Our unified mathematical framework captures a number of features arising in real world SCND problems that affect the design of a supply chain network. (2) To evaluate the impact of combining in-house production and partial product outsourcing, we further develop two additional models for two alternative strategies. One mathematical formulation results from adapting the original model to the case of manufacturing all products in-house. In the third model, product outsourcing is not enforced and a minimum level of demand satisfaction is imposed. Valid inequalities are developed to tighten the three formulations. (3) We report on computational experiments using randomly generated instances and make a comparative analysis of the quality of the solutions obtained for each model with a general purpose optimization solver. (4) We measure the value of incorporating external sourcing into the decision space by providing additional managerial insights. The latter illustrate the far-reaching implications of the three different strategies on total cost, network design, capacity utilization of facilities, and various supply chain functions.

The remainder of this paper is organized as follows. Section 2 provides an overview of the relevant literature in SCND. In Section 3, we formally describe our problem and present a mathematical formulation. In addition, two alternative strategies for network design are considered and the corresponding formulations are introduced. Together, the three models will allows us to evaluate the value of combining in-house production and partial product outsourcing. In Section 4, additional inequalities are proposed to enhance the original formulations. Computational results are reported and discussed in Section 5. Section 6 concludes the paper with a summary of our findings and directions for future research.

2 Literature review

At the strategic planning level, the design of production-distribution networks has been an active research area for many years. In their early seminal work, Geoffrion and Graves [12] address the problem of finding the optimal configuration for a network comprising plants, distribution centers (DCs), and customers. The aim is to select DCs from a finite set of candidate locations and to plan the material flows through the network so as to satisfy customer demands for multiple products at minimal total cost. Subsequent research has evolved into the development of more comprehensive mathematical programming models that integrate facility location decisions with a number of supply chain management functions such as supplier selection, procurement and production planning, technology acquisition, inventory control, and transportation mode selection, just to name a few (Melo et al. [17]). However, the consideration of various logistics functions simultaneously usually comes at the expense of added problem complexity. In this section, we review selected research articles on SCND. Our aim is not to provide an exhaustive review of this field but to analyze the extent to which the features proposed in our work have been addressed in the literature. Table 1 summarizes these features.

Since production and distribution are among the most important functions performed by a supply chain, it is not surprising that a large body of research in SCND has given emphasis to the development of models that help firms find the best locations for plants and warehouses simultaneously (Cordeau et al. [5]; Elhedhli and Gzara [7]; Eskandarpour et al. [8]; Pirkul and Jayaraman [19]; Sadjady and Davoudpour [23]; Shankar et al. [24]). In the SCND problems studied by Manzini [15] and Zhang et al. [26], two types of storage facilities, namely central and regional DCs, are located in addition to production facilities. Varsei and Polyakovskiy [25] present a case study for an Australian wine company that needs to find the locations of wineries, bottling plants, and DCs. In all cited works, an *a priori* multi-stage network structure is imposed. A few SCND models have been developed that can handle an arbitrary number of production and distribution stages, and do not impose location decisions to be restricted to a specific stage of the supply chain network. These include Alumur et al. [1] and Rohaninejad et al. [22].

Capacity sizing is an integral part of facility location models in SCND. Typically, when potential sites for opening facilities are identified, also the maximum capacities that can be built in those sites are exogenously determined. The latter are affected by a variety of reasons, e.g. availability of land. In terms of the underlying SCND model, capacity constraints are imposed stating that different materials share the capacity of the facility where they are processed. This case often concerns warehousing facilities and the models developed by Eskandarpour et al. [8], Pirkul and Jayaraman [19], and Shankar et al. [24] capture this aspect. In some situations, however, technological requirements, e.g. dictated by production operations or specific storage conditions, impose establishing a facility with dedicated capacity for each type of product. In this case, product-dependent capacity constraints need to be considered at the facilities (Alumur et al. [1]; Cordeau et al. [5]; Manzini [15]). Additionally, both types of capacity restrictions (global and product-oriented) are integrated into the models in [1, 5] for all facilities.

Capacities can have a significant impact on location decisions, and therefore, on supply chain performance. Moreover, economies of scale can also be encountered in capacity acquisition, making the cost of establishing a facility dependent on its size. Therefore, from a practical perspective, it is important to include the amount of installed capacity into the decision process. Frequently, capacity acquisition decisions take the form of choosing the size of a facility from a discrete set of capacity levels. This approach, which is adopted in the present work for production and warehousing facilities, is also taken by Askin et al. [2], Elhedhli and Gzara [7], Sadjady and Davoudpour [23], and Varsei and Polyakovskiy [25], through incorporating the cost associated with installing a capacity level at a particular location into the objective function. In addition, in our work, a facility cannot be run economically if its activity level is lower than a pre-specified threshold, which is a feature that is not supported by most SCND models.

Location and capacity acquisition decisions for production facilities can be affected by the structure of the products to be manufactured, by way of their bill of materials (BOM), and by the availability of raw materials. These aspects are important when there are multiple products with component commonality among them, and raw material procurement depends upon the proximity to external suppliers, their costs and capacities. Apart from our study, only a few authors have integrated the BOM of finished products into their SCND models (Alumur et al. [1]; Cordeau et al. [5]; Varsei and Polyakovskiy [25]). The model proposed by Baud-Lavigne et al. [4] allows for complex BOM with several product structure levels and various substitution options for sub-assemblies. Moreover, different technologies are available in each production facility and a choice has to be made along with the selection of the capacity level to install. Regarding raw material sourcing, those studies that include procurement decisions usually assume that a plant can purchase a specific raw material from multiple suppliers (Cordeau et al. [5]; Eskandarpour et al. [8]; Shankar et al. [24]; Varsei and Polyakovskiy [25]). To take advantage of volume discounts, we make the assumption in our model that an individual raw material required by a given plant must be procured from a single supplier. However, different suppliers may provide the same raw material to different plants. This strategy diminishes the risk of supply disruption due to single-source dependency and is used in various industries, e.g. consumer goods industry.

The distribution process through the supply chain can be organized in different ways. A popular modeling approach is to assume a hierarchy of facilities in the network (e.g., plants, DCs, and customers), where each facility can receive materials from the immediately upper stage and distribute materials to the next lower stage (Melo et al. [17]). Direct shipments to customers are also suitable, especially when customers have large demands. The major advantage of this delivery scheme is the reduction of transportation and warehousing costs. This approach is taken in our study and has been also considered by a few authors, e.g. Alumur et al. [1], Askin et al. [2], Babazadeh et al. [3], Eskigun et al. [9], and Zhang et al. [26]. Transportation between locations can be performed using different shipping modes (air, marine, railway, road), and a few authors have recognized the importance of including the choice of transportation modes in their SCND models (Melo et al. [17]). With each transportation option available between an origin and a destination there is a cost associated with the amount of freight flow, and possibly also a fixed charge (Eskandarpour et al. [8]; Eskigun et al. [9]; Rahmaniani and Ghaderi [21]). In the previous references [8, 9, 21], a single transportation mode may be selected on an arc. In contrast, Kazemi and Szmerekovsky [13] and Varsei and Polyakovskiy [25] allow several transportation options to be used between an origin and a destination. The latter authors also address environmental concerns by minimizing the total cost of CO_2 emissions generated by transportation activities through the supply chain. Sadjady and Davoudpour [23] consider a transit time associated with each arc and mode, in addition to a variable transportation cost. Interestingly, usually no limits are imposed on the amount of flow traversing an arc with a given transportation mode. This is an important research gap that we address in our work through specifying both a minimum usage level and a maximum capacity associated with each transportation mode. In the SCND model developed by Eskandarpour et al. [8], a lower bound is imposed on the volume of goods that can be shipped with certain transportation choices, but no maximum limit is enforced. Rahmaniani and Ghaderi [21] adopt the opposite approach by imposing capacity constraints on each link and mode. Kazemi and Szmerekovsky [13] set an upper bound on the fraction of the total demand that can be satisfied using a specific transportation mode.

Regarding the level of service delivered to customers, most SCND models ensure the satisfaction of all demands. Some studies allow a fraction of the total demand to be unmet (Alumur et al. [1]; Poudel et al. [20]; Rohaninejad et al. [22]; Shankar et al. [24]) through incorporating a penalty cost into the objective function that represents the additional expense of purchasing a substitute product. In order to be able to meet all customer demands, the required level of production, warehousing, and distribution activities must be made available. Alternatively, supply chain operations can be combined with product outsourcing, an option that has received little attention in the SCND literature. In defining the BOM for each end product, Baud-Lavigne et al. [4] include the possibility of purchasing sub-assemblies from subcontractors, and thus reduce the investment in installing capacity at production centers. Babazadeh et al. [3] combine in-house manufacturing with partial product outsourcing, and impose a limit on the quantity of products that may be purchased by a plant from an external source. This feature is present in our work, but in our case outsourced products are consolidated in warehouses instead of plants.

In the early contribution by Geoffrion and Graves [12], each customer has to be served by a single DC, thereby taking advantage of lower transportation costs due to larger shipments. In addition to our work, there are only a few authors that include single-assignment conditions into their SCND problems (Askin et al. [2]; Eskigun et al. [9]; Olivares-Benitez et al. [18]; Zhang et al. [26]).

Table 1 presents a classification of the works that are reviewed in this section. Its purpose is to illustrate the extent to which our research goes beyond existing contributions. Since the table is not meant to be exhaustive, we have left out characteristics that are outside the scope of our work, such as SCND problems over a multi-period planning horizon, multiple objective functions, and uncertain parameters.

Our classification scheme has five categories. The category 'Supply chain network' comprises the number of stages in the network, including the customer level (column 2), the number of stages involving facility location decisions (column 3), and whether products can be directly shipped to customers from higher level facilities (column 4). The category 'Facility sizing' indicates if capacity acquisition decisions include the selection of a capacity option from a set of available sizes (column 5), and the type of capacity constraints imposed on production facilities (column 6) and warehouses (column 7). The category 'Transportation' includes shipping mode selection (column 8) and restrictions on the flow that traverses an arc when a given mode is used (column 9). The category 'Commodities' gives the number of products in column 10 (single or multiple products), if a BOM is considered in the design problem (column 11), and if end products can be partially outsourced (column 12). Finally, the category 'Customer stage' shows if customer demands must be satisfied completely (column 13) and if single-assignment conditions for serving customers are enforced (column 14). The last row of the table lists the features that are captured by the models to be detailed in the next section.

In summary, although SCND is a rich research field, most of the studies do not incorporate several logistics aspects simultaneously that are relevant from a practical perspective. The present paper attempts to fill this gap by proposing models with a broader scope than those reported in Table 1.

3 Problem statement and mathematical formulations

We consider a supply chain network with four stages as depicted in Figure 1. The locations of suppliers and customer zones are known and fixed, whereas those of manufacturing plants and

Reference	Supply chain network			Facility sizing			Transportation		Commodities			Customer stage	
	# stages	# location stages	Direct shipments	Cap. options	Production capacity	Storage/ handling capacity	Mode selection	Cap. limits	Type	BOM	Partial out- sourcing	Demand satisfaction	Single- assignment
Alumur et al. [1]	N	N	⋆		P,G	P,G			M	⋆		PRTL	
Askin et al. [2]	3	1	⋆	⋆		G			M			T	⋆
Babazadeh et al. [3]	3	2	⋆	⋆	G	G	⋆		S		⋆	PRTL	
Baud-Lavigne et al. [4]	4	2		⋆	P				M	⋆	⋆	T	
Cordeau et al. [5]	4	2			P,G	P,G	⋆	max	M	⋆		T	
Elhedhli and Gzara [7]	3	2		⋆	G	G			M			T	
Eskandarpour et al. [8]	4	2			G	G	⋆	min	M			T	
Eskigun et al. [9]	3	1	⋆		´	G	⋆		S			T	⋆
Kazemi and Szmerekovsky [13]	3	1				U	⋆		M			T	
Manzini [15]	4	3			P	P	⋆		M			T	
Olivares-Benitez et al. [18]	3	1				G	⋆		S			T	⋆
Pirkul and Jayaraman [19]	3	2			G	G			M			T	
Poudel et al. [20]	4	2		⋆	G	G			S			PRTL	
Rahmaniani and Ghaderi [21]	2	1				U	⋆	max	S			T	
Rohaninejad et al. [22]	N	N		⋆	G	G			S			PRTL	
Sadjady and Davoudpour [23]	3	2		⋆	G	G	⋆		M			T	
Shankar et al. [24]	4	2			G	G			M	⋆		PRTL	
Varsei and Polyakovskiy [25]	5	3		⋆	G	G	⋆		M	⋆		T	
Zhang et al. [26]	5	3	⋆		G	G			S			T	⋆
New models	**4**	**2**	**⋆**	**⋆**	**P,G**	**G**	**⋆**	**min,max**	**M**	**⋆**	**⋆**	**T,PRTL**	**⋆**

G: Global capacity; M: Multiple products; N: Unlimited no. of stages / location stages; P: Product-dependent capacity;
PRTL: Partial demand satisfaction; S: Single product; T: Total demand satisfaction; U: Uncapacitated

Table 1: Classification of SCND features.

warehouses need to be selected from a set of candidate sites. The sizes of the new facilities are also to be chosen from a predetermined finite set of capacity levels.

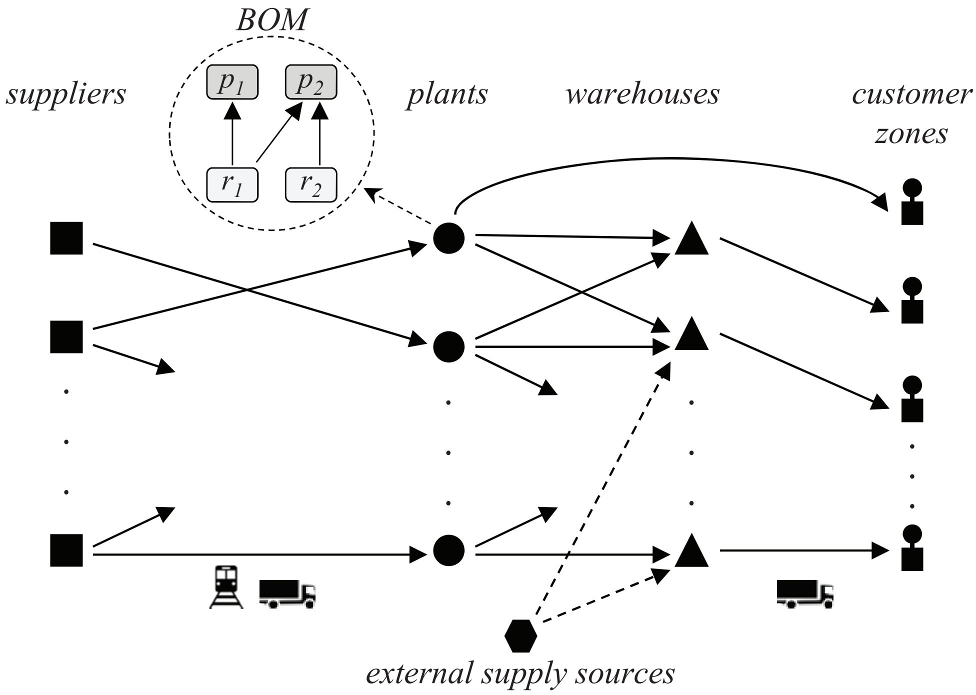

Figure 1: General topology of the supply chain network.

Raw materials are provided by suppliers and processed into different end products in plants. A BOM specifies which raw materials are needed to manufacture each end product. Focus is given to raw materials that make up a large portion of the overall end product, and items with a low unit cost impact are excluded. Figure 1 illustrates two examples of aggregated BOM. In addition to location and capacity sizing decisions, the distribution paths of raw materials and end products across the network also need to be determined. As shown in Figure 1, end products can be transported from plants to customer zones either directly or via intermediate warehouses. In any case, a customer zone must be served by a single facility, either a plant or a warehouse. Many firms strongly prefer a single-sourcing distribution strategy because it simplifies the management of their supply chain and can reduce management and operational costs. On the other hand, customers also often favor being supplied by a single facility since lower transportation costs are incurred due to larger shipment volumes along distribution lanes.

In addition to being in-house manufactured, end products can also be (partially) purchased from external sources. In this case, consolidation takes place in warehouses and is represented by the dashed arrows in Figure 1. An exogenously specified quota designates the maximum quantity of a product that can be purchased from external sources. In certain manufacturing contexts, subcontracting part of the production is a meaningful economical option for meeting demand requirements (Martínez-Costa et al. [16]).

Different modes of transportation are available between each origin-destination pair in the supply chain network. In Figure 1, rail and road freight transport are displayed as examples of possible options. Moreover, each mode has a minimum shipment quantity and a maximum transportation capacity. For example, a plant can rent a given number of freight wagons and at the same time also hire a carrier to transport goods by road. Since rail transport is often the least cost choice for large quantities of goods, it is meaningful to set a minimum shipment amount. Therefore, tactical decisions regarding the selection of distribution channels and transportation modes are also considered. All products from the same plant or warehouse are delivered to a destination using the same transportation mode to take advantage of economies of scale and to simplify the delivery process of the goods (e.g., loading, unloading, tracking, etc.). Additional features of our problem and assumptions are introduced next.

- Product-dependent capacities are considered in each plant location. Some production resources may be product-specific (e.g., equipment dedicated to a given item), while others may be shared by multiple products (e.g., a production line). In the latter case, several products may be processed on a given machine whose availability is limited to a certain number of hours.

- Each operating plant must purchase all units of a specific raw material from a single supplier. This assumption enables the manufacturer to negotiate an attractive price with the supplier for the purchase of large quantities of the raw material. Nevertheless, a plant may procure *different* raw materials from multiple suppliers. This feature overcomes the disadvantages of single-supplier dependency for all required raw materials.

- Direct shipments from a plant to a customer zone are only permitted if at least a given quantity is distributed to the customer zone. Such a delivery scheme reduces transportation costs for large quantities.

- Facilities (plants and warehouses) can only be operated economically provided that a minimum capacity utilization level is achieved.

- Customer demands, costs, and other parameters are deterministic, and assumed to be the outcome of appropriate forecasting methods and company-specific analyzes. Fixed costs are incurred for opening plants and warehouses, and choosing their capacity levels. These costs are subject to economies of scale that depend on the capacity sizes. In addition, variable costs are associated with procurement, production, transportation, and product outsourcing decisions. We do not consider fixed costs for transportation mode selection because transportation capacity is assumed to be rented from third-party logistics (3PL) providers. Therefore, the transportation cost depends on the price charged by the 3PL provider per unit of distance traveled and unit of product shipped.

3.1 Model parameters

We now introduce the notation associated with the parameters used in our models.

Index sets:

R	Set of raw materials
P	Set of end products
P^r	Subset of end products requiring raw material r ($P^r \subseteq P$; $r \in R$)
S	Set of suppliers
S^r	Subset of suppliers that can provide raw material r ($S^r \subset S$; $r \in R$)
L	Set of potential plant locations
L^p	Subset of plant locations where product p can be manufactured ($L^p \subseteq L$; $p \in P$)
Q_L	Set of capacity levels available in each potential plant location
W	Set of potential warehouse locations
W^p	Subset of warehouse locations that can handle product p ($W^p \subseteq W$; $p \in P$)
Q_W	Set of capacity levels available in each potential warehouse location
C	Set of customer zones
C^p	Subset of customer zones with demand for end product p ($C^p \subseteq C$; $p \in P$)
O, D	Set of all potential origins, resp. destinations, in the network
O^i, D^i	Subset of potential origins, resp. destinations, for item i ($O^i \subset O$; $D^i \subset D$; $i \in R \cup P$)
M	Set of transportation modes
M_{od}	Set of transportation modes available from origin o to destination d ($M_{od} \subseteq M$; $o \in O$; $d \in D$)

Observe that all suppliers of raw material r are gathered in set $O^r = S^r$. The set of locations that can handle end product p is given by $O^p = L^p \cup W^p$. Destinations for raw material r can only be plants in which products that require this raw material can be manufactured. The set of destinations for end product p is defined as $D^p = W^p \cup C^p$. Accordingly, the following sets of origin-destination pairs (o, d) are available (recall Figure 1): $\{(s, \ell) : s \in S, \ell \in L\}$, $\{(\ell, w) : \ell \in L, w \in W\}$, $\{(\ell, c) : \ell \in L, c \in C\}$, and $\{(w, c) : w \in W, c \in C\}$. Since the delivery of end products purchased from external sources to warehouses falls under the responsibility of the external suppliers, we exclude the latter from the set of origins. In particular, the choice of transportation modes and their associated costs are set by the external suppliers. Without loss of generality, we gather all external suppliers into a single source as shown in Figure 1.

Fixed costs are incurred for opening and operating plants and warehouses. Variable costs include procurement, production, transportation, and external costs. The latter are the additional costs incurred from product outsourcing and include material, transportation as well as other costs. Each transportation mode has a specific capacity, cost structure, and operating characteristics.

Fixed and variable costs:

FCF_o^q	Fixed cost of opening a facility in potential location o with capacity level q ($o \in L$; $q \in Q_L$ and $o \in W; q \in Q_W$)
CP_s^r	Unitary procurement cost for raw material r from supplier s ($r \in R$; $s \in S^r$)
CM_ℓ^p	Unitary manufacturing cost for end product p in plant ℓ ($p \in P$; $\ell \in L^p$)
CT_{od}^{im}	Unitary transportation cost for item i from origin o to destination d by mode m ($i \in R \cup P$; $o \in O$; $d \in D$; $m \in M_{od}$); this term also includes unit handling costs in the origin and destination locations
CO_w^p	Unitary purchasing cost for end product p by warehouse w from an external source ($p \in P$; $w \in W^p$)

Additional parameters are introduced next. If a plant is established in candidate location $\ell \in L$ then a capacity level, $\overline{LQ}_{\ell q}$, has to be selected from the set of available options, $q \in Q_L$. We assume that the latter are sorted in increasing order, that is, $\overline{LQ}_{\ell 1} < \overline{LQ}_{\ell 2} < \ldots < \overline{LQ}_{\ell |Q_L|}$. Moreover, product-dependent manufacturing capacities are associated with the capacity level that is established in each plant location. For each end product p, the available capacity levels are assumed to be ordered by increasing size, namely $\overline{LQP}_{\ell 1}^p < \overline{LQP}_{\ell 2}^p < \ldots < \overline{LQP}_{\ell |Q_L|}^p$.

Further parameters:

a^{rp}	Number of units of raw material r required to manufacture one unit of product p ($r \in R$; $p \in P^r$)
PU^p	Amount of production capacity used by one unit of product p in a plant ($p \in P$)
SU^p	Amount of storage capacity used by one unit of product p in a warehouse ($p \in P$)
MU^{im}	Amount of capacity used by one unit of item i with transportation mode m ($i \in R \cup P$; $m \in M$)
$\overline{SQR}_s^r$	Total capacity of supplier s for raw material r ($r \in R$; $s \in S^r$)
$\overline{LQ}_{\ell q}$	Total manufacturing capacity of plant ℓ with capacity level q ($\ell \in L$; $q \in Q_L$)
$\underline{LQ}_{\ell q}$	Minimum capacity utilization of plant ℓ with capacity level q, $\underline{LQ}_{\ell q} = \alpha_{\ell q} \overline{LQ}_{\ell q}$ with $0 \leq \alpha_{\ell q} < 1$ ($\ell \in L$; $q \in Q_L$)
$\overline{LQP}_{\ell q}^p$	Total production capacity for product p in plant ℓ with capacity level q ($p \in P$; $\ell \in L^p$; $q \in Q_L$)
$\overline{SQ}_{wq}$	Total storage capacity of warehouse w with capacity level q ($w \in W$; $q \in Q_W$)
$\underline{SQ}_{wq}$	Minimum storage capacity utilization of warehouse w with capacity level q, $\underline{SQ}_{wq} = \alpha_{wq} \overline{SQ}_{wq}$ with $0 \leq \alpha_{wq} < 1$ ($w \in W$; $q \in Q_W$)
$\overline{MQ}_{od}^m$	Total capacity of transportation mode m from origin o to destination d ($o \in O$; $d \in D$; $m \in M_{od}$)
$\underline{MQ}_{od}^m$	Minimum shipment quantity from origin o to destination d by transportation mode m ($o \in O$; $d \in D$; $m \in M_{od}$)
d_c^p	Demand of customer zone c for end product p ($p \in P$; $c \in C^p$)
β_p	Fraction of total demand for product p that can be supplied by an external source, $0 \leq \beta_p < 1$ ($p \in P$)
λ	Minimum total quantity of end products that may be shipped directly from a plant to a customer zone

Although product outsourcing is a viable option, demand requirements cannot be solely met with this business strategy. Therefore, we impose a limit $\beta_p < 1$ on the proportion of end product p that can be purchased from an external supplier. Moreover, direct shipments from plants to customer zones take place provided that large quantities are transported. This case is ruled by a pre-specified parameter λ.

3.2 Mixed-integer linear programming formulation

Our mixed-integer linear programming (MILP) formulation relies on binary variables to represent facility location and capacity acquisition decisions, along with single-assignment decisions associated with the supply of raw materials to plants and the choice of transportation modes. In addition, continuous variables are required to model distribution decisions.

$Z_o^q =$ 1 if a facility is established in potential location o with capacity level q, 0 otherwise ($o \in L$; $q \in Q_L$ and $o \in W; q \in Q_W$)

$V_{s\ell}^r =$ 1 if raw material r is procured by plant ℓ from supplier s, 0 otherwise ($r \in R$; $s \in S^r$; $\ell \in L$)

$U_{od}^m =$ 1 if destination d is supplied by origin o using transportation mode m, 0 otherwise ($o \in O$; $d \in D$; $m \in M_{od}$)

$X_{s\ell}^{rm}$: Amount of raw material r distributed from supplier s to plant ℓ with transportation mode m ($r \in R$; $s \in S^r; \ell \in L$; $m \in M_{s\ell}$)

$X_{\ell w}^{pm}$: Amount of end product p shipped from plant ℓ to warehouse w with transportation mode m ($p \in P$; $\ell \in L^p$; $w \in W^p$; $m \in M_{\ell w}$)

XE_w^p : Amount of product p provided by an external source to warehouse w ($p \in P$; $w \in W^p$)

3.2.1 Network design constraints

We now describe in detail the constraints in our formulation. The constraints are arranged according to the different supply chain-related functions that they cover.

Supplier-specific constraints

The following conditions rule the selection of suppliers and the procurement of raw materials.

$$\sum_{\ell \in L} \sum_{m \in M_{s\ell}} X_{s\ell}^{rm} \le \overline{SQR}_s^r \qquad r \in R,\ s \in S^r \tag{1}$$

$$\sum_{s \in S^r} V_{s\ell}^r \le 1 \qquad r \in R,\ \ell \in L \tag{2}$$

$$\sum_{m \in M_{s\ell}} X_{s\ell}^{rm} \le \overline{SQR}_s^r V_{s\ell}^r \qquad r \in R,\ s \in S^r,\ \ell \in L \tag{3}$$

Constraints (1) impose capacity limits on the amount of raw materials delivered by the suppliers, while constraints (2) ensure that each plant cannot choose more than one supplier to provide raw material r. Constraints (3) guarantee that a given raw material r is not transported from supplier s to plant ℓ unless supplier s has been selected by plant ℓ.

Constraints involving plants and warehouses

The conditions required for the selection of plant and warehouse locations, the choice of their capacity levels, and the operation of these facilities are given next.

$$\sum_{q \in Q_L} Z_\ell^q \leq 1 \qquad \ell \in L \tag{4}$$

$$\sum_{q \in Q_W} Z_w^q \leq 1 \qquad w \in W \tag{5}$$

$$\sum_{s \in S^r} \sum_{m \in M_{s\ell}} X_{s\ell}^{rm} = \sum_{p \in P^r} a^{rp} \left[\sum_{w \in W^p} \sum_{m \in M_{\ell w}} X_{\ell w}^{pm} + \sum_{c \in C^p} \sum_{m \in M_{\ell c}} d_c^p \, U_{\ell c}^m \right] \qquad r \in R, \; \ell \in L \tag{6}$$

$$\sum_{q \in Q_L} \underline{LQ}_{\ell q} Z_\ell^q \leq \sum_{p \in P} PU^p \left[\sum_{w \in W^p} \sum_{m \in M_{\ell w}} X_{\ell w}^{pm} + \sum_{c \in C^p} \sum_{m \in M_{\ell c}} d_c^p \, U_{\ell c}^m \right] \leq \sum_{q \in Q_L} \overline{LQ}_{\ell q} Z_\ell^q \qquad \ell \in L \tag{7}$$

$$PU^p \left[\sum_{w \in W^p} \sum_{m \in M_{\ell w}} X_{\ell w}^{pm} + \sum_{c \in C^p} \sum_{m \in M_{\ell c}} d_c^p \, U_{\ell c}^m \right] \leq \sum_{q \in Q_L} \overline{LQP}_{\ell q}^{\,p} Z_\ell^q \qquad p \in P, \; \ell \in L^p \tag{8}$$

$$\sum_{q \in Q_W} \underline{SQ}_{wq} Z_w^q \leq \sum_{p \in P} SU^p \sum_{c \in C^p} \sum_{m \in M_{wc}} d_c^p \, U_{wc}^m \leq \sum_{q \in Q_W} \overline{SQ}_{wq} Z_w^q \qquad w \in W \tag{9}$$

Constraints (4), resp. (5), ensure that at most one plant, resp. warehouse, is established in a candidate location with a given capacity level. Equalities (6) stipulate that each plant procures the exact quantity of raw material needed to manufacture end products. Constraints (7) state that the total amount of end products manufactured in a plant must be within pre-specified lower and upper limits. In addition to these global capacities, also production capacity limits per product are enforced through inequalities (8). Observe that the terms between the square brackets in (6)–(8) concern shipments from plants to warehouses and from plants to customer zones. Global storage capacity constraints are imposed for warehouses through constraints (9).

Customer-specific and flow conservation constraints

Demand satisfaction and other customer-specific conditions are as follows.

$$\sum_{\ell \in L} \sum_{m \in M_{\ell c}} U_{\ell c}^{m} + \sum_{w \in W} \sum_{m \in M_{wc}} U_{wc}^{m} = 1 \qquad c \in C \tag{10}$$

$$\sum_{c \in C^p} \sum_{m \in M_{wc}} d_c^p U_{wc}^{m} = \sum_{\ell \in L^p} \sum_{m \in M_{\ell w}} X_{\ell w}^{pm} + XE_w^p \qquad p \in P,\ w \in W^p \tag{11}$$

$$\sum_{w \in W^p} XE_w^p \leq \beta_p \sum_{c \in C^p} d_c^p \qquad p \in P \tag{12}$$

$$\sum_{m \in M_{\ell c}} \sum_{p \in P} d_c^p U_{\ell c}^{m} \geq \lambda \sum_{m \in M_{\ell c}} U_{\ell c}^{m} \qquad \ell \in L,\ c \in C \tag{13}$$

Constraints (10) guarantee the satisfaction of demand. Due to the binary nature of variables U_{od}^m, each customer zone is assigned either to a plant or to a warehouse. Moreover, a single mode of transportation must be used for the delivery of end products to a customer zone. Equalities (11) impose the conservation of flow per product in each warehouse. These constraints along with inequalities (9) state that outsourced products also use the handling capacity installed in warehouses. Furthermore, an upper limit on the total outsourced quantity per product is enforced through constraints (12). Inequalities (13) permit the direct delivery of a customer zone from a plant unless a given minimum total quantity is transported.

Transportation-related constraints

The following conditions rule the selection and usage of transportation modes across the supply chain network.

$$\underline{MQ}_{s\ell}^{m} U_{s\ell}^{m} \leq \sum_{r \in R} MU^{rm} X_{s\ell}^{rm} \leq \overline{MQ}_{s\ell}^{m} U_{s\ell}^{m} \qquad s \in S,\ \ell \in L,\ m \in M_{s\ell} \tag{14}$$

$$\underline{MQ}_{\ell w}^{m} U_{\ell w}^{m} \leq \sum_{p \in P} MU^{pm} X_{\ell w}^{pm} \leq \overline{MQ}_{\ell w}^{m} U_{\ell w}^{m} \qquad \ell \in L,\ w \in W,\ m \in M_{\ell w} \tag{15}$$

$$\underline{MQ}_{\ell c}^{m} U_{\ell c}^{m} \leq \sum_{p \in P} MU^{pm} d_c^p U_{\ell c}^{m} \leq \overline{MQ}_{\ell c}^{m} U_{\ell c}^{m} \qquad \ell \in L,\ c \in C,\ m \in M_{\ell c} \tag{16}$$

$$\underline{MQ}_{wc}^{m} U_{wc}^{m} \leq \sum_{p \in P} MU^{pm} d_c^p U_{wc}^{m} \leq \overline{MQ}_{wc}^{m} U_{wc}^{m} \qquad w \in W,\ c \in C,\ m \in M_{wc} \tag{17}$$

Constraints (14) enforce minimum and maximum limits on the amount of raw materials distributed from suppliers to plants using a given transportation mode. For moving end products, constraints (15)–(17) also enforce minimum and maximum limits on transportation modes.

Domains of variables

Finally, binary and non-negativity conditions are set by (18)-(23).

$$Z_o^q \in \{0,1\} \qquad o \in L,\ q \in Q_L;\ o \in W,\ q \in Q_W \tag{18}$$

$$V_{s\ell}^r \in \{0,1\} \qquad r \in R,\ s \in S^r,\ \ell \in L \tag{19}$$

$$U_{od}^m \in \{0,1\} \qquad o \in O,\ d \in D,\ m \in M_{od} \tag{20}$$

$$X_{s\ell}^{rm} \geq 0 \qquad r \in R,\ s \in S^r,\ \ell \in L,\ m \in M_{s\ell} \tag{21}$$

$$X_{\ell w}^{pm} \geq 0 \qquad p \in P,\ \ell \in L^p,\ w \in W^p,\ m \in M_{\ell w} \tag{22}$$

$$XE_w^p \geq 0 \qquad p \in P,\ w \in W^p \tag{23}$$

3.2.2 Objective function

The objective function (24) minimizes the sum of all strategic and tactical costs. The first two components represent the fixed costs for opening plants and warehouses, and installing capacity in these facilities. The remaining components account for variable costs for procurement, production, and transportation operations, along with costs for purchasing end products from external sources.

$$\begin{aligned}
\text{Min } & \sum_{\ell \in L} \sum_{q \in Q_L} FCF_\ell^q Z_\ell^q + \sum_{w \in W} \sum_{q \in Q_W} FCF_w^q Z_w^q + \\
& \sum_{r \in R} \sum_{s \in S^r} \sum_{\ell \in L} \sum_{m \in M_{s\ell}} [CP_s^r + CT_{s\ell}^{rm}]\, X_{s\ell}^{rm} + \\
& \sum_{p \in P} \sum_{\ell \in L^p} \sum_{w \in W^p} \sum_{m \in M_{\ell w}} [CM_\ell^p + CT_{\ell w}^{pm}]\, X_{\ell w}^{pm} + \\
& \sum_{p \in P} \sum_{c \in C^p} d_c^p \left[\sum_{\ell \in L^p} \sum_{m \in M_{\ell c}} (CM_\ell^p + CT_{\ell c}^{pm})\, U_{\ell c}^m + \sum_{w \in W^p} \sum_{m \in M_{wc}} CT_{wc}^{pm} U_{wc}^m \right] + \\
& \sum_{p \in P} \sum_{w \in W^p} CO_w^p\, XE_w^p
\end{aligned} \tag{24}$$

3.3 The value of product outsourcing

Partial product outsourcing is a business strategy often adopted by firms when the available production capacity is insufficient to cover all customer demand requirements and the level of investment needed to install additional capacity is too high. The mathematical model presented in the previous section enables a firm to identify the optimal configuration for its supply chain network, and at the same time finds the best mix between in-house manufacturing and product outsourcing. It is meaningful to enforce a maximum limit on the proportion of each end product that may be purchased from an external source through setting $0 < \beta_p < 1$ ($p \in P$) since otherwise manufacturing processes could be entirely deactivated and demands could be solely satisfied through subcontracted production. In this case, the firm would simply become a wholesaler, an extreme strategy with significant disadvantages such as losing control over business-critical tasks, weakening the firm's market position, and being exposed to various risks (Fredriksson et al. [11]; Kerkhoff et al. [14]). For these reasons, we will not consider this business strategy in our study. We denote by $(\mathbf{P}_\beta)$ the MILP formulation (1)–(24) representing the combination of in-house manufacturing and partial product outsourcing.

For the firm managing the supply chain network it would also be interesting to assess the impact on the design of its network of manufacturing all products in-house. To address this alternative strategy, model $(\mathbf{P}_\beta)$ is restricted by imposing $\beta_p = 0$ for every $p \in P$. Accordingly, variables XE^p_w are eliminated, constraints (12) and (23) are removed, and the flow conservation constraints (11) are replaced by the following equalities:

$$\sum_{c \in C^p} \sum_{m \in M_{wc}} d^p_c \, U^m_{wc} = \sum_{\ell \in L^p} \sum_{m \in M_{\ell w}} X^{pm}_{\ell w} \qquad p \in P, \; w \in W^p \tag{11'}$$

Moreover, the last cost component in the objective function (24) is also eliminated. Let $(\mathbf{P}_0)$ denote this particular case of formulation $(\mathbf{P}_\beta)$ which involves constraints (1)–(10), $(11')$, (13)–(22). A comparison of the optimal solutions to $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$ will provide various insights, for example, into the investment effort required for locating and sizing facilities, especially at the plant level. In addition, similarities and differences in raw material sourcing, product distribution, and transportation mode selection will also be revealed.

A common feature of formulations $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$ is the enforcement of 100% service level through complete demand coverage. A further analysis of the value of product outsourcing is to compare this strategy with the option of allowing demand requirements to be partially met and keeping the single-assignment conditions. In this case, product outsourcing is not permitted and therefore, any end products delivered to customer zones must be in-house manufactured. Under this new scenario, cost savings are expected to be achieved in the configuration of the supply chain network since lower production and storage capacities may be required. Therefore, the number, size, and location of plants and warehouses will likely differ from the choices made in $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$. Furthermore, it will also be possible to identify those customer zones whose demands are not attractive to be (completely) satisfied. In this way, a firm will gain a clearer perception of the consequences of service level reduction as opposed to full demand satisfaction, the latter being achieved either by total in-house manufacturing capabilities (model $(\mathbf{P}_0)$) or by resorting to partial product outsourcing (model $(\mathbf{P}_\beta)$).

In order to adapt formulation $(\mathbf{P}_0)$ to the partial demand satisfaction case, we introduce the following continuous variables for shipments from warehouses to customer zones.

X_{wc}^{pm} : Amount of product p delivered from warehouse w to customer zone c with transportation mode m $(p \in P;\ w \in W^p; c \in C^p;\ m \in M_{wc})$

Flow variables for direct deliveries from plants to customers are not additionally defined because we keep the requirement of serving all the demand of a customer zone if the latter is assigned to a plant. Recall that direct shipments from plants to customer zones are only possible for large demands. By retaining such customers, their strategic importance for the firm is emphasized. Partial demand satisfaction is only allowed for customer zones assigned to warehouses.

Constraints (9), $(11')$ and (17) need to be modified through replacing the term $d_c^p\,U_{wc}^m$ by the new variables, X_{wc}^{pm}. In addition, the single-assignment constraints (10) become inequalities and new constraints are defined to guarantee that each customer zone receives at most the quantity of product ordered (cf. (25)). In view of the performance measure adopted to design the supply chain network, namely the minimization of total cost, the relaxation of constraints (10) calls for the enforcement of a minimum service level. The choice of a minimum demand satisfaction level is directly related to the maximum product outsourcing level considered in formulation $(\mathbf{P}_\beta)$ in order to be able to compare the new scenario with $(\mathbf{P}_\beta)$. This is accomplished by imposing the proportion of demand satisfied for every product p to be at least equal to $1-\beta_p$ $(p \in P)$ through the new constraints (26). For example, imposing a maximum outsourcing level of 20% in $(\mathbf{P}_\beta)$ for each end product corresponds to setting a minimum demand satisfaction level of 80% in the new scenario. Hence, in both cases, at least 80% of all demand requirements for a product must be covered by in-house production. These modifications give rise to the following new constraints:

$$\sum_{q\in Q_W} \underline{SQ}_w^q\, Z_w^q \le \sum_{p\in P} SU^p \sum_{c\in C^p} \sum_{m\in M_{wc}} X_{wc}^{pm} \le \sum_{q\in Q_W} \overline{SQ}_w^q\, Z_w^q \quad w \in W \qquad (9')$$

$$\sum_{\ell\in L} \sum_{m\in M_{\ell c}} U_{\ell c}^m + \sum_{w\in W} \sum_{m\in M_{wc}} U_{wc}^m \le 1 \qquad c \in C \qquad (10')$$

$$\sum_{c \in C^p} \sum_{m \in M_{wc}} X_{wc}^{pm} = \sum_{\ell \in L^p} \sum_{m \in M_{\ell w}} X_{\ell w}^{pm} \qquad p \in P, \; w \in W^p \tag{11''}$$

$$\underline{MQ}_{wc}^m U_{wc}^m \leq \sum_{p \in P} MU^{pm} X_{wc}^{pm} \leq \overline{MQ}_{wc}^m U_{wc}^m \qquad w \in W, \; c \in C, \; m \in M_{wc} \tag{17'}$$

$$\sum_{\ell \in L^p} \sum_{m \in M_{\ell c}} d_c^p U_{\ell c}^m + \sum_{w \in W^p} \sum_{m \in M_{wc}} X_{wc}^{pm} \leq d_c^p \qquad p \in P, \; c \in C^p \tag{25}$$

$$\sum_{\ell \in L^p} \sum_{c \in C^p} \sum_{m \in M_{\ell c}} d_c^p U_{\ell c}^m + \sum_{w \in W^p} \sum_{c \in C^p} \sum_{m \in M_{wc}} X_{wc}^{pm} \geq (1 - \beta_p) \sum_{c \in C^p} d_c^p \qquad p \in P \tag{26}$$

$$X_{wc}^{pm} \geq 0 \qquad p \in P, \; w \in W^p, \; c \in C^p, \; m \in M_{wc} \tag{27}$$

Finally, the objective function of the new formulation is as follows:

$$\begin{aligned}
\text{Min} \; & \sum_{\ell \in L} \sum_{q \in Q_L} FCF_\ell^q Z_\ell^q + \sum_{w \in W} \sum_{q \in Q_W} FCF_w^q Z_w^q + \\
& \sum_{r \in R} \sum_{s \in S^r} \sum_{\ell \in L} \sum_{m \in M_{s\ell}} [CP_s^r + CT_{s\ell}^{rm}] \, X_{s\ell}^{rm} + \\
& \sum_{p \in P} \sum_{\ell \in L^p} \sum_{w \in W^p} \sum_{m \in M_{\ell w}} [CM_\ell^p + CT_{\ell w}^{pm}] \, X_{\ell w}^{pm} + \\
& \sum_{p \in P} \sum_{c \in C^p} d_c^p \left[\sum_{\ell \in L^p} \sum_{m \in M_{\ell c}} (CM_\ell^p + CT_{\ell c}^{pm}) \, U_{\ell c}^m \right] + \\
& \sum_{p \in P} \sum_{w \in W^p} \sum_{c \in C^p} \sum_{m \in M_{wc}} CT_{wc}^{pm} X_{wc}^{pm}
\end{aligned} \tag{28}$$

The MILP model for the partial demand satisfaction scenario, denoted by $(\mathbf{PDS})$, is given by (1)–(8), (9′), (10′), (11″), (13)–(16), (17′), (18)–(22), (25)–(28).

To measure the relevance of combining in-house manufacturing and partial product outsourcing, we will compare the (optimal) network configuration and the associated costs obtained with formulation $(\mathbf{P}_\beta)$ with the (optimal) solutions to problems $(\mathbf{P}_0)$ and $(\mathbf{PDS})$. This comparison, which we call the *value of product outsourcing*, will enable a firm to gain insight into the trade-offs that are achieved with different strategies.

Finally, we remark that the three problems that we study belong to the class of NP-hard problems as they generalize the single-source capacitated facility location problem (Cortinhal and Captivo [6]). Furthermore, single-sourcing conditions for raw material procurement, decisions regarding the selection of transportation modes, and single-assignment constraints for serving customers pose significant additional challenges because of the very large number of binary variables that need to be defined.

3.4 Comparison of formulations

Formulations $(\mathbf{P}_\beta)$, $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ share the same number of binary variables, namely

$$\begin{aligned}\mathcal{O}\,(&|L|\cdot|Q_L| + |W|\cdot|Q_W| + |S|\cdot|L|\cdot|R| + |M|\cdot(|S|\cdot|L| + |L|\cdot|W| + \\ &|L|\cdot|C| + |W|\cdot|C|))\,.\end{aligned}$$

Moreover, formulation $(\mathbf{P}_\beta)$ has in total $\mathcal{O}(|M|\cdot|L|\cdot(|S|\cdot|R| + |W|\cdot|P|) + |W|\cdot|P|)$ continuous variables. Model $(\mathbf{P}_0)$ has slightly fewer variables owing to the elimination of the product outsourcing variables, XE^p_w. In contrast, formulation $(\mathbf{PDS})$ has significantly more continuous variables due to the introduction of flow variables between warehouses and customer zones. Specifically, the total number of additional variables is $\mathcal{O}(|W|\cdot|C|\cdot|P|\cdot|M|)$. Since the number of customer zones is typically much larger than the number of potential locations for warehouses, the new variables X^{pm}_{wc} have a major impact on the total size of model $(\mathbf{PDS})$. In the problem instances that were generated for our computational study (cf. Section 5), the total number of continuous variables increases by a factor of almost 5.5 when formulation $(\mathbf{PDS})$ is considered instead of formulations $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$.

Regarding the number of constraints, there are no striking differences between the three formulations. Model $(\mathbf{P}_\beta)$ has in total

$$\begin{aligned}\mathcal{O}\,(&|R|\cdot|L|\cdot(|S|+2) + |R|\cdot|S| + 2|M|\cdot(|S|\cdot|L| + |L|\cdot|W| + |L|\cdot|C| + \\ &|W|\cdot|C|) + |P|\cdot(|L| + |W| + 1) + 3|L| + 3|W| + |C|\cdot(|L| + 1))\end{aligned}$$

constraints. Model $(\mathbf{P}_0)$ has $|P|$ fewer constraints, while formulation $(\mathbf{PDS})$ has $|P|\cdot|C|$ additional constraints.

4 Enhancing the mathematical formulations

As our comparative analysis in the previous section has shown, we are dealing with three large-scale MILP formulations even for moderate sizes of the sets S, L, W, C, R, and P. Extensive computational experience on MILP models suggests that when the lower bounds provided by the solutions to their linear programming (LP) relaxations are tight, the chance of a standard, off-the-shelf MILP solver of being computationally effective increases. Therefore, it is important to strengthen formulations $(\mathbf{P}_\beta)$, $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ with additional inequalities. In this section, we present eight classes of valid inequalities that can be added to our formulations.

Plants play a key role in the supply chain network as they are linked to facilities in the other three stages of the network. By developing a lower bound (np) on the total number of plants that must be open, we can add the following inequality:

$$\sum_{l\in L}\sum_{q\in Q_L} Z_\ell^q \geq np \tag{29}$$

The lower bound np depends on the minimum amount of total demand that needs to be satisfied for each end product through in-house manufacturing. For formulations $(\mathbf{P}_\beta)$ and $(\mathbf{PDS})$, the latter is given by $\underline{D}^p = (1-\beta_p)\sum_{c\in C^p} d_c^p$ for every $p \in P$. Since $\beta_p = 0$ in formulation $(\mathbf{P}_0)$, in that case $\underline{D}^p$ represents the total demand for end product p. The minimum demand requirements $\underline{D}^1,\ldots,\underline{D}^{|P|}$ pose, in turn, different requirements with respect to the total quantity of raw materials to be procured and the total production capacity to be installed. Regarding the first factor, the minimum total quantity of raw material r needed for manufacturing the end products is determined by

$$\underline{A}^r \;=\; \sum_{p\in P} a^{rp}\underline{D}^p \qquad\qquad r\in R$$

We now identify the minimum number of suppliers that must be selected to provide (in total) at least $\underline{A}^r$ units of raw material r. To this end, we sort the suppliers by non-increasing capacities and denote the corresponding sequence by $\overline{SQR}^r_{[1]} \geq \overline{SQR}^r_{[2]} \geq \ldots \geq \overline{SQR}^r_{[|S^r|]}$, with $\overline{SQR}^r_{[i]}$ indicating the capacity of the ith supplier for raw material r in this list. We then calculate the value of m^r such that the following inequalities hold

$$\sum_{i=1}^{m^r-1}\overline{SQR}^r_{[i]} < \underline{A}^r \leq \sum_{i=1}^{m^r}\overline{SQR}^r_{[i]}$$

After obtaining m^r for each $r \in R$, we take $m = \max_{r\in R}\{m^r\}$. Since each open plant must purchase all units of a specific raw material from a single supplier, the value of m represents the minimum number of plants that must be operated to ensure an adequate provision of raw materials.

The second factor affecting the lower bound np in (29) is the total plant capacity that needs to be available so that at least $\underline{D}^p$ units of product p can be in-house manufactured. We first consider the largest product-dependent capacity level that can be selected in each candidate plant location $\ell \in L^p$, and build a sequence with these capacity sizes $\overline{LQP}^p_{\ell|Q_L|}$, sorted by non-increasing order. Therefore, by denoting $LPQ^p_{[i]}$ the potential plant location with the ith largest capacity level for product p, this sequence is given by $LPQ^p_{[1]} \geq LPQ^p_{[2]} \geq \ldots \geq LPQ^p_{[|L^p|]}$. We then identify the number k^p that satisfies the following inequalities:

$$\sum_{i=1}^{k^p-1} LPQ^p_{[i]} \; < \; PU^p \underline{D}^p \; \leq \; \sum_{i=1}^{k^p} LPQ^p_{[i]}$$

Hence, k^p is the minimum number of plants that need to be established to achieve the required level of in-house production for end product p. By calculating $k = \max_{p \in P}\{k^p\}$, we obtain the total minimum number of plants to be open from the perspective of the required in-house production capacity. Finally, the right-hand side of inequality (29) is determined by $np = \max\{m, k\}$. When every candidate plant location may manufacture all types of products (i.e. $L^p = L$ for every $p \in P$), we can additionally take into account the minimum global capacity that needs to be available. In this case, we sort the potential plants by non-increasing order of their largest global capacity levels $\overline{LQ}_{\ell|Q_L|}$ as follows: $\overline{LQ}_{[1]} \geq \overline{LQ}_{[2]} \geq \ldots \geq \overline{LQ}_{[|L|]}$. Next, we determine the value of j for which the following conditions hold:

$$\sum_{i=1}^{j-1} \overline{LQ}_{[i]} < \sum_{p \in P} PU^p \, \underline{D}^p \; \leq \; \sum_{i=1}^{j} \overline{LQ}_{[i]}$$

The lower bound imposed by inequality (29) is then $np = \max\{m, k, j\}$. Usually, the minimum global capacity requirement dictates a value of j that is smaller than the other two parameters, m and k.

Five classes of additional valid inequalities are now presented. Inequalities (30) ensure that a transportation mode can only be used for raw material distribution when the destination plant is open. Analogously, the choice of a particular transportation mode for deliveries from plants to warehouses is only permitted if both facilities are operated as enforced by inequalities (31) and (32). Conditions (33) make sure that raw materials may only be procured by operating plants. Inequalities (34) result from the fact that there is positive demand for every end product. Therefore, all products will be manufactured and consequently, at least one supplier must be selected to deliver a specific raw material. Recall that complete product outsourcing is not permitted in formulation $(\mathbf{P}_\beta)$ since $0 < \beta_p < 1$ for every $p \in P$. In formulation $(\mathbf{PDS})$, a minimum demand satisfaction level $(1 - \beta_p)$ is enforced which can only be achieved through in-house production. We assume that parameter β_p is assigned a meaningful value, thus preventing any given end product from not being in-house manufactured.

$$U_{s\ell}^m \leq \sum_{q \in Q_L} Z_\ell^q \qquad s \in S,\ \ell \in L,\ m \in M_{s\ell} \tag{30}$$

$$U_{\ell w}^m \leq \sum_{q \in Q_L} Z_\ell^q \qquad \ell \in L,\ w \in W,\ m \in M_{\ell w} \tag{31}$$

$$U_{\ell w}^m \leq \sum_{q \in Q_W} Z_w^q \qquad \ell \in L,\ w \in W,\ m \in M_{\ell w} \tag{32}$$

$$\sum_{s \in S^r} V_{s\ell}^r \leq \sum_{q \in Q_L} Z_\ell^q \qquad r \in R,\ \ell \in L \tag{33}$$

$$\sum_{s \in S^r} \sum_{\ell \in L} V_{s\ell}^r \geq 1 \qquad r \in R \tag{34}$$

Two other classes of inequalities – (35) and (36) – were also developed that guarantee the assignment of each customer zone to an open facility, either a plant or a warehouse. The form of these inequalities results from the single-assignment requirements and the selection of a single mode of transportation for product distribution (cf. constraints (10) and $(10')$). Conditions (35)–(36) proved to be computationally expensive since they include a significant number of constraints given the sizes of our test problems. In fact, they represent almost twice the total number of the other six groups of inequalities (29)–(34). For this reason, we have excluded them from our computational study.

$$\sum_{m \in M_{\ell c}} U_{\ell c}^m \leq \sum_{q \in Q_\ell} Z_\ell^q \qquad \ell \in L,\ c \in C \tag{35}$$

$$\sum_{m \in M_{wc}} U_{wc}^m \leq \sum_{q \in Q_w} Z_w^q \qquad w \in W,\ c \in C \tag{36}$$

5 Computational study

In recent years, remarkable advances have been witnessed in the capabilities of general purpose optimization software to solve many difficult real-world problems effectively. As a result, many firms resort nowadays to standard, off-the-shelf solvers for decision support. Optimality is often of no primary interest for practitioners due to, for example, errors contained in the data of real-life applications (Cordeau et al. [5]) and the computational burden incurred to identify an optimal solution. In fact, greater importance is given to obtaining good feasible solutions within reasonable time limits for practical purposes. Moreover, many firms lack the skills or cannot afford the high costs of expertise advice to develop specially tailored algorithms (e.g., heuristics) for their individual problems. Hence, general purpose solvers have become increasingly attractive and their use is now widespread. In this section, we evaluate the performance of CPLEX on a set of randomly generated test instances. We first briefly describe the methodology developed to obtain these instances in Section 5.1, followed by a summary of the numerical results in Section 5.2. In addition, relevant insights into the characteristics of the best solutions identified are discussed in Sections 5.2.1 and 5.2.2, and the value of product outsourcing is measured.

5.1 Characteristics of test instances

As benchmark instances are not available for the problems at hand, we randomly generated a set of test instances by combining the values indicated in Table 2. The size of an instance is mainly dictated by the total number of customer zones, which is used to define the total number of suppliers, plants, warehouses, raw materials, and end products. It is assumed that any type of end product may be manufactured in each potential plant location, i.e. $L^p = L$ for every $p \in P$. Likewise, each warehouse may handle all end products, and thus $W^p = W$ ($p \in P$).

Symbol	Description	Value
$\|C\| = n$	Number of customer zones	$100, 125, 150, 175, 200$
$\|L\|$	Number of potential plant locations	$\lceil \frac{n}{10} \rceil$
$\|W\|$	Number of potential warehouse locations	$\lceil \frac{n}{5} \rceil$
$\|R\|, \|P\|$	Number of raw materials, resp. end products	$\lceil \frac{n}{5} \rceil$
$\|S\|$	Number of suppliers	$\lceil \frac{n}{10} \rceil$
$\|M\|$	Number of transportation modes	3
$\|Q_L\|, \|Q_W\|$	Number of capacity levels for plants, resp. warehouses	3

Table 2: Cardinality of index sets.

In total, three different transportation modes are considered. Mode 1 represents rail freight transportation and is available for long-haul shipments of raw materials from suppliers to plants, and for moving end products from plants to warehouses. Modes 2 and 3 are associated with road freight transportation as this is one of the most used modes of transportation, in particular for international shipments, and for which operators offer several options [10]. For that reason, we assume that road freight transportation can be selected between any origin and destination in the supply chain network. Moreover, two types of vehicles are considered, hereafter named small and large trucks. Shipments with large trucks (mode 3) are less expensive than with small trucks (mode 2), but the usage of the former is constrained by a minimum vehicle load which is not enforced for transports with mode 2. Furthermore, since vehicles are rented from a 3PL provider no capacity limits are imposed on the amount of goods that can be transported by truck, i.e. $\overline{MQ}_{od}^{m} = +\infty$ for $o \in O$, $d \in D$ and $m = 2, 3$. For rail transports, minimum and maximum usage levels are pre-specified.

Three global capacity levels are available, both at plant and warehouse locations, representing small, medium, and large sizes. We first generate the largest capacity level that may be installed in a potential plant location, $\overline{LQ}_{\ell 3}$ ($\ell \in L$), resp. warehouse location, $\overline{SQ}_{w3}$ ($w \in W$) (see Appendix A for details). Any other global size is equal to 70% of the capacity of the subsequent level. Hence, the smallest (medium) capacity level corresponds to 49% (70%) of the largest capacity level. In addition, three capacity options are also available for manufacturing an end product in a plant. The largest capacity size for product p is defined as $0.6\,\overline{LQ}_{\ell 3}$. The medium (small) capacity level for product p is fixed at 60% of the largest (medium) size.

The demand of each customer zone for a given end product is randomly generated from a continuous uniform distribution in the interval $[1, 10]$. Furthermore, $C^p = C$ for every $p \in P$, and so all customers have a positive demand for every end product. The minimum total amount of end products that may be delivered directly from a plant to a customer zone, λ, is equal to the third quartile of the total demand of a customer. In formulation $(\mathbf{P}_\beta)$, the maximum fraction of the total demand for product p that can be outsourced is fixed at 0.2. As a result, we enforce at least 80% of the total demand for product p to be satisfied in formulation $(\mathbf{PDS})$ by setting $1 - \beta_p = 0.8$ ($p \in P$).

Further details on the generation of the test instances are provided in Appendix A. In particular, a sophisticated scheme for obtaining the BOM, and the capacity and cost parameters is described. Even though the test instances are generated randomly, they reflect realistic characteristics of SCND problems.

5.2 Summary of numerical results

Formulations $(\mathbf{P}_\beta)$, $(\mathbf{P}_0)$, and $(\mathbf{PDS})$, including their enhancements, were coded in C++ using IBM ILOG Concert Technology and solved with IBM ILOG CPLEX 12.5. All experiments were conducted on a PC with a 2.9 GHz Intel® Core™ i7-3520M processor, 8 GB RAM, and running Windows 7 (64-bit). Since the problems that we study have a strategic nature, fast solution times are not of paramount importance. Therefore, we set a limit of 8 hours of CPU time for each solver run. Furthermore, a deterministic parallel mode was selected to ensure that multiple runs with a particular instance reproduce the same solution path and results. For each choice of $|C|$, five instances were randomly generated. Each one of these instances was considered with the three formulations. In addition, the enhancements proposed in Section 4 were tested by combining different families of additional inequalities. In total, 450 runs were performed for the purpose of our study. Preprocessing tests were also implemented with the goal of reducing the size of the formulations. Accordingly, the binary variables $U_{\ell c}^m$ are fixed at zero for all plants $\ell \in L$ and all transportation modes $m \in M_{\ell c}$ if the total demand of customer zone c is less than the minimum threshold λ (cf. constraints (13)). Moreover, the variable U_{wc}^3 is set equal to zero if the total demand of customer c is less than the minimum quantity that can be shipped from warehouse w using mode $m = 3$ (large trucks).

Table 3 provides a summary of the results obtained for different sizes of the customer set (column 1). For each one of the three problems, six formulations were tested. The original formulations $(\mathbf{P}_\beta)$, $(\mathbf{P}_0)$ and $(\mathbf{PDS})$, that were presented in Section 3, are designated *base* formulations. Besides combining the additional inequalities in several different ways, we also tested the assignment of priority orders to some of the binary variables during branching. Preliminary tests indicated that often better solutions can be achieved when higher branching priority is given to the plant location variables, Z_ℓ^q. This is possibly explained by the fact that plants interact with all the other entities in the network (i.e., suppliers, warehouses, and customer zones with large demands). Therefore, giving preference to these variables during the branch-and-cut algorithm seems to help CPLEX identify promising network configurations. Similar tests were also conducted by assigning higher priorities to the warehouse location variables but, on average, the quality of the solutions obtained was inferior. As displayed in column 2 in Table 3, branching priorities (BP) were used with some of the enhanced formulations.

For each type of problem and formulation, Table 3 also reports the number of instances that were solved to optimality (#opt), the number of instances for which the optimal solution

$\lvert C \rvert$	Formulation	Complete demand satisfaction								Partial demand satisfaction			
		In-house production and outsourcing ($\mathbf{P}_\beta$)				In-house production ($\mathbf{P}_0$)				In-house production (**PDS**)			
		#opt/ #nopt/ #nf	Avg MIP gap (%)	Dev. to base (%)	Avg LP gap (%)	#opt/ #nopt/ #nf	Avg MIP gap (%)	Dev. to base (%)	Avg LP gap (%)	#opt/ #nopt/ #nf	Avg MIP gap (%)	Dev. to base (%)	Avg LP gap (%)
100	Base	3/2/0	0.94		8.72	0/5/0	3.82		11.05	0/5/0	5.97		13.45
	Base+(29)–(32)	1/4/0	2.23	-136.73	8.61	0/5/0	3.86	-0.99	10.46	0/5/0	4.73	20.78	10.70
	Base+(29)–(32)+BP	3/2/0	0.50	47.13	8.08	1/4/0	0.92	75.86	10.08	0/5/0	3.34	44.05	10.37
	Base+(29)+(33)+(34)	3/2/0	0.95	-0.85	7.21	0/5/0	3.89	-1.94	9.47	0/5/0	5.27	11.70	10.74
	Base+(29)+(33)+(34)+BP	4/1/0	**0.14**	**99.34**	7.13	2/3/0	**0.67**	**82.46**	8.69	0/5/0	3.73	37.41	10.39
	Base+(29)–(34)+BP	3/2/0	0.54	97.36	**6.65**	2/3/0	0.80	79.11	**8.27**	0/5/0	**2.34**	**60.74**	**9.16**
125	Base	0/5/0	3.11		8.48	0/5/0	3.22		8.73	0/5/0	7.91		12.78
	Base+(29)–(32)	0/5/0	3.40	-9.31	8.11	0/5/0	3.71	-15.22	8.60	0/5/0	8.68	-9.79	12.66
	Base+(29)–(32)+BP	0/5/0	0.69	77.84	7.87	0/5/0	0.68	78.88	8.14	0/5/0	7.65	3.31	12.61
	Base+(29)+(33)+(34)	0/5/0	3.81	-22.29	7.65	0/5/0	4.24	-31.61	7.82	0/5/0	8.13	-2.86	11.87
	Base+(29)+(33)+(34)+BP	1/4/0	**0.54**	**82.66**	7.04	0/5/0	**0.52**	**86.34**	7.48	0/5/0	**6.87**	**13.10**	**11.68**
	Base+(29)–(34)+BP	0/5/0	0.86	72.51	**6.83**	0/5/0	0.94	75.29	**7.31**	0/5/0	6.98	11.76	11.71
150	Base	0/5/0	6.72		10.89	0/5/0	7.63		11.47	0/5/0	14.65		18.82
	Base+(29)–(32)	0/5/0	5.88	12.53	10.26	0/5/0	6.22	18.53	10.47	0/5/0	**8.40**	42.63	12.25
	Base+(29)–(32)+BP	0/5/0	2.97	55.79	9.44	0/5/0	**3.56**	**53.38**	9.99	0/5/0	8.80	39.90	12.77
	Base+(29)+(33)+(34)	0/5/0	5.81	13.49	9.38	0/5/0	6.27	17.87	9.91	0/5/0	9.43	35.61	12.86
	Base+(29)+(33)+(34)+BP	0/5/0	**2.30**	**65.82**	**8.52**	0/5/0	3.67	51.86	**9.65**	0/5/0	10.43	28.81	13.84
	Base+(29)–(34)+BP	0/5/0	4.44	33.85	9.34	0/5/0	4.54	40.57	9.69	0/5/0	**8.40**	**42.67**	**12.01**
175	Base	0/5/0	11.35		16.15	0/5/0	12.24		17.04	0/4/1	22.43		18.07
	Base+(29)–(32)	0/5/0	11.19	1.41	16.18	0/5/0	12.27	-0.25	17.06	0/5/0	13.32	40.62	16.92
	Base+(29)–(32)+BP	0/5/0	8.76	22.82	15.20	0/5/0	10.31	15.74	16.39	0/5/0	13.32	40.59	16.92
	Base+(29)+(33)+(34)	0/5/0	9.20	18.96	13.74	0/5/0	8.40	31.34	**13.01**	0/5/0	15.24	32.05	18.41
	Base+(29)+(33)+(34)+BP	0/5/0	8.09	28.70	12.95	0/5/0	**8.30**	**32.18**	13.28	0/5/0	15.13	32.53	18.32
	Base+(29)–(34)+BP	0/5/0	**7.08**	**37.64**	**12.41**	0/5/0	8.58	29.91	13.41	0/4/1	**12.28**	**67.30**	**15.38**
200	Base	0/5/0	19.16		23.35	0/4/1	20.56		24.72	0/4/1	37.55		34.81
	Base+(29)–(32)	0/4/1	12.35	35.53	17.58	0/5/0	13.18	35.91	18.34	0/5/0	**17.21**	**54.16**	**20.48**
	Base+(29)–(32)+BP	0/4/1	10.73	44.02	16.26	0/5/0	10.34	49.73	15.94	0/5/0	17.24	54.10	20.50
	Base+(29)+(33)+(34)	0/5/0	12.36	35.51	16.80	0/5/0	12.58	38.83	16.79	0/4/1	27.05	27.97	29.61
	Base+(29)+(33)+(34)+BP	0/5/0	11.56	39.69	16.02	0/5/0	10.20	50.40	14.77	0/4/1	26.93	28.30	29.49
	Base+(29)–(34)+BP	0/5/0	**8.45**	**55.90**	**13.03**	0/5/0	**8.97**	**56.36**	**13.68**	0/0/5			

Table 3: Summary of the results obtained.

was not identified within the given time limit (#nopt), and the number of instances for which no feasible solution was found after 8 hours of CPU time (#nf). The average optimality gaps are shown in columns 4, 8, and 12 for the three problems, with MIP gap $= (z^{UB} - z^{LB})/z^{UB} \times 100\%$, z^{UB} denoting the value of the best feasible solution, and z^{LB} representing the best lower bound. Columns 5, 9, and 13 present the average deviation of the MIP gap of an enhanced formulation to the optimality gap obtained with the base formulation. This value is calculated for each instance as follows: $(z^b - z^{UB})/z^b \times 100\%$ with z^b denoting the best objective value of base formulation b (i.e., $(\mathbf{P}_\beta)$, $(\mathbf{P}_0)$ and $(\mathbf{PDS})$). A positive deviation indicates an improvement, while a negative value reveals the opposite. In addition, the average relative percentage deviation between the objective value of the best feasible solution available (z^{UB}) and the LP-relaxation bound (z^{LP}) is displayed in columns 6, 10, and 14, which is determined by $(z^{UB} - z^{LP})/z^{UB} \times 100\%$. Finally, the best average values with respect to the evaluation criteria are shown in boldface.

Finding the optimal solution within the pre-specified time limit is challenging even for some of the smallest test instances. Over the 450 runs performed, optimal solutions could only be identified in 23 runs (5%), 18 of these are associated with instances involving formulation $(\mathbf{P}_\beta)$ and the remaining 5 runs concern instances involving model $(\mathbf{P}_0)$. All optimal solutions, except one, are obtained for the smaller instances with 100 customer zones. Table 12 in Appendix B displays the individual CPU times of these 23 runs. It can be seen that, on average, 12,052 seconds of CPU time are required to find the optimal network configuration when the base formulation $(\mathbf{P}_\beta)$ and its various enhancements are considered for $|C| = 100$. The computational effort is twice as large in the 5 runs of formulation $(\mathbf{P}_0)$ with some of the families of valid inequalities.

As the size of an instance grows, so does the computational burden. This is reflected by an increased difficulty in finding feasible solutions within the time limit as well as by larger MIP gaps. In fact, the results obtained suggest that it is significantly more demanding to design a supply chain network under partial demand coverage. Among the 13 runs (2.9%) without any feasible solution, 10 of them are associated with instances of this problem.

Table 3 further reveals the positive impact of the enhancements over the original formulations. Not only the MIP and LP gaps decrease, but also more feasible solutions are identified when certain sets of inequalities are added to the base formulations. For the problems enforcing total demand satisfaction, $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$, and instances with up to 150 customer zones, the best performance is almost always achieved by adding inequalities (29), (33) and (34), and assigning higher branching priority to the plant location variables. This is evidenced by small MIP gaps ($< 4\%$), which also show a remarkable improvement over the MIP gaps for the original formulations, with an average gap reduction of more than 50%. Recall that the above three sets of inequalities impose a lower bound on the total number of plant locations that must be selected and also guide the choice of suppliers for raw material delivery to plants. For the largest instances with 175 and 200 customers, the best performance is mostly achieved when all the proposed enhancements and the branching priorities for the plant location variables are considered. In this case, the average MIP gaps range from 7.08% to 8.97%, and the improvement over the gaps of the base formulations is again noteworthy (32%–57%). These instances are more challenging due to their very large sizes, comprising approximately 44,000 binary variables and 145,000 continuous variables (see Table 11 in Appendix B). Moreover, the base formulations have around 54,000 constraints. Adding all families of inequalities (29)–(34) to such large instances (cf. Table 11) is computationally expensive, and thus their success is negatively affected. This aspect is even more evident in the partial demand satisfaction problem for $|C| = 200$, since CPLEX cannot find a single feasible solution within the given time limit for any of the corresponding instances. As shown in columns 11–14 in Table 3, all formulations associated with $(\mathbf{PDS})$ are clearly more challenging. This is due to a large extent to their huge number of continuous variables compared with the other formulations (details are provided in Table 11). Moreover, it seems to be harder to identify those customer demands that are not attractive to be completely satisfied. A closer analysis of the feasible solutions obtained reveals that CPLEX strives at installing plants and warehouses such that their total capacity satisfies exactly the minimum service level (i.e., 80% of total demand) as there is no incentive to provide a higher service level. Finding such solutions entails the evaluation of many alternative network configurations, a task that is time consuming. Hence, the CPU time is often used up without identifying good solutions. In view of these features, it does not seem surprising that the best MIP gaps are usually achieved when all sets of inequalities are added to the original formulation $(\mathbf{PDS})$. However, the computational cost of this approach is too high for instances with 200 customer zones since they have almost 785,000 continuous variables (cf. Table 11). As a result, CPLEX fails to find a feasible solution within 8 hours. For these particular instances, adding inequalities (29), (30), (31), and (32) helps CPLEX identify better feasible network configurations, and this results in more than 50% reduction of the MIP gap of the base formulation.

Regarding the linear relaxation, it can be observed that the impact of the best combination of valid inequalities for a given problem becomes stronger as the size of an instance increases. In particular, the LP bound is strengthened the most for instances with 200 customer zones. For the SCND problems with complete demand coverage, $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$, the optimal solution to the LP relaxation is always found in less than 5 CPU minutes. As expected, larger computational time is required to solve the LP relaxation of the partial demand satisfaction problem. In this case, and depending on the enhanced formulation chosen, the CPU time can range from 26 seconds up to almost 35 minutes. Nevertheless, the computational effort is not critical given the strategic nature of the problems. Table 13 in Appendix B summarizes these findings.

It is also worth mentioning that giving higher branching priority to the binary plant location variables seems to be a useful strategy in identifying good solutions, and thus decreasing the MIP gap. Interestingly, this approach seems to be more effective for the smallest test instances.

5.2.1 Measuring the value of product outsourcing

The aim of this section is to gain a broader insight into the characteristics of the best solutions identified by CPLEX, and consequently understand the main trade-offs achieved by each of the three strategies considered for SCND. In this way, a decision maker will be aware of the value of product outsourcing compared with alternative strategies.

$\|C\|$	Location & cap. acquisition cost (%)		Logistics costs (%)					Outs. (%)	
			Procurement	Production	Transportation			cost	qty
	Plants	Warehouses			Rail	Small trucks	Large trucks		
100	21.3	29.1	3.1	10.1	4.2	10.8	17.9	3.6	6.2
125	22.6	28.3	4.2	11.9	3.3	11.1	16.9	1.9	3.1
150	16.9	27.5	5.6	12.1	2.8	12.3	17.4	5.4	8.2
175	18.6	25.7	6.9	13.6	5.2	13.8	13.6	2.5	5.0
200	18.5	22.6	7.7	14.5	6.3	14.1	13.7	2.6	4.7
All	19.6	26.6	5.5	12.4	4.4	12.4	15.9	3.2	5.4

Table 4: Average contribution of different cost categories for combining in-house manufacturing and product outsourcing, $(\mathbf{P}_\beta)$.

Table 4 shows the average relative contribution of various cost categories to the overall cost of designing a supply chain network by combining in-house manufacturing and product outsourcing. The information in this table stems from the best solution available for each instance. The category 'Location & cap. acquisition cost' represents the total investment made on opening facilities and installing capacity. Independently of the size of an instance, this investment accounts for around half of the total cost. The categories 'Procurement' and

'Production' include the costs of purchasing raw materials and transforming them into end products, respectively. As expected, these costs increase with the number of customer zones due to greater demand requirements. The category 'Transportation' is divided into three cost components according to the type of transportation mode. Together, these costs represent nearly one-third of the total spending. In particular, road transports with large trucks have the largest share. Since every plant must procure each type of raw material from a single supplier, a large quantity tends to flow from a supplier to each assigned plant. As a result, this transportation mode is the cheapest choice in many cases. Large trucks are also the preferred mode for shipments between plants and customers. Regarding deliveries to customers, again large trucks are used for those customer zones whose total demand is equal to or greater than the third quartile. All other customers are served by smaller vehicles due to their lower total demand requirements. Rail transportation is mainly selected for moving end products from plants to warehouses. The last two columns in Table 4 give the percentage of the outsourcing cost and the percentage of the total deliveries to customer zones that are purchased from an external source. The rather small rate of outsourced products, which is well below the maximum allowed limit of 20%, indicates that there is a selective use of this strategy. Accordingly, the product outsourcing cost has a small contribution to total cost. Tables 14 and 15 in Appendix B present similar shares of the location, procurement, production, and transportation costs relative to the overall cost for problems $(\mathbf{P}_0)$ and $(\mathbf{PDS})$.

Figure 2 displays the average deviation of the total cost of the best solutions available for problems $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ to the best solutions identified to problem $(\mathbf{P}_\beta)$. It can be seen that enforcing the satisfaction of all customer demands through in-house production results, in general, in network configurations that are moderately more costly than networks designed under a limited level of product outsourcing. This feature does not seem to be present in all test instances with 200 customer zones which may be attributed to the lower quality of the solutions obtained in this case. Since instances associated with $(\mathbf{P}_\beta)$ resort to relatively small quantities of outsourced products (cf. Table 4), it is not surprising that the overall cost does not increase significantly when this option is not available. In contrast, designing a network that allows for partial demand satisfaction clearly results in a significant reduction in the total cost.

To further analyze the differences between the three strategies, we compare the individual components of the total cost in the best solutions to problems $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ with those to problem $(\mathbf{P}_\beta)$. Figure 3 clearly shows that a pure in-house manufacturing strategy requires

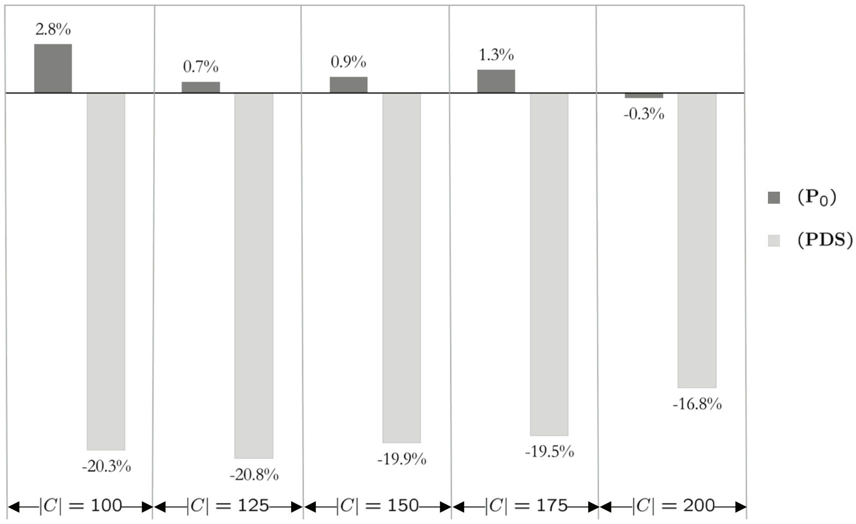

Figure 2: Average cost differences of $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ to total cost of in-house manufacturing and product outsourcing case, $(\mathbf{P}_\beta)$.

a significant higher investment in production capacity. This is reflected through opening more plants and installing larger capacities in some locations than in the problem with partial product outsourcing. On average, this results in 13.7% higher expenditures as these decisions are typically capital intensive. Naturally, the plant location and capacity acquisiton decisions also affect the procurement and production costs, which grow each by 6%. Moreover, the quantity of raw materials moved from suppliers to plants increases as well as the quantity of end products delivered from plants to warehouses and from plants to customers, resulting in 2.6% higher transportation costs. Only the investment in warehouse capacity is not affected since all outsourced commodities and part of the in-house manufactured products are consolidated in these facilities.

Regarding the design of the supply chain network under a partial demand satisfaction strategy, lower requirements for manufacturing capacity lead to decreased expenditures on opening plants (6.4% cost reduction compared with the product outsourcing case) and as a consequence, to lower procurement and production costs (14.9%, resp. 15%, less than with $(\mathbf{P}_\beta)$). Moreover, since customer demand requirements are not completely covered, also less investment spending in warehouse capacity is needed (19.7% cost reduction compared with the outsourcing strategy). Naturally, these features also impact the delivery costs of raw materials and end products which decline by 20.4%. Even though significant cost savings can be achieved under this sce-

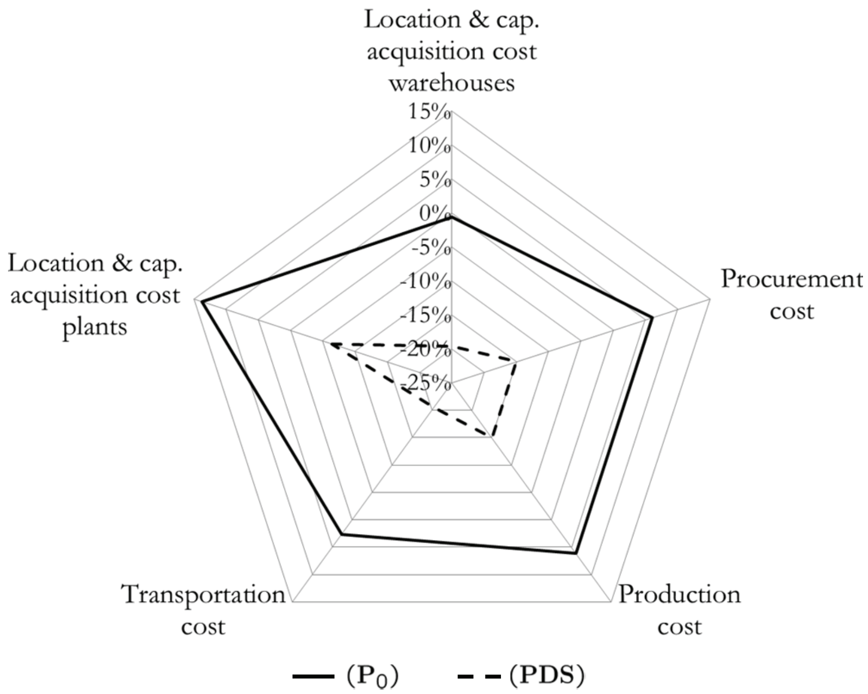

Figure 3: Comparison of different cost categories of $(\mathbf{P}_0)$ and $(\mathbf{PDS})$ with in-house manufacturing and product outsourcing case, $(\mathbf{P}_\beta)$.

nario, they may not offset future financial losses experienced by the firm. In particular, some customers may choose to buy products from competitors, thus altering the pattern of future demand. Estimating the consequences of the loss of customer goodwill is, in practice, very difficult. Hence, the firm is exposed to additional risks under the partial demand satisfaction scenario.

The trade-offs displayed in Figure 3 between the three alternative strategies are complemented with information with respect to the minimum ($\perp$), average, and maximum ($\top$) number of new facilities in Figures 4 and 5. Figure 4 reveals that the largest number of plant locations is established when all customer demands must be met through in-house production. In contrast, Figure 5 shows that the same number of warehouses are opened in the $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$ scenarios due to identical capacity needs for handling end products. The significant cost reduction in storage capacity in scenario $(\mathbf{PDS})$ is due to opening fewer warehouses. Decisions regarding the location and the size of a facility to be established are intertwined since the costs of capacity acquisition are location dependent. This aspect along with the rate of capacity usage in the new facilities will be analyzed in the next section.

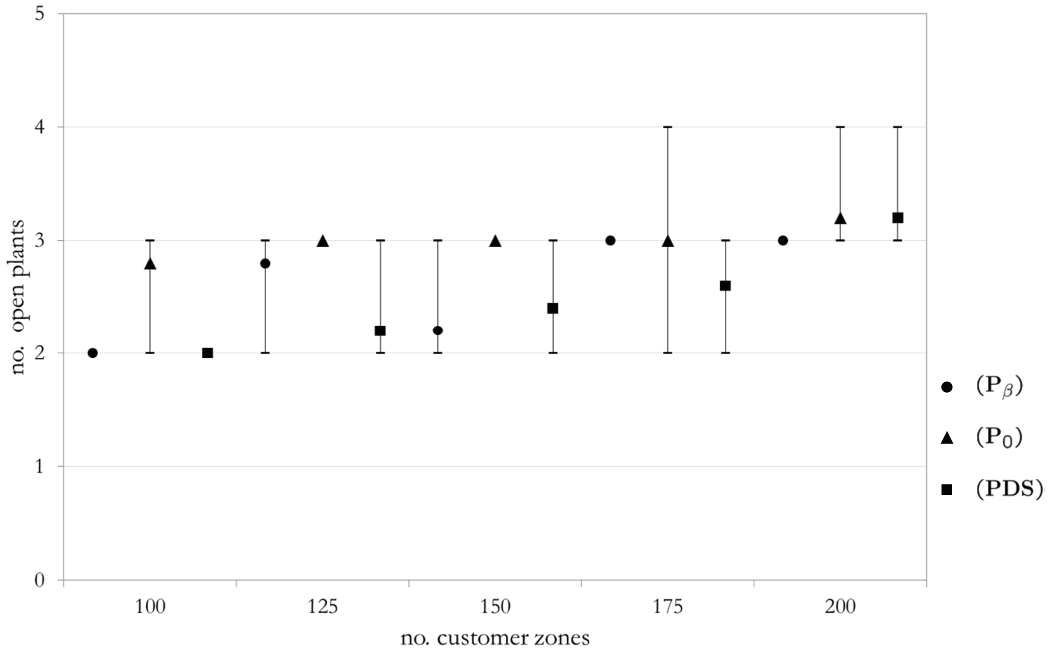

Figure 4: Minimum, maximum and average number of selected plant locations.

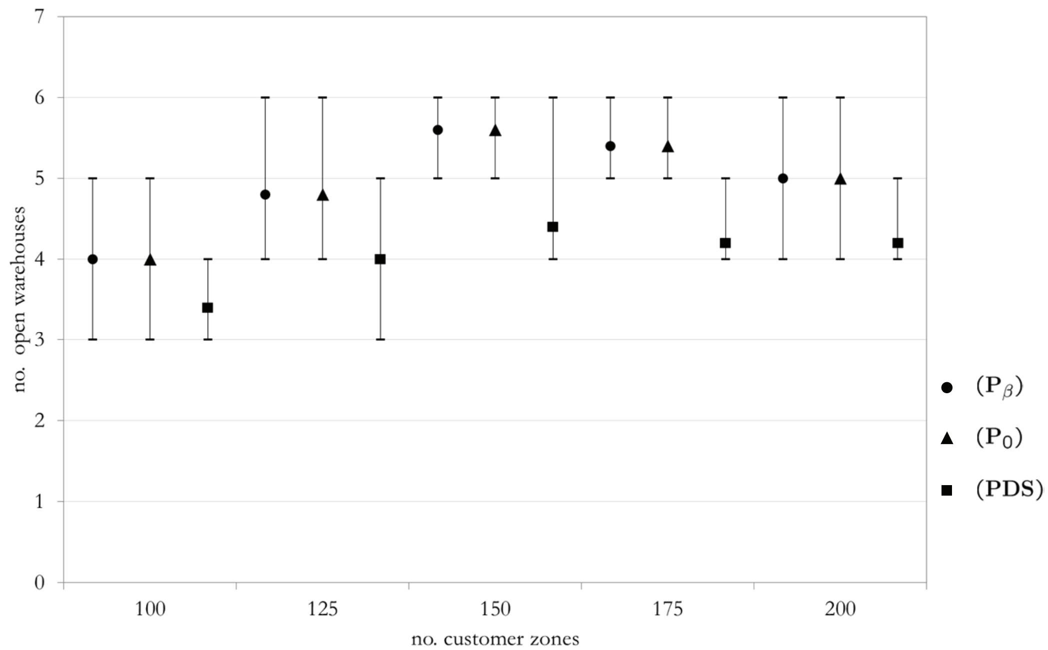

Figure 5: Minimum, maximum and average number of selected warehouse locations.

5.2.2 Additional insights

From a managerial perspective, a further relevant aspect is the extent to which the installed production and warehousing capacities are used in the supply chain network. Regarding the plants, Table 5 gives in columns 2, 5, and 8 the number of small (S), medium (M) and large-capacity (L) facilities that are selected over all test instances for each choice of $|C|$ and each type of problem. Columns 3, 6, and 9 present the average capacity utilization rates of the plants. Similar information is provided in Table 6 for warehouses. In addition, the average relative amount of end products that are delivered directly from plants to customer zones are shown in columns 4, 7, and 10 of Table 5.

$\lvert C\rvert$	Complete demand satisfaction						Partial demand satisfaction		
	In-house production and outsourcing ($\mathbf{P}_\beta$)			In-house production ($\mathbf{P}_0$)			In-house production ($\mathbf{PDS}$)		
	Capacity		Avg direct deliveries (%)	Capacity		Avg direct deliveries (%)	Capacity		Avg direct deliveries (%)
	Total no. sizes S/M/L	Avg usage (%)		Total no. sizes S/M/L	Avg usage (%)		Total no. sizes S/M/L	Avg usage (%)	
100	1/0/9	100.0	12.5	6/3/5	97.5	12.5	2/2/6	94.0	12.2
125	2/6/6	100.0	8.4	1/9/5	97.9	8.2	0/5/6	96.3	8.4
150	2/1/8	98.5	7.8	5/4/6	96.6	7.8	4/2/6	91.3	7.7
175	6/9/0	98.3	6.9	5/7/3	91.8	6.9	3/8/2	92.0	6.8
200	9/2/4	92.0	6.0	8/4/4	93.2	5.8	10/5/1	83.2	5.8
All	20/18/27	97.8	8.3	25/27/23	95.4	8.3	19/22/21	91.3	8.2

Table 5: Capacity choice, average capacity utilization rate in plant locations and direct deliveries to customer zones.

Supply chain networks associated with problem ($\mathbf{P}_0$) have the largest number of plants and therefore, also the highest amount of installed capacity. The latter is provided by selecting all three available sizes. In contrast, problem ($\mathbf{PDS}$) has the least production capacity needs and this is reflected through the installation of less capacity in plant locations. Problem ($\mathbf{P}_\beta$), which is between these two cases, gives preference to opening large-sized plants, thus making higher use of the economies of scale. The capacity utilization level in these facilities is also, on average, the highest, whereas the network configurations identified for the instances of problem ($\mathbf{PDS}$) have more slack capacity available. This feature may be explained by the lower quality of the solutions obtained to the latter instances. Observe that capacity bottlenecks may occur in problem ($\mathbf{P}_\beta$) for $|C| \in \{100, 125\}$ should the future demand grow beyond the forecast used for SCND. Interestingly, the share of direct shipments from plants to customer zones does not seem to be affected by the type of strategy followed for network design.

The solutions to problems $(\mathbf{P}_\beta)$ and $(\mathbf{P}_0)$ exhibit similar characteristics with respect to the number and size of selected locations for warehouses, and the utilization rate of the available capacity. This is not surprising since storage requirements do not depend on the outsourcing strategy chosen. The impact of incomplete demand coverage results in lower storage capacity needs. In this case, fewer warehouses are opened and the largest capacity size is chosen in the majority of the new locations to take advantage of economies of scale.

$\|C\|$	Complete demand satisfaction				Partial demand satisfaction	
	In-house production and outsourcing $(\mathbf{P}_\beta)$		In-house production $(\mathbf{P}_0)$		In-house production $(\mathbf{PDS})$	
	Capacity		Capacity		Capacity	
	Total no. sizes S/M/L	Avg usage (%)	Total no. sizes S/M/L	Avg usage (%)	Total no. sizes S/M/L	Avg usage (%)
100	2/1/17	99.3	2/1/17	99.4	2/1/14	98.5
125	0/1/23	97.8	0/1/23	98.3	0/2/19	97.0
150	0/2/26	98.4	0/3/25	98.0	0/1/21	98.8
175	1/3/23	95.3	1/3/23	96.4	0/3/18	95.2
200	0/9/16	95.1	0/9/16	96.2	1/2/18	91.0
All	3/16/105	97.2	3/17/104	97.7	3/9/87	96.1

Table 6: Capacity choice and average capacity utilization rate in warehouse locations.

The analysis in this section and in Section 5.2.1 has provided insights on how sensitive the design of the plant stage is to respond to different production capacity needs. In particular, combining in-house manufacturing and product outsourcing results in less costly network configurations due to lower investment spending in establishing plants and choosing larger capacity sizes. Such decisions have further implications: the total procurement and production costs decrease as well as the transportation costs for moving raw materials to plants and for distributing end products from plants to warehouses. Moreover, the available production capacity is better utilized. Even though a firm will have to resort to an external source to complement its in-house manufactured products, the level of outsourcing turns out to be quite low which also results in a small risk of dependency. If a firm adopts the strategy of meeting all customer demands through in-house production then total network design costs grow but the percentage increase is moderate. In contrast, if a firm decides to reduce the level of customer service then this strategy will greatly affect the design of the supply chain network through lower expenditures in manufacturing and warehousing facilities. At the same time, this strategy will negatively impact the risk exposure of the firm due to possibly declining future customer goodwill.

6 Conclusions

In this article, we have considered several important strategic decisions for designing a multi-stage supply chain network. These include the location and sizing of plants and warehouses, the selection of suppliers, the procurement of raw materials, their transformation into end products, the partial acquisition of end products from an external source, the selection of transportation modes for distributing raw materials and end products, and the satisfaction of customer demands from warehouses or directly from manufacturing facilities under a single-assignment policy. We have developed a MILP formulation for this new problem and proposed two additional formulations to compare the value of product outsourcing with two alternative strategies that exclude this option. Despite the very large number of binary variables, computational testing on randomly generated large-sized instances has revealed that an optimization solver such as CPLEX is a viable option for obtaining good solutions when complete demand satisfaction is enforced, both with and without product outsourcing. However, the success of this option greatly depends on enhancing the original formulations by adding various families of inequalities. Not only do the enhancements allow to find substantially better feasible solutions and in some cases even optimal solutions, but also to identify feasible solutions for those instances where none are available in the absence of additional inequalities. Under partial demand satisfaction the SCND problem becomes even more challenging due to the introduction of a huge number of continuous variables. In this case, enhancing the original formulation becomes computationally expensive and this approach has limited success. Suitable decomposition techniques could be applied to alleviate the difficulties associated with the size of the formulation.

In our computational study, additional insights were gained by analyzing the main characteristics of a supply chain network that allows for a limited level of product outsourcing. In particular, our analysis has illustrated the far-reaching implications of this strategy on the structure of the supply chain network, its overall cost, and the level of capacity utilization in plants and warehouses. Moreover, the trade-offs achieved by considering two alternative SCND problems that resort exclusively to in-house production were also studied.

Even though we have addressed the SCND problem from a greenfield perspective, it would be easy to extend the proposed models to redesign a network that is already in place with a number of plants and warehouses being operated at fixed locations. Accordingly, the set of location decisions would also include closing some of the existing facilities and/or expanding their capacities. A future line of research could be the development of heuristic procedures for the problems at hand. Furthermore, since some input parameters for long-term planning are inherently uncertain (e.g. demand), focus could also be given to the design of a stochastic model to explicitly account for the uncertainty associated with future conditions. In a stochastic framework, it is important to measure the impact of having complete and accurate information on the future at the moment decisions are made. This entails solving the deterministic counterpart of each problem for a finite set of scenarios. In that respect, our study makes a relevant contribution towards developing a deeper understanding of the deterministic problems.

Appendix A. Data generation

In what follows, we denote by $U[a,\, b]$ the generation of random numbers over the range $[a,\, b]$ according to a continuous uniform distribution. Drawing random numbers from a discrete uniform distribution in the same interval is denoted by $I[a,\, b]$.

Raw materials, end products, and suppliers

Three classes of raw materials, denoted by R_1, R_2, R_3, are considered, with sizes depending on the number of customer zones, n. Accordingly, we select $R_1 = \{1, \ldots, I[\delta_n, \delta_n + 2]\}$, $R_2 = \{|R_1| + 1, \ldots, I[\theta_n, \theta_n + 2]\}$, and $R_3 = \{|R_1| + |R_2| + 1, \ldots, |R|\}$, where δ_n and θ_n are parameters defined as shown in Table 7.

n	100	125	150	175	200
δ_n	7	9	11	12	15
θ_n	15	19	23	25	31

Table 7: Parameters used for selecting the number of raw materials.

The suppliers are also partitioned into three groups, S_1, S_2 and S_3, with $|S_1| = |S_2| = \lceil 0.4\, \frac{n}{10} \rceil$ and $|S_3| = \lceil \frac{n}{10} \rceil - |S_1 \cup S_2|$. For simplicity, it is assumed that suppliers in the first group are numbered $1, 2, \ldots, |S_1|$, suppliers in the second group are numbered $|S_1|+1, \ldots, |S_1|+|S_2|$, and suppliers in the last group are numbered $|S_1| + |S_2| + 1, \ldots, |S|$. Moreover, all suppliers belonging to set S_i may deliver all raw materials in set R_i ($i = 1, 2, 3$).

Regarding the end products, two groups are defined, P_1 and P_2, whose sizes depend on the total number of customer zones. To this end, we consider $P_1 = \{1, \ldots, I[\nu_n, \nu_n + 2]\}$ and $P_2 = \{|P_1| + 1, \ldots, |P|\}$. Table 8 presents the values selected for parameter ν_n.

n	100	125	150	175	200
ν_n	9	11	14	16	19

Table 8: Choice of end products for set P_1.

End products belonging to set P_1 use raw materials that are randomly chosen from sets R_1 and R_3. For each end product $p \in P_1$, we first select the total number of raw materials in R_1 needed to manufacture this product. This number is given by $I[\lceil \frac{|R_1|}{2} \rceil,\ \lceil \frac{3}{4}|R_1| \rceil]$. The actual raw materials are then randomly selected from R_1. The choice of raw materials in R_3 follows the same logic, but the total number is now dictated by $I[\lceil \frac{|R_3|}{2} \rceil,\ \lceil \frac{3}{4}|R_3| \rceil]$. A similar selection procedure is employed to decide on the raw materials needed by each product $p \in P_2$, but in this case the choices are made from sets R_2 and R_3. Hence, raw materials belonging to set R_3, and which account for 20% of all raw materials, are required by all finished products, whereas raw materials in set R_1, respectively R_2, are needed by end products $p \in P_1$, respectively $p \in P_2$. After having generated the three classes of raw materials and the two groups of end products, the supplier subsets S^r and the product subsets P^r are identified for every $r \in R$.

Production and storage capacities

A simple BOM is considered in every plant, meaning that $a^{rp} = 1$ for any raw material r required to manufacture end product p. Table 9 describes the generation of parameters related to capacities in potential plant and warehouse locations. Recall from Section 5.1 that the demand d_c^p of each customer zone c for end product p is randomly generated according to $U[1, 10]$.

Symbol	Description	Value
$\overline{SQR}_s^r$	Capacity of supplier $s \in S_i^r$ for raw material $r \in R_i,\ i = 1, 2, 3$	$\frac{U[1, \lvert S_i \rvert] \sum_{p \in P} \sum_{c \in C^p} a^{rp} d_c^p}{\lvert S_i^r \rvert}$ if $s \in S_i^r$
PU^p, SU^p	Production, resp. storage, capacity used by one unit of product $p \in P$ in any plant, resp. warehouse	$I[1,\ 10]$
$\overline{LQ}_{\ell\,\lvert Q_L \rvert}$	Largest global capacity for plant $\ell \in L$	$\frac{U[t-1, t+1] \sum_{p \in P} PU^p \sum_{c \in C^p} d_c^p}{\lvert L \rvert}$ with $t = \left\lceil \frac{\lvert L \rvert}{2} \right\rceil$

Symbol	Description	Value
$\overline{LQ}_{\ell q}$	Global capacity associated with size $q = 1, \ldots, \lvert Q_L\rvert - 1$ for plant $\ell \in L$	$0.7\,\overline{LQ}_{\ell\, q+1}$
$\overline{LQP}^{\,p}_{\ell\, \lvert Q_L\rvert}$	Largest manufacturing capacity for product $p \in P$ that can be installed in plant $\ell \in L$	$0.6\,\overline{LQ}_{\ell\, \lvert Q_L\rvert}$
$\overline{LQP}^{\,p}_{\ell q}$	Manufacturing capacity for product $p \in P$ associated with size $q = 1, \ldots, \lvert Q_L\rvert - 1$ in plant $\ell \in L$	$0.6\,\overline{LQ}_{\ell\, q+1}$
$\overline{SQ}_{w\, \lvert Q_W\rvert}$	Largest storage capacity for warehouse $w \in W$	$\frac{U[1,t] \sum_{p \in P} SU^p \sum_{c \in C^p} d^p_c}{\lvert W\rvert}$ with $t = \left\lceil \frac{\lvert W\rvert}{4} \right\rceil$
$\overline{SQ}_{wq}$	Storage capacity associated with size $q = 1, \ldots, \lvert Q_W\rvert - 1$ for warehouse $w \in W$	$0.7\,\overline{SQ}_{w\, q+1}$
α_{jq}	Factor to set a minimum throughput level on facility $j \in L \cup W$ with capacity level q, that is, to set $\underline{LQ}_{\ell q}$ ($q \in Q_L$) and $\underline{SQ}_{wq}$ ($q \in Q_W$)	0.2

Table 9: Generation of parameters related to capacities.

Transportation modes

As described in Section 5.1, up to three alternative transportation modes are available for each origin-destination pair in the network depicted in Figure 1. For mode 1 (rail), we introduce sets $\mathcal{S}^1$, $\mathcal{L}^1$, $\mathcal{W}^1$ to represent those suppliers, resp. plants, resp. warehouses, that can be accessed by rail. Each one of these sets is defined by randomly selecting 75% of the elements of the corresponding sets, S, L, and W. Since mode 1 is not available for deliveries to customer zones, we set $\overline{MQ}^{\,1}_{o,c} = 0$ for every $o \in L \cup W$ and $c \in C$. The other two modes of transportation are associated with road freight transport, with mode 2 (mode 3) designating small (large) trucks. Maximum limits on their capacities are not imposed because vehicles are rented from a 3PL provider. Therefore, $\overline{MQ}^{\,m}_{o,d} = +\infty$ for $o \in O$, $d \in D$, and $m = 2, 3$. Moreover, no minimum transportation quantity is set for mode 2, i.e. $\underline{MQ}^{2}_{od} = 0$ for every $o \in O$ and $d \in D$. Table 10 shows how the remaining parameters associated with the three transportation modes were generated.

Symbol	Description	Value
MU^{im}	Capacity utilization factor for one unit of item $i \in R \cup P$ with transportation mode $m \in M$	$I[1,\ 10]$
$\overline{MQ}^1_{s\ell}$	Capacity of mode 1 for shipments between supplier $s \in \mathcal{S}^1$ and plant $\ell \in \mathcal{L}^1$	$U[0.5\,A,\ 0.6\,A]$ with $A = \lvert\mathcal{S}^1\rvert \frac{\sum_{j\in R_i}\sum_{p\in P}\sum_{c\in C^p} a^{jp}\, d^p_c\, MU^{j1}}{\lvert S_i\rvert}$ and $s \in S_i$ (in that case, R_i is the associated set of raw materials)
$\underline{MQ}^1_{s\ell}$	Minimum shipment quantity between supplier $s \in \mathcal{S}^1$ and plant $\ell \in \mathcal{L}^1$ with mode 1	$U[0.2\,A,\ 0.3\,A]$ (with A given above)
$\overline{MQ}^1_{\ell w}$	Capacity of mode 1 for shipments between plant $\ell \in \mathcal{L}^1$ and warehouse $w \in \mathcal{W}^1$	$U[2.9\,B,\ 3.1\,B]$ with $B = \lvert\mathcal{L}^1\rvert \frac{\sum_{p\in P}\sum_{c\in C^p} d^p_c}{\lvert L\rvert}$
$\underline{MQ}^1_{\ell w}$	Minimum shipment quantity between plant $\ell \in \mathcal{L}^1$ and warehouse $w \in \mathcal{W}^1$ by mode 1	$U[2.4\,B,\ 2.6\,B]$ (with B given above)
$\underline{MQ}^3_{s\ell}$	Minimum shipment quantity between supplier $s \in S_i$ and plant $\ell \in L$ by mode 3	$0.75\,\frac{\sum_{p\in P}\sum_{c\in C^p}\sum_{r\in R_i} MU^{r3} a^{rp}\, d^p_c}{\lvert S_i\rvert}$ with R_i the set of raw materials supplied by s
$\underline{MQ}^3_{od}$	Minimum shipment quantity between origin $o \in L \cup W$ and destination $d \in W \cup C$ by mode 3	third quartile of the capacity utilization in mode 3 for covering the total demand of a customer zone

Table 10: Generation of parameters related to transportation modes.

Fixed costs

The fixed cost of opening a facility (plant or warehouse) is subject to economies of scale that depend on the capacity choice as follows:

$$
\begin{aligned}
FCF_{\ell}^{q} &= 1000\sqrt{\frac{\overline{LQ}_{\ell q}}{\overline{\mu}}} \quad \ell \in L,\ q \in Q_L \\
FCF_{w}^{q} &= 1000\sqrt{\frac{\overline{SQ}_{wq}}{\overline{\gamma}}} \quad w \in W,\ q \in Q_W
\end{aligned}
$$

with $\overline{\mu}$, resp. $\overline{\gamma}$, denoting the average utilization of the capacity of a plant, resp. warehouse, by one unit of product. These parameters are given by

$$
\overline{\mu} = \frac{\sum_{p \in P} PU^p}{|P|} \qquad \overline{\gamma} = \frac{\sum_{p \in P} SU^p}{|P|}
$$

Procurement, production, and transportation costs

The following scheme was employed to generate the variable costs for procuring raw materials, manufacturing end products, and transporting goods across the supply chain network.

- The cost CP_s^r of purchasing one unit of raw material $r \in R$ from supplier $s \in S^r$ is chosen from the interval $U[0.75\,\phi_r,\ 1.25\,\phi_r]$ with $\phi_r = U[0.1,\ 0.5]$.
- The cost CM_{ℓ}^p of manufacturing one unit of product $p \in P$ in plant $\ell \in L$ is selected from the interval $U[0.75\,\phi_p,\ 1.25\,\phi_p]$ with $\phi_p = U[0.5,\ 1]$.
- The cost of transporting one unit of an item (raw material or end product) from an origin o to a destination d relies on the Euclidean distance $dist_{od}$ between the two locations. The coordinates of all locations are chosen randomly in the square $[0,\ 10] \times [0,\ 10]$. For each end product $p \in P$, we take $CT_{od}^{pm} = U[0.1,\ 0.5]\, dist_{od}\, \xi_m$ with $\xi_1 = 0.7$ $(m = 1)$, $\xi_2 = 1.25$ $(m = 2)$, and $\xi_3 = 1.0$ $(m = 3)$. Observe that the transportation of goods by rail $(m = 1)$ incurs a lower cost than by truck $(m = 2$ and $m = 3)$, whereas shipments using small trucks $(m = 2)$ incur a higher cost than using large trucks $(m = 3)$. The origin-destination pairs in this case concern plants, warehouses, and customer zones. For distributing raw materials from suppliers to plants, the unit transportation cost is defined in a slightly different way, namely

$$
CT_{s\ell}^{rm} = \frac{U[0.1,\ 0.5]\, dist_{s\ell}\, \xi_m}{\sum_{p \in P} \sum_{r \in R^p} \sum_{c \in C^p} a^{rp}\, d_c^p} \qquad r \in R,\ s \in S^r,\ \ell \in L
$$

Parameter ξ_m takes the same values as above for $m = 1, 2, 3$. The denominator in the above expression represents the total quantity of raw materials that are required to manufacture all end products demanded by the customer zones.

Product outsourcing costs

The generation of the cost of purchasing one unit of product from an external source relies on the following scheme which reflects the network costs. This is required to ensure that product outsourcing is more expensive than in-house manufacturing.

- Average cost of acquiring raw materials to manufacture one unit of product $p \in P$:

$$\overline{CP}_p = \frac{\sum\limits_{\ell \in L} \sum\limits_{r \in R^p} \sum\limits_{s \in S^r} a^{rp}\, CP_s^r}{|S'|\,|R^p|\,|L^p|}$$

  with S' denoting the subset of suppliers that provide the raw materials required to manufacture end product p.

- Average cost of manufacturing one unit of product $p \in P$:

$$\overline{CM}_p = \frac{\sum\limits_{\ell \in L} CM_\ell^p}{|L^p|}$$

- Average cost of transporting one unit of product $p \in P$ from a plant:

$$\overline{CT}_p^{\,1} = \frac{\sum\limits_{\ell \in L} \sum\limits_{d \in W^p \cup C^p} \sum\limits_{m \in M_{\ell d}} CT_{\ell d}^{pm}}{2\,|L^p||C^p| + 3\,|L^p||W^p|}$$

  Recall that two types of trucks are available for deliveries to customer zones, whereas all three types of transportation modes are available for shipments to warehouses.

- Average cost of transporting raw materials from suppliers to plants to manufacture one unit of product $p \in P$:

$$\overline{CT}_p^{\,2} = \frac{\sum\limits_{\ell \in L^p} \sum\limits_{r \in R^p} \sum\limits_{s \in S^r} \sum\limits_{m \in M_{s\ell}} a^{rp}\, CT_{s\ell}^{rm}}{|L^p|\,|S'|\,|R^p|\,|M|}$$

  with S' as defined above in $\overline{CP}_p$.

- Average cost of operating a plant, resp. warehouse, with the largest capacity level, per unit of product $p \in P$:

$$\overline{FCF1}_p = \frac{\sum\limits_{\ell \in L^p} FCF_{\ell}^{|Q_L|}}{\sum\limits_{\ell \in L^p} \overline{LQ}_{\ell |Q_L|}} \cdot PU^p \qquad \overline{FCF2}_p = \frac{\sum\limits_{w \in W^p} FCF_{w}^{|Q_W|}}{\sum\limits_{w \in W^p} \overline{SQ}_{w |Q_W|}} \cdot SU^p$$

Finally, for every warehouse $w \in W$ and product $p \in P$, the unit outsourcing costs CO_w^p is chosen from the interval $U[0.7A_p,\ 0.9A_p]$ with $A_p = \overline{CP}_p + \overline{CM}_p + \overline{CT}_p^1 + \overline{CT}_p^2 + \overline{FCF1}_p + \overline{FCF2}_p$.

Appendix B. Complementary results

Table 11 presents the average number of variables and constraints in each original formulation and in the different enhanced models. Since giving higher branching priority to the plant location variables does not affect the size of a MILP model, we have omitted those formulations where branching priorities were used.

$\|C\|$	Formulation	Complete demand satisfaction						Partial demand satisfaction		
		In-house production and outs. ($\mathbf{P}_\beta$)			In-house production ($\mathbf{P}_0$)			In-house production ($\mathbf{PDS}$)		
		no. of variables		no. of	no. of variables		no. of	no. of variables		no. of
		binary	continuous	constraints	binary	continuous	constraints	binary	continuous	constraints
100	Base	8990	18401	11610	8990	18001	11590	8990	98001	16910
	Base+(29)–(32)			13111			13091			18411
	Base+(29)+(33)–(34)			11831			11811			17131
	Base+(29)–(34)			13331			13311			18631
125	Base	15321	37676	19515	15321	37051	19490	15321	193301	27884
	Base+(29)–(32)			21973			21948			30342
	Base+(29)+(33)–(34)			19866			19841			28235
	Base+(29)–(34)			22323			22298			30692
150	Base	22410	61651	28215	22410	60751	28185	22410	330751	40140
	Base+(29)–(32)			31591			31561			43516
	Base+(29)+(33)–(34)			28696			28666			40621
	Base+(29)–(34)			32071			32041			43996
175	Base	32911	101396	40970	32911	100171	40935	32911	528921	57324
	Base+(29)–(32)			45723			45688			62077
	Base+(29)+(33)–(34)			41636			41601			57990
	Base+(29)–(34)			46388			46353			62742
200	Base	43780	145601	54020	43780	144001	53980	43780	784001	75220
	Base+(29)–(32)			60021			59981			80261
	Base+(29)+(33)–(34)			54861			54821			76061
	Base+(29)–(34)			60861			60821			82061

Table 11: Average size of test instances for problems ($\mathbf{P}_\beta$), ($\mathbf{P}_0$) and ($\mathbf{PDS}$).

For all available optimal solutions, Table 12 shows the CPU time required by CPLEX. We denote by 'Opt x' an individual optimal solution ($x = 1, 2, 3, 4$).

$\|C\|$	Formulation	Complete demand satisfaction					
		In-house production and outsourcing ($\mathbf{P}_\beta$)				In-house production ($\mathbf{P}_0$)	
		CPU (sec)				CPU (sec)	
		Opt 1	Opt 2	Opt 3	Opt 4	Opt 1	Opt 2
100	Base	15984.3	8510.4	6630.8			
	Base+(29)–(32)	19531.6					
	Base+(29)–(32)+BP	10956.5	6164.7	10910.6		24582.9	
	Base+(29)+(33)+(34)	28181.8	11561.6	6852.6			
	Base+(29)+(33)+(34)+BP	9457.9	3354.0	20664.9	4181.7	17412.5	28417.5
	Base+(29)–(34)+BP	12142.3	6648.6	23155.7		25248.1	28191.6
125	Base+(29)+(33)+(34)+BP	22002.9					

Table 12: CPU time required to identify optimal solutions.

Table 13 summarizes the CPU time needed to solve the linear relaxation of the different models to optimality.

$\|C\|$	Formulation	Complete demand satisfaction						Partial demand satisfaction		
		In-house production and outsourcing ($\mathbf{P}_\beta$)			In-house production ($\mathbf{P}_0$)			In-house production (**PDS**)		
		LP CPU (sec)			LP CPU (sec)			LP CPU (sec)		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
100	Base	1.3	2.4	3.7	1.8	2.2	2.9	33.3	36.9	41.3
	Base+(29)–(32)	2.1	3.8	5.2	2.0	3.4	4.0	28.3	32.0	36.9
	Base+(29)–(32)+BP	1.7	3.3	5.1	2.0	3.2	4.5	27.8	32.4	35.8
	Base+(29)+(33)+(34)	2.8	5.0	6.7	3.9	6.3	7.4	26.9	34.9	39.6
	Base+(29)+(33)+(34)+BP	3.3	5.4	6.7	3.9	5.9	7.4	26.0	35.7	38.8
	Base+(29)–(34)+BP	6.2	7.4	8.6	5.9	6.7	8.2	37.0	41.6	46.2
125	Base	6.2	7.4	9.4	5.6	6.5	7.5	78.8	99.1	114.4
	Base+(29)–(32)	7.5	9.0	11.9	7.2	9.4	13.2	66.7	91.2	117.9
	Base+(29)–(32)+BP	7.3	8.7	10.3	7.1	9.0	10.5	46.2	85.1	104.1
	Base+(29)+(33)+(34)	12.8	15.2	17.9	14.7	15.9	17.1	92.9	112.6	127.3
	Base+(29)+(33)+(34)+BP	11.7	14.8	17.2	14.0	15.0	16.0	99.1	107.4	120.3
	Base+(29)–(34)+BP	15.1	16.7	18.6	15.3	17.8	19.5	112.0	129.3	148.9
150	Base	10.0	14.6	21.3	10.2	15.3	18.4	137.4	181.0	205.1
	Base+(29)–(32)	15.4	20.6	25.3	15.5	21.9	27.7	172.9	196.2	225.5
	Base+(29)–(32)+BP	15.2	19.6	23.7	15.4	22.0	158.8	178.3	194.9	220.5
	Base+(29)+(33)+(34)	28.0	39.7	47.9	27.1	36.4	40.3	179.2	207.9	224.7
	Base+(29)+(33)+(34)+BP	30.4	39.3	46.9	27.4	36.5	41.0	214.1	232.9	266.4
	Base+(29)–(34)+BP	37.1	43.0	48.3	35.7	43.7	52.1	233.5	298.8	352.8
175	Base	23.3	32.3	43.3	21.5	31.8	44.8	253.8	354.2	399.1
	Base+(29)–(32)	30.8	40.4	60.0	23.6	34.6	44.0	220.7	358.9	400.6
	Base+(29)–(32)+BP	30.4	40.3	61.5	25.7	33.7	41.1	288.3	375.7	413.5

$\|C\|$	Formulation	Complete demand satisfaction						Partial demand satisfaction		
		In-house production and outsourcing $(\mathbf{P}_\beta)$			In-house production $(\mathbf{P}_0)$			In-house production $(\mathbf{PDS})$		
		LP CPU (sec)			LP CPU (sec)			LP CPU (sec)		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
	Base+(29)+(33)+(34)	67.7	103.4	162.8	68.4	87.8	102.3	334.7	490.2	604.3
	Base+(29)+(33)+(34)+BP	69.0	99.8	150.9	68.3	87.6	104.1	344.4	479.1	599.5
	Base+(29)–(34)+BP	104.4	109.1	125.7	105.4	111.2	119.3	419.7	657.5	855.0
200	Base	41.5	57.0	77.4	40.5	57.4	78.9	557.0	619.2	713.4
	Base+(29)–(32)	42.5	87.4	132.9	49.5	102.0	163.3	539.0	687.9	1124.4
	Base+(29)–(32)+BP	42.8	80.6	121.6	50.2	97.9	158.8	543.7	697.2	1102.2
	Base+(29)+(33)+(34)	160.2	209.3	252.2	173.3	177.0	252.2	720.5	878.0	1155.6
	Base+(29)+(33)+(34)+BP	158.6	204.4	252.4	169.4	175.8	252.4	692.1	866.4	1183.6
	Base+(29)–(34)+BP	178.7	234.9	275.0	195.8	251.0	302.5	1048.1	1451.4	2085.1

Table 13: Average CPU time required by the linear relaxation.

Table 14, resp. Table 15, gives the average relative contribution of various cost components to the overall cost of problem $(\mathbf{P}_0)$, resp. $(\mathbf{PDS})$. The information provided in these tables stems from the best solutions available.

$\|C\|$	Location & cap. acquisition cost (%)		Logistics costs (%)				
			Procurement	Production	Transportation		
	Plants	Warehouses			Rail	Small trucks	Large trucks
100	25.7	28.6	3.2	10.5	5.4	10.5	16.1
125	23.9	28.1	4.3	12.2	3.3	10.9	17.3
150	21.0	27.3	6.0	13.1	3.9	12.7	16.0
175	19.6	24.7	7.2	14.2	5.1	14.3	14.9
200	19.0	22.1	8.1	15.3	6.1	13.8	15.5
All	21.8	26.2	5.8	13.1	4.8	12.4	16.0

Table 14: Average contribution of different cost categories in the pure in-house manufacturing model, $(\mathbf{P}_0)$.

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$\lvert C \rvert$	Location & cap. acquisition cost (%)		Logistics costs (%)				
			Procurement	Production	Transportation		
	Plants	Warehouses			Rail	Small trucks	Large trucks
100	25.3	29.5	3.2	10.9	4.2	10.9	15.8
125	23.3	28.9	4.3	12.5	4.8	8.9	17.3
150	21.9	26.7	6.1	13.2	4.1	10.7	17.3
175	20.5	25.1	7.1	14.4	5.9	12.9	13.9
200	21.1	22.5	8.0	14.5	6.1	12.6	15.3
All	22.4	26.5	5.8	13.1	5.0	11.2	15.9

Table 15: Average contribution of different cost categories in the partial demand satisfaction model, (**PDS**).

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