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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

An LP-rounding heuristic to solve a multi-period facility relocation problem

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Abstract

A general multi-period network redesign problem arising in the context of strategic supply chain planning (SCP) is studied. Several aspects of practical relevance in SCP are captured namely, multiple facility layers with different types of facilities, flows between facilities in the same layer, direct shipments to customers, and facility relocation. An efficient two-phase heuristic approach is proposed for obtaining feasible solutions to the problem, which is initially modeled as a large-scale mixed-integer linear program. In the first stage of the heuristic, a linear programming rounding strategy is applied to find initial values for the binary location variables in the model. The second phase of the heuristic uses local search to correct the initial solution when feasibility is not reached or to improve the solution when its quality does not meet given criteria. The results of an extensive computational study performed on randomly generated instances are reported.

Keywords: Supply Chain Design, Heuristic, Linear Programming, Rounding.

1 Introduction

Over the past decades, real-world production and distribution networks have become increasingly complex logistics systems comprising multiple facilities linked by transportation channels. Strategic network design is concerned with long-term decisions regarding the configuration of the supply chain network. Typically, it involves selecting sites for the location of new facilities, deciding on their number and size, and choosing distribution channels as well as transportation modes to meet customer demands. Clearly, these decisions have a major impact on the long-term profitability and competitive advantage of a company. Determinant elements include customer service levels, flexibility to deal with potential pitfalls (e.g., equipment breakdown) and shipment reliability. According to Harrison [12], up to 80% of the total cost of a product is driven by decisions made during the design phase of the supply chain network.

Network design decisions are mostly triggered by changing market conditions rather than by the need to build a new supply chain from scratch (see Simchi-Levi et al. [30]). Therefore, in practice a company considers changing the structure of its distribution network from time to time. Due to the globalization of the economy and advances in information technology, redesign processes have become more frequent and their efficiency more important. This has been experienced, for example, by many European companies as a result of the economic transition that started in Eastern Europe during the last decade and the successive enlargement of the European Union. The impact of these changes has been noticed, for example, on markets, freight rates, transport infrastructures, and road networks. Expansion opportunities to new markets have appeared, thereby giving rise to the need to redesign existing supply chains. Usually, expansion plans take the form of opening new facilities in new geographical areas either because of the lack of room for capacity increase at the present locations or simply to be closer to new markets. In other cases, fierce competition has forced companies to relocate their facilities to areas with more favorable economic conditions (e.g., lower labor costs). Finally, mergers, acquisitions and strategic alliances often motivate network design studies for supply chain consolidation. Hammami et al. [11] provide a detailed discussion of the factors leading to supply chain reconfiguration, in particular in a delocalization context.

The contribution of this paper is to propose an efficient heuristic approach to solve a comprehensive network redesign problem. Given a supply chain network with the general structure depicted in Figure 1, a multi-echelon, capacitated facility relocation problem is considered. It is assumed that a number of customer zones have known demands for multiple commodities over a multi-period horizon. In addition, several potential sites are available for establishing new facilities. The operation of the latter is triggered by moving capacity from existing facilities to new sites over the planning horizon. This enables modeling real-world situations in which the operating activity of a new facility gradually increases until it reaches a desired level. At the same time, the activity level of an existing facility progressively decreases until the facility is eventually removed from service. Capacity transfers lead thus to facility relocation and are financed by a limited budget, which also pays for establishing new facilities and closing existing facilities.

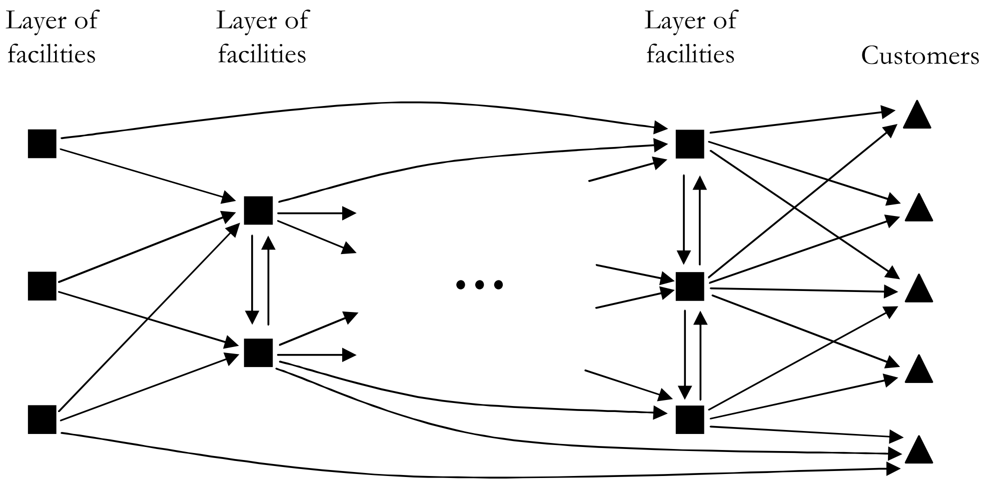


Figure 1: A generic supply chain network

The main strategic decisions to be taken are outlined as follows:

- Which existing facilities should have their capacities partially or totally transferred and in which periods should relocation take place?
- Which potential facility sites should be selected to receive the transferred capacities and when should they start operating?
- How should commodities flow through the network and in particular, from which facilities should customer demands be satisfied in each period?
- Which facilities should hold stock? How large should stock levels be in each period?
- How should the available budget be invested? Which amount of money should be retained in each period to gain interest and be used in future investments?

The objective is to redesign the distribution network so as to minimize the sum of variable and fixed costs associated with the above location and supply chain decisions.

We recently proposed in Melo et al. [24] a comprehensive modeling framework for this problem. We also showed that many multi-period facility location models widely known from the literature are special cases of our new model, in particular those dealing exclusively with pure opening and closing location decisions. The new modeling framework stems from the practical experience we gained over the past few years by running various supply chain design projects (see Bender et al. [4] and Nickel et al. [26]) and thus, integrates key features relevant to many industries. These include multiple planning periods to allow modeling the dynamics of markets and changes in the supply chain configuration over time, a generic network structure for handling an arbitrary number of echelons, and strategic planning of supply chain activities (production/procurement, inventory, distribution) in addition to facility location and relocation decisions. Moreover, finite capacities for distribution facilities, minimum product throughput for a meaningful facility operation as well as budget constraints are also incorporated into the model.

Although Melo et al. [24] could solve medium sized instances to optimality with commercial, off-the-shelf (COTS) optimization software within a reasonable time limit, it is clear that this approach fails when supply chain redesign problems of realistic size need to be solved. Furthermore, most companies need an optimization-based decision support tool able to handle the complexity and the dynamic nature of their supply chains. At the same time, such tools should allow rapid prototyping and the evaluation of alternative network configurations. In other words, companies need analytical tools with re-optimization capabilities for performing "what-if" analyzes in a reasonable amount of computing time. This calls for the development of heuristic methods with a good trade-off between solution quality and computational effort. Hence, the main contribution of this paper is to propose a new heuristic approach that explores the structure of one of the mixed-integer linear programming (MILP) formulations in [24] to obtain high-quality feasible solutions.

The remainder of the paper is organized as follows. Section 2 provides a critical review of multi-period network design models in a supply chain management (SCM) context. For the sake of completeness, Section 3 presents one of the MILP formulations introduced in Melo et al. [24] that renders the general setting for the heuristic development. Section 4 is dedicated to the new solution methodology, which combines a linear programming rounding based strategy with local search. The results of an extensive computational study are reported in Section 5. Finally, in Section 6 conclusions and directions for further research are given.

2 Related work

Since the mid-1960s, discrete facility location has evolved into a mature field of research. The vast majority of the literature is dedicated to single-period problems with static customer demand patterns. The recent reviews by Klose and Drexl [16] and ReVelle et al. [27] describe the important developments in this area. In the last few years, the interaction between facility location and supply chain design has received increasing attention as shown by the extensive survey by Melo et al. [25]. Driven by the need to model real-world problems, researchers have attempted to go beyond the classic facility location setting by considering key features to SCM such as supplier selection, production, inventory management, distribution, routing and other logistics activities (see Daskin et al. [8]). Moreover, globalization trends have also strongly impacted the development of new facility location models as described by Goetschalckx et al. [9] and Meixell and Gargeya [20]. Our paper follows this trend by proposing a comprehensive model that includes SCM decisions in addition to location planning.

Facility location decisions are inherently strategic and long-term in nature due to the large capital outlays that are involved. Consequently, the timing of facility locations, expansions and relocations over an extended planning horizon is of major importance to decision-makers. In contrast to the static case, significantly less papers have been published on dynamic (i.e. multi-period) facility location problems. Within this problem class, focus has been mostly given to rather simple networks comprising a single echelon of facilities and a single product, thus disregarding the supply chain context (see the recent review by Melo et al. [25] and references therein). However, many real-world supply chain networks exhibit a multi-layer structure with at least two facility echelons, in addition to the customer layer. Moreover, the flow of multiple commodities through the network is often conveyed by an elaborated distribution system, linking facilities belonging to the same layer as well as to different layers (see Figure 1).

Hinojosa et al. [13, 14] address a two-echelon multi-commodity network redesign problem that captures some SCM features by considering an initial network configuration which gradually changes over a multi-period horizon through opening new facilities and closing existing ones. A lower bound on the number of facilities operating in each location layer is imposed both in the first and last period of the planning horizon. The initial model developed in [14] was later extended in [13] through the integration of strategic inventory decisions. In both papers, a lagrangian-relaxation-based approach is employed. The application of this decomposition technique is possible due to the assumption that commodities flow downstream from one layer to the layer immediately below, thus enabling the separation of the network structure. However, other types of material flows such as direct shipments from upper layer facilities to customers are frequent in many supply chains. Canel et al. [5] partly capture this supply chain feature in a two-echelon, capacitated, multi-commodity facility location model by allowing customers to be directly delivered from manufacturing plants as well as from intermediate level facilities.

Location decisions are confined to the latter facilities which may be opened and closed more than once during the planning horizon. This feature is more suited to new facilities that are rented instead of being built, since in that case lower fixed setup costs are incurred. A two-phase algorithm, combining branch-and-bound and dynamic programming techniques, is proposed and applied to a rather small instance. Ambrosino and Scutellà [1] broaden the scope of the previous models [5,13,14] through a three-echelon model that integrates strategic and operational decisions. Location and inventory decisions concern intermediate echelons comprising central and regional depots, while the operational aspect involves the design of vehicle routes to service customer demands. Randomly generated instances, some of which based on an Italian case study, are solved with COTS software which proves to be an unsuitable tool due to the huge computational time requirements and the poor quality of the solutions obtained, even though a single commodity is assumed.

In the context of reverse logistics, Srivastava [31] address the problem of locating new collection and rework centers for product recovery over a given time horizon. Instead of following a holistic approach by considering the supply chain as a whole, the authors decompose the problem into two sequential sub-systems. Based on the decisions taken in the first phase with respect to the location of new collection centers, the capacities of the rework facilities (i.e. remanufacturing as well as repair and refurbishing centers) are determined in the second phase. Profit maximization shapes the transportation and capacity decisions in this phase. Ko and Evans [17] also study the problem of expanding an existing multi-commodity network through the location of new warehouses and repair centers. The former facilities receive end products from manufacturing plants and distribute them to end users, while the latter facilities distribute products returned by customers to the plants. In contrast to [31], location and supply chain decisions are integrated in a single model. Moreover, a non-linear cost minimization objective for network reconfiguration is considered. This is a feature that has received little attention in the literature since it adds further complexity. The authors develop a genetic algorithm to solve the problem. The setup of the new facilities is phased during the time horizon by allowing their operating activity to gradually increase through capacity expansion, which is a feature that is seldom considered by classic location models (see also the critical review by Julka et al. [15]). Thanh et al. [32] incorporate this and other relevant supply chain features in a multi-period model. In addition to the usual facility location and transportation decisions, the authors include decisions regarding supplier selection, multi-stage production planning, inventory management, and capacity operating levels. Furthermore, in a three-echelon network, materials flow downstream not only between adjacent layers but also across facilities in different layers. The resulting large-scale MILP model is solved with COTS software. For a set of randomly generated instances the corresponding optimality gap of the best feasible solutions does not exceed 3% within a time limit of three hours.

The two-echelon model developed by Vila et al. [36] has an even broader scope than the one in [32] due to the integration of multiple features relevant to international supply chains. In particular, it includes transfer prices and various financial rates (currency exchange, import duties and income taxes) in different countries. A global after tax profit maximization objective function is considered in contrast to the frequently used cost minimization objective. Multi-stage production, inventory and distribution decisions are modeled. In addition, each site is subject to layout decisions (use or reconfigure an existing site, build a new facility) and sizing decisions. The latter allow the capacity of a facility to be expanded and later removed to deal with demand fluctuations. To tackle such a complex problem with COTS software, the location decisions are decoupled from all other decisions by fixing the values of the location variables at the beginning of the planning horizon. The model is applied to a real-case from the Canadian softwood lumber industry. The application context of the mathematical model developed by Troncoso and Garrido [34] is also the forest industry. The objective is to select the optimal location and size of a new saw-mill in Chile among potential sites having different characteristics. Although a single commodity is modeled, it may flow between any pair of facilities in the network, including facilities belonging to the same layer. This feature is also present in [36]. In addition to location and transportation decisions, capacity decisions are addressed by allowing the initially installed production capacity to increase during the planning horizon. The case study presented in [34] is solved with COTS software for different input data sets, which require up to eight hours CPU time. This limits the application of the model especially if large instances or various scenarios are to be run.

The literature reviewed so far has several features in common, namely a network topology with at least two facility echelons and transportation channels that go beyond links between adjacent layers. Furthermore, location and supply chain decisions are often integrated in a multi-period, multi-commodity model. In particular, location planning is not confined to fixing the time periods for opening and closing facilities. Capacity expansion decisions are also modeled. The framework developed by Melo et al. [24] takes all these features into account and even extends the scope of the existing models by explicitly considering facility relocation through gradual capacity transfers from existing locations to new sites over time. Following the seminal article by Ballou [3], this aspect remained overlooked until recently. Melachrinoudis and Min [21] consider a simple network structure with a single facility layer and a single commodity. A limited budget is available for facility relocation which is a feature rarely captured by network design models (see Melo et al. [25]). Hammami et al. [11] identify the key features that impact the redesign of a supply chain in a delocalization context and criticize the lack of mathematical models that incorporate all the relevant decisions. The large scope and complexity of the problem along with difficulties in data collection account for this gap.

3 Mathematical formulation

In this section we first introduce the notation that will be used throughout the paper. As the new heuristic solution method that will be presented in Section 4 relies upon one of the MILP formulations proposed by Melo et al. [24], we will briefly describe it. Details regarding the motivating assumptions and the underlying supply chain context can be found in [24].

The network topology shown in Figure 1 is the starting point for our network redesign model. It comprises different types of operating facilities (any number of facility layers may be considered as well as any system of transportation channels). In addition, a finite set of candidate sites for locating new facilities has been identified. Over the planning horizon, facility relocation takes place by gradually moving capacity from existing facilities to the selected new sites. Table 1 describes the index sets.

Symbol	Description
L	Set of all facilities
S^c	Set of *existing* facilities that can be closed
S^o	Set of potential sites for establishing *new* facilities
S	Set of *selectable* facilities; $S = S^c \cup S^o$, $S \subset L$
$L \setminus S$	Set of *non-selectable* facilities
P	Set of product families
T	Set of periods; $\mid T \mid = n$

Table 1: Index sets

Non-selectable facilities refer to facilities that are not subject to capacity relocation. Such facilities may include plants and warehouses that must operate throughout the planning horizon. Customer locations always belong to this class.

Table 2 summarizes all costs. Since the establishment of a new facility is often a time-consuming process, it is assumed that it takes place in the period immediately preceding the start-up of operations. On the other hand, when an existing facility ceases operating, the corresponding fixed closing costs are charged in the following period. Relocation costs due to capacity shifts depend on the amount moved from an existing facility to a new site, and account, for example, for workforce and equipment transfers. Capacities moved to new sites cannot be withdrawn in later periods.

Symbol	Description
$PC^t_{i,p}$	Variable cost of producing or purchasing (from an external supplier) one unit of product $p \in P$ by facility $i \in L$ in period $t \in T$
$TC^t_{i,j,p}$	Variable cost of shipping one unit of product $p \in P$ from facility $i \in L$ to facility $j \in L$ $(i \neq j)$ in period $t \in T$
$IC^t_{i,p}$	Variable inventory carrying cost per unit on hand of product $p \in P$ in facility $i \in L$ at the end of period $t \in T$
$MC^t_{i,j}$	Variable cost of moving one unit of capacity at the beginning of period $t \in T \setminus \{1\}$ from the existing facility $i \in S^c$ to a new facility established at site $j \in S^o$
OC^t_i	Fixed cost of operating facility $i \in L$ in period $t \in T$
FC^t_i	Fixed setup cost charged in period $t \in T \setminus \{n\}$ when a new facility established at site $i \in S^o$ starts its operation at the beginning of period $t + 1$
SC^t_i	Fixed cost charged in period $t \in T \setminus \{1\}$ for closing the existing facility $i \in S^c$ at the end of period $t - 1$

Table 2: Costs

Table 3 introduces additional input parameters. The capacity of each existing facility is assumed to be non-increasing over the planning horizon. Similarly, potential new facilities have non-decreasing capacities throughout the time horizon.

Table 4 describes the decision variables. Existing facilities may have an initial positive inventory level which in that case fixes the values of the inventory variables $y^0_{i,p}$ for every $i \in L \setminus S^o$ and $p \in P$. Clearly, potential sites do not hold initial stock so that $y^0_{j,p} = 0$ for every $j \in S^o$ and $p \in P$. The statuses of the facilities over the time horizon are ruled by the binary variables η^t_i. If an existing facility $i \in S^c$ ceases to operate at the end of period t then $\eta^t_i = 1$. Similarly, if a new facility starts to operate in site $j \in S^o$ at the beginning of period t then $\eta^t_j = 1$. Observe that a new facility can never operate in the first period since that would incur a setup cost prior to the beginning of the planning horizon. Analogously, an existing facility cannot be closed at the end of the last period since the fixed closing cost would be charged in

Symbol	Description
$\overline{K}_i^t$	Capacity of facility $i \in L$ in period $t \in T$
$\underline{K}_i^t$	Lower limit on the amount shipped by the selectable facility $i \in S$ in period $t \in T$
$\mu_{i,p}$	Amount of capacity required by one unit of product $p \in P$ at facility $i \in L$
$D_{i,p}^t$	Demand of customer/facility $i \in L$ for product $p \in P$ in period $t \in T$
B^t	Available budget in period $t \in T$
α^t	Unit return factor on capital not invested in period $t \in T \setminus \{n\}$
ϵ	Sufficiently small positive number

Table 3: Other input parameters

a period beyond the planning horizon. Hence, $z_{i,j}^1 = 0$ for every $i \in S^c$ and $j \in S^o$. Moreover, $\eta_i^1 = 0$ for every $i \in S^o$ and $\eta_j^n = 0$ for every $j \in S^c$.

Symbol	Description
$b_{i,p}^t$	Amount of product $p \in P$ produced/purchased by facility $i \in L$ in period $t \in T$
$x_{i,j,p}^t$	Amount of product $p \in P$ shipped from facility $i \in L$ to facility $j \in L$ $(i \neq j)$ in period $t \in T$
$y_{i,p}^t$	Amount of product $p \in P$ held in stock in facility $i \in L$ at the end of period $t \in T \cup \{0\}$; $y_{i,p}^0$ denotes the initial inventory level
$z_{i,j}^t$	Amount of capacity shifted at the beginning of period $t \in T$ from the existing facility $i \in S^c$ to a newly established facility at site $j \in S^o$
ξ^t	Amount of capital not invested in period $t \in T$
η_i^t	$= 1$ if the selectable facility $i \in S$ changes its status in period $t \in T$; 0 otherwise

Table 4: Decision variables

Melo et al. [24] proposed two alternative MILP formulations for the above problem. The heuristic procedure to be presented in Section 4 is based on the following MILP model:

$$(P) \quad \text{MIN} \sum_{t\in T}\sum_{i\in L}\sum_{p\in P} PC_{i,p}^t\, b_{i,p}^t + \sum_{t\in T}\sum_{i\in L}\sum_{j\in L\setminus\{i\}}\sum_{p\in P} TC_{i,j,p}^t\, x_{i,j,p}^t + \sum_{t\in T}\sum_{i\in L}\sum_{p\in P} IC_{i,p}^t\, y_{i,p}^t$$

$$+ \sum_{t\in T}\sum_{i\in S^c} OC_i^t \left(1 - \sum_{\tau=1}^{t-1}\eta_i^\tau\right) + \sum_{t\in T}\sum_{i\in S^o} OC_i^t \sum_{\tau=1}^{t}\eta_i^\tau + \sum_{t\in T}\sum_{i\in L\setminus S} OC_i^t \qquad (1)$$

s.t.

$$b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1} = D_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{i,j,p}^t + y_{i,p}^t \qquad i\in L,\, p\in P, t\in T \tag{2}$$

$$\overline{K}_i^1 - \sum_{\tau=1}^{t}\sum_{j\in S^o} z_{i,j}^\tau \le \overline{K}_i^t \left(1-\sum_{\tau=1}^{t-1}\eta_i^\tau\right) \qquad i\in S^c,\, t\in T \tag{3}$$

$$\sum_{\tau=1}^{t}\sum_{i\in S^c} z_{i,j}^\tau \le \overline{K}_j^t \sum_{\tau=1}^{t}\eta_j^\tau \qquad j\in S^o,\, t\in T \tag{4}$$

$$\sum_{\tau=1}^{t}\sum_{j\in S^o} z_{i,j}^\tau + \epsilon\left(1-\sum_{\tau=1}^{t-1}\eta_i^\tau\right) \le \overline{K}_i^1 \qquad i\in S^c,\, t\in T \tag{5}$$

$$\sum_{p\in P}\mu_{i,p}\left(b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1}\right) \le \overline{K}_i^1 - \sum_{\tau=1}^{t}\sum_{j\in S^o} z_{i,j}^\tau \qquad i\in S^c,\, t\in T \tag{6}$$

$$\sum_{p\in P}\mu_{i,p}\left(b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1}\right) \le \sum_{\tau=1}^{t}\sum_{j\in S^c} z_{j,i}^\tau \qquad i\in S^o,\, t\in T \tag{7}$$

$$\sum_{p\in P}\mu_{i,p}\left(b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1}\right) \le \overline{K}_i^t \qquad i\in L\setminus S,\, t\in T \tag{8}$$

$$\sum_{p\in P}\mu_{i,p}\left(b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1}\right) \ge \underline{K}_i^t \left(1-\sum_{\tau=1}^{t-1}\eta_i^\tau\right) \qquad i\in S^c,\, t\in T \tag{9}$$

$$\sum_{p\in P}\mu_{i,p}\left(b_{i,p}^t + \sum_{j\in L\setminus\{i\}} x_{j,i,p}^t + y_{i,p}^{t-1}\right) \ge \underline{K}_i^t \sum_{\tau=1}^{t}\eta_i^\tau \qquad j\in S^o,\, t\in T \tag{10}$$

$$\sum_{t\in T}\eta_i^t \le 1 \qquad i\in S \tag{11}$$

$$\sum_{i\in S^o} FC_i^1\left(\sum_{\tau=1}^{2}\eta_i^\tau\right) + \xi^1 = B^1 \tag{12}$$

$$\begin{aligned}&\sum_{i\in S^c}\sum_{j\in S^o} MC_{i,j}^t\, z_{i,j}^t + \sum_{i\in S^c} SC_i^t \eta_i^{t-1} + \sum_{j\in S^o} FC_j^t\, \eta_j^{t+1} + \xi^t \\ &\quad = B^t + \alpha^{t-1}\,\xi^{t-1} \qquad t\in T\setminus\{1,n\}\end{aligned} \tag{13}$$

$$\sum_{i\in S^c}\sum_{j\in S^o} MC_{i,j}^n\, z_{i,j}^n + \sum_{i\in S^c} SC_i^n \eta_i^{n-1} + \xi^n = B^n + \alpha^{n-1}\,\xi^{n-1} \tag{14}$$

$$b_{i,p}^t \ge 0,\ y_{i,p}^t \ge 0,\ x_{i,j,p}^t \ge 0,\ \xi^t \ge 0 \qquad i\in L,\, j\in L\setminus\{i\},\ p\in P,\, t\in T \tag{15}$$

$$z_{i,j}^t \geq 0 \qquad i \in S^c,\, j \in S^o,\, t \in T \quad (16)$$

$$\eta_i^t \in \{0,1\} \qquad i \in S,\, t \in T \quad (17)$$

The objective function (1) minimizes total network reconfiguration costs which comprise variable supply, transportation and inventory holding costs as well as fixed facility operating costs. Constraints (2) are the usual flow conservation conditions and also ensure the satisfaction of customer demands. Inequalities (3) guarantee that only operating existing facilities can have their capacities transferred to new facilities. Constraints (4) state that a new facility can only start receiving capacity after its setup, while constraints (5) ensure that an existing facility is only closed after complete removal of its capacity. Capacity constraints are imposed by inequalities (6)–(8). Constraints (9)–(10) ensure that a selectable facility operates with at least a given throughput. Constraints (11) allow the status of each selectable facility to change at most once over the time horizon. This means that a facility that is removed cannot be re-opened and once open, a new facility cannot be closed. Conditions (12)–(14) guarantee that the available budget is invested in capacity transfers, the setup of new facilities and the removal of existing facilities upon complete relocation. Capital not used in a given period earns interest and can later be invested. Finally, constraints (15)–(17) represent non-negativity and binary conditions.

Observe that model (P) captures several of the features identified by Hammami et al. [11] associated with realistic relocation scenarios.

4 Heuristic approach

The MILP model (P) contains two types of inherently different decisions: on the one hand, the yes/no-decisions to change the operating status of facilities (variables η_i^t) and, on the other hand, a large number of strategic and tactical supply chain decisions modeled by non-negative continuous variables. Once the binary choice for facility operation has been made, the resulting problem is linear and thus much simpler to solver. Hence, the design of solution procedures that decouple the binary decisions variables from the continuous variables is a natural approach to overcome the computational hurdle resulting from model (P) being NP-hard and therefore, being extremely difficult to solve real-size instances to optimality.

Approximation algorithms based on linear programming (LP) have been used extensively to obtain near-optimal solutions for many classes of discrete optimization problems (see e.g., Gonzalez [10] and Vazirani [35] for some applications). A basic technique is to solve the linear relaxation of the integer program and then convert the fractional solution into an integer solution, trying to ensure that in the process the objective value does not deteriorate much. A variety of facility location problems have been solved efficiently by LP-rounding techniques (see e.g., Chudak and Shmoys [6] and Shmoys [29]). In contrast, this algorithmic approach has been scarcely applied to facility location problems in an SCM context due to the real challenges presented by this class of difficult problems. Recently, Thanh et al. [33] proposed an LP-rounding heuristic for a large-scale multi-period network design problem. Unfortunately, large running times are reported while solving medium-size instances.

Our motivation for designing an LP-rounding heuristic stems not only from this being a natural approach to explore the structure of our problem, but also from the tight lower bound provided by the linear relaxation of model (P). For a large set of randomly generated instances, Melo et al. [24] observed that on average the LP relaxation is within 2% of the corresponding optimal solution.

Our solution approach consists of a fast construction phase where four rounding strategies are applied to iteratively replace the fractional variables in the LP relaxation by binary values. If during this process infeasibility arises, the incumbent solution will be repaired in the second phase. Otherwise, local search is used in an attempt to improve the quality of the feasible solution delivered by the construction phase.

4.1 Construction phase

The aim of the construction phase is to identify an initial feasible solution. Table 5 introduces the required notation.

The steps performed during this phase are summarized below. The procedure starts by solving the linear relaxation of the original problem (Step 0). It is widely known that simply rounding all fractional facility status variables to their nearest integer values frequently causes constraint violation. Hence, we devised four variable fixing strategies (VFS1-VFS4) to gradually assign binary values to the location variables η_i^t, $i \in S$, $t \in T$. The procedure ends when all facility status variables are binary (Step 4).

The algorithm relies on a careful selection of variables to be made binary. Priority is given to rounding fractional values to zero as this decision usually has little impact on the network configuration. The variable fixing strategies VFS1 and VFS3 comprise selection mechanisms

Symbol	Description
H_0	Set of pairs (i,t) with $i \in S$ and $t \in T$ such that $\eta_i^t = 0$
H_1	Set of pairs (i,t) with $i \in S$ and $t \in T$ such that $\eta_i^t = 1$
H	Union of sets H_0 and H_1; the elements of set H correspond to facility status variables η_i^t that take binary values
$\overline{H}$	Set of pairs (i,t) with $i \in S$ and $t \in T$ such that $(i,t) \notin H$; the elements of set $\overline{H}$ refer to facility status variables η_i^t that take fractional values
LP_H	Linear relaxation of problem (P) with the facility status variables associated with set H being binary
Sol_{LP}	$0-1$ flag indicating whether LP_H is feasible (value 1) or infeasible (value 0)
P_H	Problem (P) when *all* facility status variables η_i^t have given fixed binary values
Δ_H	Gap between the upper bound $v(P_H)$ provided by the solution of P_H and the lower bound $v(LP)$ given by the linear relaxation of (P); $\Delta_H = (v(P_H) - v(LP))/v(LP)$
$\underline{\eta}$	Threshold for variable fixing at zero
$\overline{\eta}$	Threshold for variable fixing at one
$\widetilde{\eta}$	Threshold for variable fixing at zero or one
i_{max}	Maximum number of fractional facility status variables that are rounded to zero

Table 5: Notation used in Algorithm 1

for rounding to zero. In contrast, fixing a facility status variable at one triggers a sequence of changes in the network configuration that in the worst case may violate several constraints. If it is decided to round some variable η_i^t with $i \in S^c$ to one then the corresponding existing facility i will cease to operate at the end of period t. This decision can only be performed if capacity and budget conditions allow moving the entire capacity of facility i to new sites until period t. On the other hand, the selection of some variable η_i^t with $i \in S^o$ to be fixed at one leads to opening a new facility in the potential site i at the beginning of period t. This action is mainly limited by the available budget in period $t-1$ to pay the setup of the new facility. The variable fixing strategies VFS2 and VFS4 were devised to perform rounding to one.

Steps 1-3, which form the first part of Algorithm 1, focus on iteratively rounding fractional variables using pre-specified lower and upper thresholds (see the description of VFS1 and VFS2 below). Each time one or several variables $\{\eta_i^t\}_{(i,t)\in\overline{H}}$ become integer, a new LP relaxation with the remaining non-binary variables allowed to take values in the interval $[0,1]$, is solved. If variable fixing leads to an infeasible LP problem then we proceed to the second part of the algorithm, where all variables that are still fractional are made binary according to two additional strategies (VFS3 and VFS4). In particular, the parameter i_{max} limits the number of variables

Algorithm 1: Construction phase

Step 0:	Initialize sets H_0 and H_1, solve LP_H, set $\mathsf{Sol}_{LP} = 1$ and $k = 0$
Step 1:	Apply VFS1
	If unsuccessful *then* go to Step 3
Step 2:	Solve LP_H
	If LP_H infeasible *then* set $\mathsf{Sol}_{LP} = 0$ and go to Step 4
Step 3:	Apply VFS2
	If VFS1 or VFS2 successful *then* return to Step 1
....	....
Step 4:	*If* $\overline{H} = \emptyset$ *then* calculate Δ_H and STOP
Step 5:	*If* $k \leq i_{max}$ *then*
	Set $k = k + 1$ and apply VFS3
	If successful *then*
	If $\mathsf{Sol}_{LP} = 1$ *then* go to Step 7 *else* return to Step 4
Step 6:	Set $k = 0$ and apply VFS4
	If $\mathsf{Sol}_{LP} = 0$ *then* return to Step 4
Step 7:	Solve LP_H
	If LP_H infeasible *then* set $\mathsf{Sol}_{LP} = 0$ and return to Step 4
Step 8:	Apply VFS2
	If successful *then* return to Step 1
	else
	Apply VFS1
	If successful *then* return to Step 2 *else* return to Step 4

to be rounded to zero before exploring the possibility of fixing a location variable at one.

An alternative outcome of the first part of Algorithm 1 is a feasible fractional solution for which further rounding is not possible as the non-binary facility status variables are bounded by the lower and upper thresholds. In this case, we continue with the second part (Steps 5-8) by first selecting a fractional variable to be rounded to zero. The impact of this choice is evaluated by solving the remaining linear program (Step 7). If the LP relaxation is feasible then we try to round one more variable to one (Step 8). When this measure proves to be successful the variable fixing process is restarted by returning to the first part of the algorithm.

In the following sections we describe in detail the strategies that were implemented.

4.1.1 Initialization

In view of the assumptions made in Section 3 with respect to the periods in which the fixed setup cost of a new facility and the fixed closing cost of an existing facility may be incurred, it is natural to solve the linear relaxation to problem (P) with an already fixed set of variables. Hence, $H = H_0 \cup H_1$ with $H_0 = \{(i,1) : i \in S^o\} \cup \{(i,n) : i \in S^c\}$ and $H_1 = \emptyset$.

4.1.2 Variable fixing strategies

Each of the following procedures aims at rounding one or several fractional variables $\{\eta_i^t\}_{(i,t)\in\overline{H}}$ to one or zero.

VFS1

All facility status variables with fractional values not exceeding a user-defined lower threshold $\underline{\eta}$ are assumed to remain unchanged and therefore have their values rounded to zero:

Set $\eta_i^t = 0$ for every $(i,t) \in \overline{H}$ such that $\eta_i^t \leq \underline{\eta}$.

If rounding occurs then sets H_0 and H are updated accordingly.

VFS2

All facility status variables with fractional values above a given upper threshold $\overline{\eta}$ are potential candidates to be rounded to one, that is, $\eta_i^t \geq \overline{\eta}$ with $(i,t) \in \overline{H}$.

Since the resulting linear relaxation is very sensitive to variable fixing at one, at most *one* of these variables will be selected. Among the candidate variables for which feasibility of the corresponding LP relaxation is retained, the one yielding the highest objective value is chosen. If such a variable can be found let us denote it by η_j^τ. It follows that the pair (j,τ) is moved from set $\overline{H}$ to set H_1. Furthermore, due to constraints (11), set H_0 is extended with pairs (j,t) for every $t \in T \setminus \{\tau\}$. Finally, set $\overline{H}$ includes those pairs (i,t) for which η_i^t take fractional values in the feasible solution to the retained LP relaxation.

VFS3

The aim of this strategy is to round to zero a fractional variable corresponding to an *existing* facility. To this end, among the pairs $(i,t) \in \overline{H}$ with $i \in S^c$, the facility status variable η_i^t with lowest fractional value is identified and fixed at zero. If such variable can be found then sets H_0 and H are updated accordingly.

VFS4

This strategy aims at setting a fractional variable corresponding to a *potential new* facility to a binary value. Let η_j^t denote the status variable with current largest fractional value such that

$(j,t) \in \overline{H}$ and $j \in S^o$. If $\eta_j^t \geq \widetilde{\eta}$, with $\widetilde{\eta}$ a user-defined threshold, then $\eta_j^t = 1$, otherwise $\eta_j^t = 0$. Depending on the action implemented, one of the sets H_1 or H_0 is updated.

4.2 Repair and improvement phase

Three solution outcomes are possible at the end of the construction phase:

a) Problem P_H is infeasible and therefore, $\Delta_H = +\infty$.

b) Problem P_H is feasible but $\Delta_H > \underline{\Delta}$.

c) Problem P_H is feasible and $\Delta_H \leq \underline{\Delta}$.

The parameter $\underline{\Delta}$ denotes a pre-specified solution quality criterion. In the first case, a repair mechanism is needed to transform the initial infeasible solution into a feasible one. In the second case, although a feasible solution has been identified its quality is unsatisfactory and thus an improvement scheme is required. In the last case, no further steps are applied since a feasible solution to the original problem (P) with a good LP gap is already available.

The aim of the second phase is to handle cases 1 and 2 simultaneously. Table 6 introduces the required notation. The algorithm is divided into two parts - 2a and 2b - that are outlined below.

Symbol	Description
h_ℓ	ℓ-th element of set H_1 (in case $H_1 \neq \emptyset$)
$i(h_\ell)$	First component of h_ℓ representing a facility
$t(h_\ell)$	Second component of h_ℓ representing a time period
$\underline{\Delta}$	Gap threshold
ℓ_{max}	Maximum number of facility status variables to be investigated
j_{max}	Maximum number of facility status variables that have their binary values changed from 1 to 0
k_{max}	Maximum number of visited solutions starting from a given solution

Table 6: Notation used in Algorithm 2

In the first part of the algorithm (Algorithm 2a), a non-exhaustive search of a simple neighborhood is performed. For the sake of simplicity, let us assume that the current solution includes a non-empty set of facility status variables fixed at one, i.e. $\{\eta_i^t\}_{(i,t)\in H_1} \neq \emptyset$. In other words, set H_1 corresponds to facilities whose statuses change over the planning horizon. The neighborhood of this solution is defined by the following two types of exchanges:

1. Undo the status change of some facility i in period t such that $(i,t) \in H_1$.

2. Perform move 1 and at the same table enable another facility to have its status be changed in the same period t.

A move of type 2 corresponds in fact to a swap of two variables. The variable to be switched from zero to one is randomly selected from the set H_0. This procedure is repeated for each element of the set H_1. In case this set is empty, variable swapping is not possible and therefore, only the second part of a move of type 2 can be performed for $t = 1$. In addition, a user-defined parameter (k_{max}) controls the number of times this procedure is repeated. Whenever a new best feasible solution is identified it becomes incumbent.

Algorithm 2a: First part of repair and improvement phase

If $\Delta_H > \underline{\Delta}$ *then*
  For $\ell = 1, ..., \ell_{max}$ *do*
    Set $t = 1$
    If $|H_1| > 0$ *then*
      Add h_ℓ to H_0 and remove it from H_1
      Set $t = t(h_\ell)$
    For $k = 1, ..., k_{max}$ *do*
      Select at random facility $i \in S$ such that $i \neq i(h_\ell)$
      If $(i,t) \in H_0$ *then* add (i,t) to H_1 and remove this pair from H_0
      Check for new incumbent best solution and update Δ_H if necessary
      Restore H_0 and H_1

In the second part of the algorithm (Algorithm 2b), the neighborhood search is enlarged if the quality of the incumbent solution is still not satisfactory. This encompasses mutually exchanging the values of more than two facility status variables. Hence, k-swaps involve randomly selecting $k/2$ pairs from set H_1 and $k/2$ pairs from set H_0. Observe that similar to moves of type 1 in Algorithm 2a, it is possible to restrict the number of variables to be changed to one, and thus avoid drastic modifications to the network configuration which may cause constraint violation.

Algorithms 1 and 2 rely on a number of user-defined parameters whose values are dynamically modified during the whole procedure. As it is typical in heuristic development, the tuning of these parameters is a critical issue. Based on a number of empirical computational experiments, we present in Section 5.2 the parameter settings that best contributed to a good performance of our heuristic procedure.

Algorithm 2b: Second part of repair and improvement phase

for $j = 2, ..., j_{max}$ *do*
  If $\Delta_H > \underline{\Delta}$ *and* $|H_1| \neq 1$ *then*
    Set $t_1 = \ldots = t_j = 1$
    For $k = 1, ..., k_{max}$ *do*
      If $|H_1| \geq j$ *then*
        Select at random j different elements $h_1, \ldots, h_j \in H_1$
        Add $h_1, \ldots, h_j$ to H_0 and remove them from H_1
        Set $t_1 = t(h_1), \ldots, t_j = t(h_j)$
      Select at random j different facilities $i_1, \ldots, i_j \in S$ such that $i_\ell \neq i(h_\ell)$
      for at least one ℓ $(1 \leq \ell \leq j)$
      For $\ell = 1, \ldots, j$ *do*
        If $(i_\ell, t_\ell) \in H_0$ *then* add (i_ℓ, t_ℓ) to H_1 and remove this pair from H_0
      Check for new incumbent best solution and update Δ_H if necessary
      Restore H_0 and H_1

5 Computational experiments

In this section we report on the efficiency and effectiveness of the new heuristic based on considerable computational testing carried out on three sets of randomly generated instances. The first set includes 45 instances, denoted by P1-P45, and is associated with simple networks having DCs and customers. The second set comprises 25 instances, denoted by P46-P70, and refers to two-echelon networks with plants and DCs. These two sets coincide with classes 1 and 2 used by Melo et al. [24] and were generated following the procedure described by Melo et al. [23]. In all instances P1-P70 facility relocation decisions concern the DC layer.

Melo et al. [24] also studied a third set of instances associated with three-echelon networks comprising plants, central and regional DCs. However, since only a few instances of small size were considered, we decided to strengthen this class by generating 45 new test problems capturing realistic characteristics. In Section 5.1 we describe the methodology employed to generate these instances. The parameter settings used by our heuristic are presented in Section 5.2, while the computational results are discussed in Section 5.3.

5.1 Data generation

The literature on strategic SCM is rather scarce with respect to the instances that have been considered either in practical or empirical studies. Nevertheless, the recent overview by Melo et al. [25] on facility location in SCM shows that problem sizes vary considerably. Some empirical studies performed with randomly generated instances are provided for example by Amiri [2] and Romeijn et al. [28].

Taking into account the existing literature and the information therein, supply chain networks comprising three facility echelons were considered for generating 45 new instances. Table 7 presents the main settings of this new class, denoted by set 3. The values of the parameters defining each instance as well as the size of the instances are given in Table 11 in Appendix A. Relocation decisions are restricted to central and regional DCs. As a result, the set of existing selectable facilities is $S^c = S^c_c \cup S^c_r$ whereas the set of potential new facilities is $S^o = S^o_c \cup S^o_r$. The set of all facilities is given by $L = C \cup F \cup S^c \cup S^o$.

Symbol	Description	Values tested
C	Set of all customers	50, 100, 200
F	Set of plants	5
S^c_c	Set of existing central DCs	4, 8
S^o_r	Set of existing regional DCs	10, 20
S^o_c	Set of potential new central DCs	8, 12
S^o_r	Set of potential new regional DCs	20, 30
P	Set of products	5, 10, 20, 50
T	Set of time periods	3, 4, 6, 8

Table 7: Facilities, products and time horizons of instances in set 3

Table 8 gives the details with respect to the generation of cost and other input data. In this table, $U[a, b]$ denotes the random generation of numbers in the interval $[a, b]$ according to a uniform distribution. Entries of the type $U[a, b] \cdot (1 + U^{t-1}[c, d]\%)$ indicate that values between a and b are drawn from a uniform distribution in period $t = 1$. In each subsequent period $t \in T \setminus \{1\}$, the generated value is not smaller than that of the previous period $t - 1$, while the percentage increase varies between $c\%$ and $d\%$. For example, having $D^t_{\ell,p} = U[1, 25] \cdot (1 + U^{t-1}[5, 10]\%)$ means that the demand of customer ℓ for product p is randomly generated according to a uniform distribution in $[1, 25]$ in the first period. The demand in the second period is given by $D^2_{\ell,p} = D^1_{\ell,p} \cdot (1 + \gamma/100)$ with $\gamma \in U[5, 10]$. This implies that the demand increase in this period is at least 5% and at most 10% compared to the first period. All costs follow a non-decreasing pattern since in our view this reflects real-life situations better, as supply chain networks are often redesigned to cope with rising costs driven by an expanding global economy. Observe that unlike classes 1 and 2, in the new set facility closing costs are considerably lower than opening costs and may even take negative values. The latter account for revenues due to the termination of leasing contracts or the selling of property.

The intervals for generating the input parameters were selected with the aim of obtaining a wide variety of instances close to real-life problems.

Parameter	Symbol	Value
Customer demand	$D^t_{\ell,p}$, $\ell \in C$	$U[0,25] \cdot (1 + U^{t-1}[0,5]\%)$
Initial stock	$H_{\ell,p}$, $\ell \in F \cup S^c$	0
Interest rate	α^t	$U[3,5]$
Available budget	B^t	$U[10234, 46025]$
Costs:		
Purchasing/production	$PC^t_{\ell,p}$, $\ell \in F$	$U[15,25] \cdot (1 + U^{t-1}[15,25]\%)$
Transportation	$TC^t_{\ell,\ell',p}$, $\ell, \ell' \in L$	$U[5,50] \cdot (1 + U^{t-1}[0,5]\%)$
Inventory carrying	$IC^t_{\ell,p}$, $\ell \in F \cup S$	$U[5,10] \cdot (1 + U^{t-1}[0,5]\%)$
Operating	OC^t_{ℓ}, $\ell \in F \cup S$	$U[1000,2000] \cdot (1 - U^{t-1}[0,5]\%)$
Capacity relocation	$MC^t_{i,j}$, $i \in S^c$, $j \in S^o$	$U[2,5] \cdot (1 - U^{t-1}[0,5]\%)$
Closing (existing fac.)		
central DCs	SC^t_{ℓ}, $\ell \in S^c_c$	$U[-200,1200] \cdot (1 - U^{t-1}[0,5]\%)$
regional DCs	SC^t_{ℓ}, $\ell \in S^c_r$	$U[-200,1200] \cdot (1 - U^{t-1}[0,5]\%)$
Opening (new fc.)		
central DCs	FC^t_{ℓ}, $\ell \in S^o_c$	$U[8000,12000] \cdot (1 - U^{t-1}[0,5]\%)$
regional DCs	FC^t_{ℓ}, $\ell \in S^o_r$	$U[8000,10000] \cdot (1 - U^{t-1}[0,5]\%)$
Max. capacities:		
plants	$\overline{K}^t_{\ell}$, $\ell \in F$	$U[LB(F), 1.1 \cdot LB(F)] \cdot (1 - U^{t-1}[0,3]\%)$
existing central DCs	$\overline{K}^t_{\ell}$, $\ell \in S^c_c$	$U[LB(S^c_c), 1.1 \cdot LB(S^c_c)] \cdot (1 - U^{t-1}[0,3]\%)$
existing regional DCs	$\overline{K}^t_{\ell}$, $\ell \in S^c_r$	$U[LB(S^c_r), 1.1 \cdot LB(S^c_r)] \cdot (1 - U^{t-1}[0,3]\%)$
new central DCs	$\overline{K}^t_{\ell}$, $\ell \in S^o_c$	$U[0.9 \cdot LB(S^c_c), LB(S^c_c)] \cdot (1 - U^{t-1}[0,3]\%)$
new regional DCs	$\overline{K}^t_{\ell}$, $\ell \in S^o_r$	$U[0.9 \cdot LB(S^c_r), LB(S^c_r)] \cdot (1 - U^{t-1}[0,3]\%)$
Min. throughput:	$\underline{K}^t_{\ell}$, $\ell \in S$	
central DCs	$\underline{K}^t_{\ell}$, $\ell \in S^c_c \cup S^o_c$	$U[0.6 \cdot LB(S^c_c), 0.9 \cdot LB(S^c_c)]$
regional DCs	$\underline{K}^t_{\ell}$, $\ell \in S^c_r \cup S^o_r$	$U[0.6 \cdot LB(S^c_r), 0.9 \cdot LB(S^c_r)]$
Capacity consumption factor	$\mu_{\ell,p}$, $\ell \in F \cup S$	1
Transp. arcs between facilities		$5 - 70\%$
Products assigned to arcs		70%

Table 8: Parameters used in the random generation of instances in set 3 with $t = 1, 2, \ldots, n$

The capacities of plants and DCs in the first period (i.e. $\overline{K}^1_{\ell}$, $\ell \in F \cup S$) are based on the following estimation of the total demand requirements over the planning horizon:

$$D = \big(0.75 \cdot \overline{D} \cdot |P|\big) \cdot |C| \cdot 1.025^{n-1}$$

where $\overline{D}$ denotes the average customer demand for any product. We set $\overline{D}$ equal to the midpoint of the demand interval (see Table 8), that is, $\overline{D} = 12.5$. Moreover, we assume that at most 75% of the product types are requested by each customer. As a result, an overestimation of the total customer demand in the first period is given by $(0.75 \cdot \overline{D} \cdot |P|) \cdot |C|$. Since demand requirements increase every period at a rate varying between 0% and 5%, a demand peak is reached in the last period n. Assuming that demand grows on average 2.5% per period, it follows that the total increase is estimated by 1.025^{n-1}.

The capacity of a plant and of an existing DC is drawn from a uniform distribution whose lower limit is given by

$$\text{Plants} \quad : \quad LB(F) = \frac{D}{|F|} \tag{18}$$

$$\text{Existing central DCs} \quad : \quad LB(S_c^c) = \frac{D}{|S_c^c|} \tag{19}$$

$$\text{Existing regional DCs} \quad : \quad LB(S_r^c) = \frac{D}{|S_r^c|} \tag{20}$$

and the upper limit is 10% larger than the lower limit. The capacities of the new DCs are smaller than those of existing DCs as described in Table 8. The above lower bounds (19)-(20) are also used to generate suitable minimum throughputs at central and regional DCs (see Table 8).

Furthermore, in an attempt to generate realistic instances, an upper bound is set on the number of arcs available for the transportation of products through the network. Table 9 describes the various types of connections considered. In addition, only 70% of the product types can actually flow through each generated arc. This allows the volume of traffic in the network to be limited and thus mimic real-world situations.

Source	Destination	Arc density (%)
Plants	Central DCs	70
Central DCs	Regional DCs	40
Central DCs	Central DCs	100
Central DCs	Customers	5
Regional DCs	Customers	50
Regional DCs	Regional DCs	40

Table 9: Arc density used to generate three-echelon networks (set 3)

5.2 Parameter settings

To fine-tune the parameters used by the heuristic described in Section 4, we initially conducted a set of empirical experiments. Table 10 presents the numerical values that better contributed to a good performance of our heuristic procedure.

In addition, the improvement phase (Algorithm 2a) is triggered by a feasible solution with an objective value that deviates more than $\underline{\Delta} = 2.5\%$ from the lower bound of the linear relaxation.

Parameter	Value
$\underline{\eta}$	0.01 in the first iteration of Algorithm 1; 0.1 otherwise
$\overline{\eta}$	0.9
$\widetilde{\eta}$	0.5
i_{max}	2
ℓ_{max}	2 if $\lvert H_1 \rvert = \emptyset$; $\lvert H_1 \rvert$ otherwise
j_{max}	3
k_{max}	20 in Algorithm 2a; 30 in Algorithm 2b

Table 10: Parameter values for Algorithms 1, 2a and 2b

The choice of this value stems from the computational experience of Melo et al. [24] which indicates that the linear relaxation of (P) is very strong. On average the LP relaxation is within 2% of the corresponding optimal solution. The gap threshold $\underline{\Delta}$ is halved in Algorithm 2b when the neighborhood size is enlarged in an attempt to find a better solution.

Finally, due to the random nature of the second phase of the heuristic, in which facility status variables are randomly chosen to have their values exchanged, 10 runs are performed for every instance.

5.3 Summary of results

We evaluate the performance of the new heuristic by comparing the solutions identified for 115 randomly generated instances with solutions delivered by the well-known CPLEX [19] optimization solver. Over the past years, the effort invested on the development of commercial optimization engines such as CPLEX has significantly increased the possibility of tackling many complex problems. Even when an optimal solution cannot be found within acceptable computational time, it is often possible to identify a high-quality feasible solution. To verify if this also applies to our problem, we ran CPLEX with two stopping criteria: a time limit of 5 hours and a target gap. For the latter, the deviation between the best solution and the best lower bound delivered by CPLEX is at most 1%. Thus, we use CPLEX as an alternative heuristic method. Our choice is supported by Cordeau et al. [7] who argue that solving a real-life problem to optimality is usually not meaningful due to errors contained in the data estimates. Since the error margin tends to be larger than 1%, these authors claim that it is adequate to run the optimization solver until a feasible solution within 1% optimality is identified. Ambrosino and Scutellà [1] and Melkote and Daskin [22] also use an optimization solver heuristically. Hence, for the best feasible solution the solver produces there is a guarantee of the maximum deviation from optimality.

Formulation (P) presented in Section 3 was modeled using ILOG Concert Technology 2.0 [18] and solved with CPLEX 10.2. The linear relaxations LP_H associated with some of the facility status variables at fixed binary values were also solved with CPLEX. All experiments were conducted on a Pentium IV with a 3.2 GHz processor and 1 GB RAM.

Figure 2 illustrates the outcome of each phase of the heuristic procedure. Feasible solutions are found in the first phase for 61 of the 115 instances. Over 55.7% $(34$ out of $61)$ of these solutions satisfy the pre-defined quality criterion of 2.5% with respect to deviation to the linear relaxation bound. Only 10 feasible solutions could not be further improved in the second phase of the heuristic. For the remaining 54 instances no feasible solutions were identified in the first phase. Nevertheless, the subsequent phase succeeded in delivering a feasible solution for each of these instances.

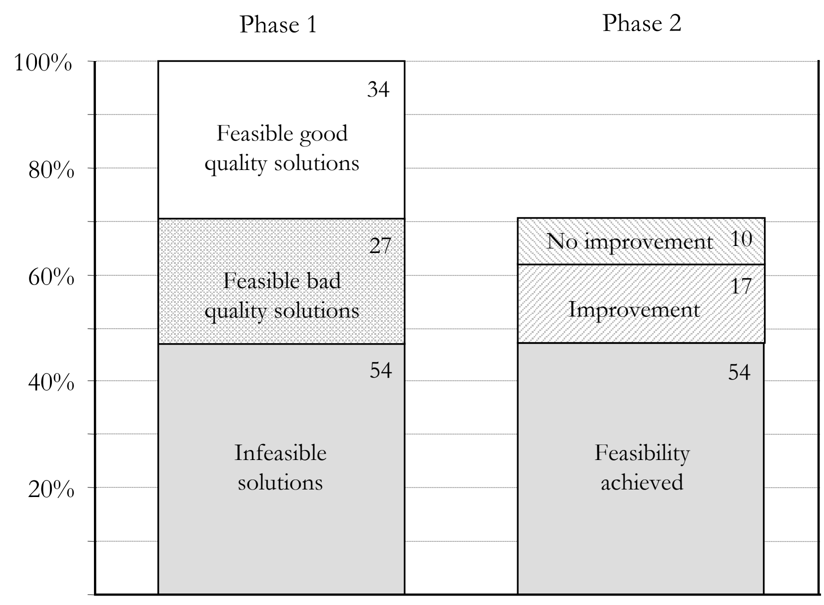
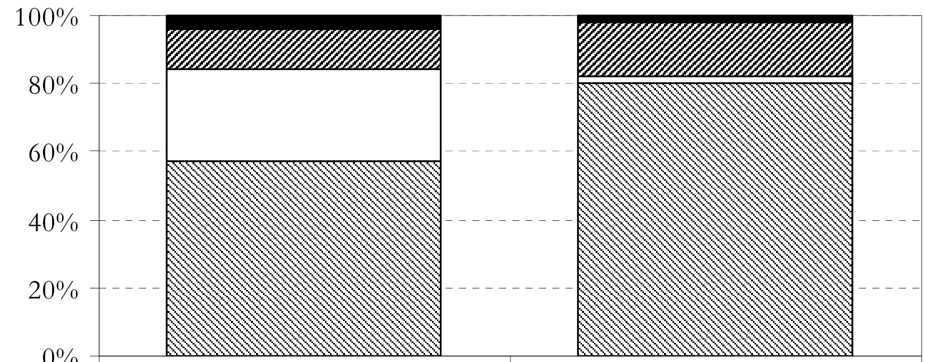


Figure 2: Outcome of phases 1 and 2 of the heuristic procedure

Figure 3 displays the quality of the feasible solutions identified by the new heuristic. The relative percentage deviation ("LP-gap") between the objective value of these solutions and the lower bound produced by the linear relaxation of (P) is grouped into four categories. The information is given separately for instances P1-P70 (sets 1 and 2) and P71-P115 (set 3) because there is an indication that the heuristic performs consistently better in the latter group. In 80% of the instances in set 3 (36 out of 45), the feasible solution is within 1% of the LP bound. In contrast, such high-quality solutions are only delivered to 57.1% (40 out of 70) of the other two sets of instances. Recall that instances P71-P115 refer to the more complex network structures whose generation was motivated by the need to capture practical features of strategic supply chain planning. Greater complexity also enlarges the number of feasible network configurations over the planning horizon compared to sets 1 and 2 (P1-P70), thus offering diversity of choice to our heuristic procedure. In contrast, the single-echelon and two-echelon networks associated with P1-P70 comprise a limited number of feasible configurations, which seems to hinder the progress of the heuristic towards feasibility, in particular during the first phase.



	P1 - P70	P71 - P115
■ LP-gap > 10%	3	1
▨ 5% < LP-gap ≤ 10%	8	7
□ 1% < LP-gap ≤ 5%	19	1
▧ LP-gap ≤ 1%	40	36

Figure 3: Deviation of the feasible solutions identified with the new heuristic from the corresponding LP bounds

In Figure 4 the performance of the new heuristic is compared to that of CPLEX for every instance. Recall that while solving the test problems with CPLEX, the branch-and-bound search is stopped either when a feasible solution within 1% of optimality is identified or the time limit of 5 hours is reached. The horizontal axis of Figure 4 represents the ratios between the objective values of the solutions identified by the heuristic ("UB heuristic") and those delivered by CPLEX. The vertical axis displays the ratios between the CPU times of the heuristic and those of CPLEX. Since phase 2 of the heuristic is performed 10 times, the average upper bound and the average CPU time obtained in this phase are considered. Moreover, note that a ratio lower than one indicates that the heuristic outperformed CPLEX.

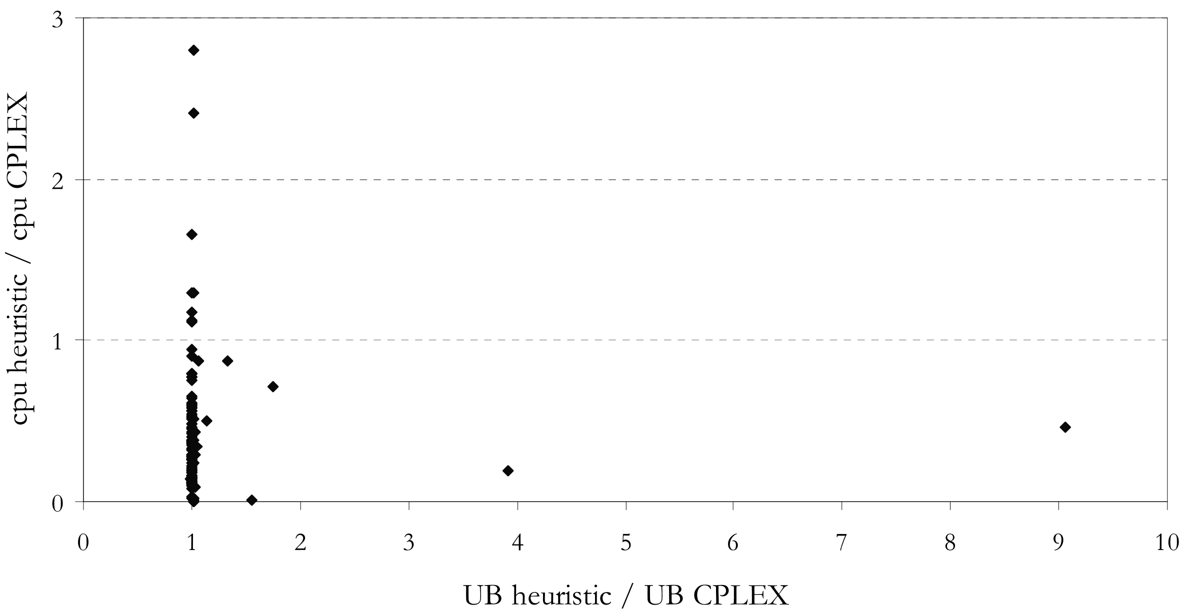


Figure 4: Comparison between the feasible solutions identified by the heuristic and by CPLEX

Regarding solution quality, Figure 4 reveals that the performance of the heuristic and of CPLEX are comparable except for a few instances. Since CPLEX identifies a feasible solution within 1% of optimality in 94.4% of the test problems, we realize that the new heuristic provides solutions within an acceptable optimality range. Regarding the CPU times, Figure 4 indicates that our new heuristic approach is significantly faster than CPLEX. The detailed results reported in Tables 12-14 in Appendix B show that in each problem set, the CPU times are reduced by a factor of three when the heuristic is used. Although seven instances in set 1 (i.e. associated with single-echelon networks) exhibit CPU ratios above 1.0, the heuristic required less than one minute in each one of them. For the more complex networks (set 3), a single instance (P114) consumed more CPU time with the heuristic than with CPLEX. Nevertheless, a good solution was identified in this case within two minutes. A close examination of Tables 12-14 reveals that CPLEX reached the pre-specified time limit of 5 hours in only 3 out of 115 instances. These instances (P77, P89 and P90) correspond to three-echelon network redesign problems and the best solutions delivered by CPLEX have optimality gaps varying between 3.16% and 6.72%.

From the above analysis along with the results displayed in Tables 12-14 we can conclude that the heuristic delivers solutions within acceptable time, thus making its implementation feasible when re-optimization is desired for performing "what-if" analyzes.

Figure 5 displays the region in Figure 4 enclosing the majority of the points. Observe that only five instances are excluded to produce this figure. As can be seen, the above analysis of results also holds.

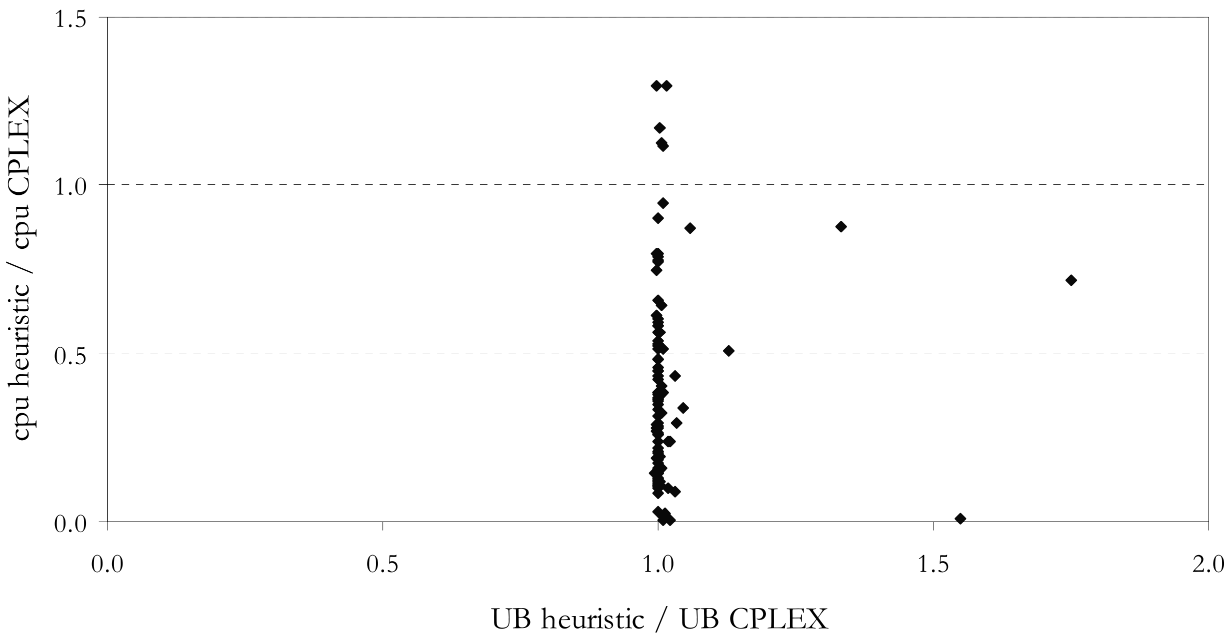


Figure 5: Zoom in of the dense region of Figure 4

6 Conclusions

In this paper we proposed an LP-based heuristic for a multi-period facility relocation problem. The underlying model captures key features relevant to supply chain network redesign. Our results suggest that the new heuristic approach is able to solve realistically sized problem instances within acceptable computational time. In particular, an effective repair mechanism is employed whenever no feasible solution is identified during the construction phase. Moreover, a local improvement step is able to deliver high-quality solutions. Compared to CPLEX, the heuristic is significantly faster and provides solutions of similar quality.

A further advantage of the new heuristic procedure is its flexibility to handle model extensions related to changing capacity requirements over the planning horizon. When growing future demand is anticipated, additional network restructuring measures need to be adopted. The latter may result in extending the capacity of existing facilities and/or establishing additional facilities. Observe that in our model the overall capacity of the network does not change over the time periods. Although capacity shifts from existing to new locations are modeled, capacity expansion scenarios are not addressed by formulation (P). Melo et al [24] propose an extension to (P) to deal with this case. The opposite occurs when markets face declining demand, e.g. due to economic downturns or because products reach their end of life. Melo et al [24] also extended model (P) to handle the network capacity reduction case. Finally, in some applications capacity transfer sizes are restricted to discrete amounts as opposed to the continuous values modeled by variables $z^t_{i,j}$ in (P). Modular capacity shifts are a natural extension to model (P) and are discussed in Melo et al. [24].

Acknowledgements

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Appendix A: Instances associated with three-echelon networks

Table 11 describes the characteristics and sizes of the new instances (set 3).

		Selectable facilities						Size		
		Exist. DCs		New DCs				# Variables		
	Customers	Central	Regional	Central	Regional	Periods	Products			
Instance	$\|C\|$	$\|S_c^c\|$	$\|S_r^c\|$	$\|S_c^o\|$	$\|S_r^o\|$	$\|T\|$	$\|P\|$	Cont.	Integer	# Constraints
P71	100	4	10	8	20	3	5	28960	126	2985
P72	100	4	10	8	20	4	5	38613	168	3966
P73	100	4	10	8	20	6	5	57919	252	5928
P74	100	4	10	8	20	8	5	77225	336	7890
P75	50	4	10	8	20	3	5	19273	126	2085
P76	50	4	10	8	20	4	5	25697	168	2766
P77	50	4	10	8	20	6	5	38545	252	4128
P78	50	4	10	8	20	8	5	51393	336	5490
P79	200	4	10	8	20	3	5	48343	126	4785
P80	200	4	10	8	20	4	5	64457	168	6366
P81	200	4	10	8	20	6	5	96685	252	9528
P82	200	4	10	8	20	8	5	128913	336	12690
P83	100	8	20	12	30	3	5	55294	210	3727
P84	100	8	20	12	30	4	5	73725	280	4946
P85	100	8	20	12	30	6	5	110587	420	7384
P86	50	8	20	12	30	3	5	40147	210	2827
P87	50	8	20	12	30	3	5	40147	210	2827
P88	50	8	20	12	30	4	5	53529	280	3746
P89	50	8	20	12	30	6	5	80293	420	5584
P90	50	8	20	12	30	8	5	107057	560	7422
P91	200	8	20	12	30	3	5	85597	210	5527
P92	200	8	20	12	30	4	5	114129	280	7346
P93	200	8	20	12	30	6	5	171193	420	10984
P94	100	4	10	8	20	3	10	56743	126	5190
P95	100	4	10	8	20	4	10	75657	168	6906
P96	50	4	10	8	20	3	10	37366	126	3540
P97	50	4	10	8	20	4	10	49821	168	4706
P98	200	4	10	8	20	3	10	95506	126	8490
P99	200	4	10	8	20	4	10	127341	168	11306
P100	100	8	20	12	30	3	10	107059	210	6352
P101	100	8	20	12	30	4	10	142745	280	8446
P102	50	8	20	12	30	3	10	76762	210	4702
P103	50	8	20	12	30	4	10	102349	280	6246
P104	200	8	20	12	30	3	10	167662	210	9652
P105	200	8	20	12	30	4	10	223549	280	12846
P106	100	4	10	8	20	3	20	112309	126	9600
P107	100	4	10	8	20	4	20	149745	168	12786
P108	50	4	10	8	20	3	20	73552	126	6450
P109	50	4	10	8	20	4	20	98069	168	8586
P110	100	8	20	12	30	3	20	210589	210	11602
P111	100	8	20	12	30	4	20	280785	280	15446
P112	50	8	20	12	30	3	20	149992	210	8452
P113	50	8	20	12	30	4	20	199989	280	11246
P114	200	8	20	12	30	3	20	331792	210	17902
P115	50	8	20	12	30	3	50	369682	210	19702

Table 11: Characteristics and sizes of instances associated with three-echelon networks with 5 plants

Appendix B: Detailed results

Tables 12, 13 and 14 summarize the results obtained with the new heuristic approach and CPLEX. The first column of these tables identifies the test problem. The columns under the heading *Heuristic* report the results delivered by the two-phase heuristic. Column 2 gives the number of runs of phase 2 (out of 10) in which a feasible solution was identified. The symbol * marks those instances in which the construction phase succeeded in identifying a feasible solution. In this case, an improvement scheme is applied in the second stage of the heuristic. Column 3 presents the value of $(UB_H - LB)/LB \cdot 100\%$ with UB_H denoting the objective value of the identified feasible solution and LB the optimal LP value. Recall that since 10 runs of phase 2 are performed, the displayed values correspond to the average over the runs yielding a feasible solution. The CPU times (in seconds) required in phase 1 and phase 2 of the heuristic are reported in columns 4 and 5, respectively. If during the construction phase a solution is identified within $\underline{\Delta} = 2.5\%$ of the LP value then the improvement scheme in phase 2 is not performed. The total CPU time is given in column 6.

The columns under the heading *CPLEX* describe the results obtained with the optimization solver. Column 7 presents the gap reported by CPLEX at the time of termination. Note that the values shown in this column may overestimate the true integrality gaps due to stopping the search as soon as a feasible solution within 1% optimality is identified. Column 8 shows the value of $(UB - LB)/LB \cdot 100\%$ with UB denoting the objective value of the best feasible solution and LB the optimal LP value. The total CPU time (in seconds) required to identify a feasible solution within 1% optimality is given in column 9.

Finally, the columns under the heading *Heuristic/CPLEX* include a direct comparison between the two solution procedures. Column 10 displays the values of UB_H/UB, while column 11 contains the ratios between the CPU times required by the heuristic and CPLEX. Recall that the values in these two columns are depicted in Figures 4 and 5.

	Heuristic					CPLEX			Heuristic/CPLEX	
Instance	# sol.	LP gap	CPU 1	CPU 2	total CPU	opt. gap	LP gap	CPU	sol. ratio	CPU ratio
P1	10	2.51	0.56	6.54	7.11	0.74	1.60	6.36	1.01	1.12
P2	*	3.96	0.55	7.90	8.45	0.98	3.15	8.94	1.01	0.95
P3	*	6.73	1.00	2.82	3.82	0.99	3.61	8.81	1.03	0.43
P4	*	4.33	0.83	25.35	26.18	0.33	3.31	9.36	1.01	2.80
P5	10	6.86	0.84	4.83	5.68	0.97	3.47	19.34	1.03	0.29
P6	10	8.59	1.38	9.21	10.59	0.99	5.33	121.17	1.03	0.09
P7	*	5.37	1.73	16.15	17.89	0.95	3.79	13.81	1.02	1.29
P8	10	13.38	0.77	4.74	5.50	0.21	0.46	10.88	1.13	0.51
P9	*	1.82	2.06	0.00	2.06	0.83	1.68	14.22	1.00	0.15
P10	10	0.07	0.53	1.10	1.63	0.03	0.05	6.36	1.00	0.26
P11	*	0.20	3.39	-	3.39	0.30	0.33	7.59	1.00	0.45
P12	10	0.63	1.83	3.43	5.25	0.74	0.02	8.56	1.00	0.61
P13	*	6.07	3.55	34.38	37.92	0.99	0.01	156.94	1.02	0.24
P14	*	1.46	4.15	-	4.15	0.74	0.01	42.33	1.00	0.10
P15	*	2.87	3.80	49.17	52.97	0.99	0.12	45.17	1.00	1.17
P16	*	0.28	5.30	7.45	12.75	0.49	0.49	9.83	1.00	1.30
P17	*	0.27	6.59	-	6.59	0.32	0.41	17.84	1.00	0.37
P18	*	2.17	6.22	34.48	40.70	0.60	1.47	63.31	1.01	0.64
P19	10	0.17	4.64	4.56	9.20	0.07	0.13	44.33	1.00	0.21
P20	*	2.50	6.77	30.30	37.07	0.69	1.54	71.88	1.01	0.52
P21	*	0.34	1.64	-	1.64	0.38	0.56	8.69	1.00	0.19
P22	*	2.24	2.67	15.19	17.87	0.93	1.58	15.89	1.01	1.12
P23	*	1.82	2.31	0.00	2.31	0.45	1.24	14.28	1.01	0.16
P24	*	0.45	1.61	-	1.61	0.48	0.56	4.20	1.00	0.38
P25	*	2.27	3.12	0.00	3.12	0.60	1.82	19.97	1.00	0.16
P26	9	78.09	3.20	10.52	13.72	0.95	1.85	19.14	1.75	0.72
P27	*	1.72	3.42	0.00	3.42	0.70	1.55	22.44	1.00	0.15
P28	*	34.86	3.25	7.65	10.90	0.91	0.47	12.45	1.33	0.88
P29	*	4.88	2.30	27.39	29.69	0.52	0.02	12.31	1.02	2.41
P30	*	0.01	0.69	-	0.69	0.04	0.02	4.34	1.00	0.16
P31	*	0.02	0.67	-	0.67	0.04	0.00	4.34	1.00	0.15
P32	*	0.02	0.80	-	0.80	0.02	0.02	6.88	1.00	0.12
P33	*	0.01	0.49	-	0.49	0.02	0.01	3.94	1.00	0.12
P34	10	0.02	0.42	1.14	1.56	0.03	0.01	2.91	1.00	0.54
P35	*	0.41	2.69	3.36	6.05	0.47	0.12	21.03	1.00	0.29
P36	10	0.59	1.97	6.59	8.56	0.94	0.95	10.73	1.00	0.80
P37	10	6.60	4.80	25.17	29.97	0.87	4.67	124.33	1.02	0.24
P38	10	1.02	2.47	8.03	10.50	0.91	1.13	13.20	1.00	0.80
P39	*	6.84	6.30	29.69	35.99	1.00	4.81	352.31	1.02	0.10
P40	*	0.02	2.16	-	2.16	0.05	0.05	9.09	1.00	0.24
P41	*	0.01	2.22	-	2.22	0.01	0.01	26.14	1.00	0.08
P44	*	0.03	1.97	-	1.97	0.09	0.09	9.70	1.00	0.20
P43	10	0.03	2.12	2.76	4.88	0.03	0.03	9.33	1.00	0.52
P44	*	0.07	3.44	-	3.44	0.06	0.06	9.00	1.00	0.38
P45	*	0.80	0.14	-	0.14	0.79	0.80	1.31	1.00	0.11
Average		4.74	2.52	12.25	10.96	0.54	1.19	31.67	-	-

Table 12: Results obtained for instances in set 1 (single-echelon networks); all gaps in % and all CPU times in seconds

Instance	Heuristic					CPLEX			Heuristic/CPLEX	
	# sol.	LP gap	CPU 1	CPU 2	total CPU	opt. gap	LP gap	CPU	sol. ratio	CPU ratio
P46	*	0.01	1.53	-	1.53	0.02	0.02	5.91	1.00	0.26
P47	*	0.01	2.38	-	2.38	0.02	0.02	6.53	1.00	0.36
P48	9	0.02	0.70	2.62	3.33	0.47	0.47	12.02	1.00	0.28
P49	10	0.02	0.91	1.97	2.87	0.02	0.02	6.25	1.00	0.46
P50	10	0.01	1.70	1.84	3.55	0.02	0.02	6.00	1.00	0.59
P51	*	0.00	1.22	-	1.22	0.00	0.00	8.39	1.00	0.15
P52	10	0.01	1.08	2.88	3.95	0.01	0.02	9.11	1.00	0.43
P53	9	0.01	0.58	3.06	3.64	0.01	0.01	7.83	9.05	0.46
P54	10	0.09	1.08	1.75	2.83	0.01	0.01	5.48	1.00	0.52
P55	*	1.27	0.28	-	0.28	0.00	0.12	12.39	1.01	0.02
P56	10	0.00	0.42	1.51	1.93	0.00	0.00	4.56	1.00	0.42
P57	*	0.00	1.30	-	1.30	0.00	0.00	9.09	1.00	0.14
P58	10	0.00	0.52	2.42	2.94	0.00	0.00	9.28	1.00	0.32
P59	*	0.00	1.22	-	1.22	0.00	0.00	8.58	1.00	0.14
P60	10	0.00	0.73	1.96	2.69	0.00	0.00	9.24	1.00	0.29
P61	10	6.12	3.55	19.80	23.35	0.16	0.26	26.73	1.06	0.87
P62	*	1.40	3.17	-	3.17	0.88	1.52	24.28	1.00	0.13
P63	*	1.59	4.38	0.00	4.38	0.80	1.58	35.30	1.00	0.12
P64	*	1.31	4.99	12.95	17.93	0.55	1.11	31.84	1.00	0.56
P65	*	2.12	5.52	0.00	5.52	0.76	1.66	46.97	1.00	0.12
P66	10	0.01	2.50	5.40	7.90	0.01	0.01	13.16	1.00	0.60
P67	10	0.02	4.82	5.21	10.02	0.02	0.03	17.17	1.00	0.58
P68	10	0.02	2.34	4.31	6.65	0.03	0.03	14.80	1.00	0.45
P69	*	0.01	4.55	-	4.55	0.01	0.02	16.41	1.00	0.28
P70	*	0.01	4.51	-	4.51	0.00	0.01	17.17	1.00	0.26
Average		0.56	2.24	4.23	4.95	0.15	0.28	14.58	-	-

Table 13: Results obtained for instances in set 2 (two-echelon networks), all gaps in % and all CPU times in seconds

	Heuristic					CPLEX			Heuristic/CPLEX	
Instance	# sol.	LP gap	CPU 1	CPU 2	total CPU	opt. gap	LP gap	CPU	sol. ratio	CPU ratio
P71	*	0.02	3.14	-	3.14	0.77	0.79	21.89	0.99	0.14
P72	*	0.25	12.59	-	12.59	0.64	0.66	46.81	1.00	0.27
P73	*	0.03	70.68	-	70.68	0.03	0.03	640.42	1.00	0.11
P74	*	0.03	323.77	-	323.77	0.27	0.28	432.88	1.00	0.75
P75	*	5.81	1.56	17.02	18.58	0.95	4.72	48.11	1.01	0.39
P76	*	0.11	4.45	-	4.45	0.10	0.13	150.84	1.00	0.03
P77	*	66.02	22.88	115.06	137.93	3.16	7.29	18000.13	1.55	0.01
P78	*	2.06	48.14	0.00	48.14	0.75	0.78	2344.24	1.01	0.02
P79	*	0.01	7.33	-	7.33	0.00	0.01	65.66	1.00	0.11
P80	7	0.01	17.98	36.50	54.48	0.01	0.01	148.33	1.00	0.37
P81	10	0.97	25.77	68.37	94.13	0.84	0.85	269.28	1.00	0.35
P82	7	0.25	196.37	63.25	259.62	0.01	0.01	1332.89	3.91	0.19
P83	3	0.02	4.20	15.24	19.45	0.01	0.02	36.91	1.00	0.53
P84	*	0.02	13.77	-	13.77	0.01	0.02	48.28	1.00	0.29
P85	10	0.06	51.98	10.94	62.92	0.02	0.03	236.22	1.00	0.22
P86	10	6.28	2.31	7.58	9.90	1.00	5.19	704.20	1.01	0.00
P87	10	6.30	2.36	7.67	10.03	1.00	5.19	707.25	1.01	0.01
P88	*	9.42	9.05	29.81	38.85	1.00	6.98	11376.80	1.02	0.00
P89	*	8.98	26.92	372.41	399.33	5.52	8.08	18001.03	1.01	0.02
P90	6	9.79	145.31	5683.02	5828.34	6.72	9.15	18001.08	1.01	0.32
P91	7	0.00	8.97	7.74	16.71	0.00	0.00	21.56	1.00	0.78
P92	4	0.00	13.22	50.20	63.42	0.00	0.00	80.45	1.00	0.79
P93	5	0.01	41.09	74.27	115.36	0.00	0.00	128.23	1.00	0.90
P94	10	0.09	8.16	6.68	14.83	0.00	0.00	97.34	1.00	0.15
P95	9	0.21	23.59	14.15	37.74	0.00	0.00	348.17	1.00	0.11
P96	*	0.02	8.83	-	8.83	0.01	0.02	50.25	1.00	0.18
P97	*	6.95	30.26	135.48	165.74	0.99	2.38	490.53	1.04	0.34
P98	10	0.05	4.70	6.99	11.69	0.00	0.00	113.03	1.00	0.10
P99	10	0.00	15.91	21.50	37.41	0.00	0.00	204.98	1.00	0.18
P100	4	0.00	9.74	17.32	27.05	0.00	0.00	71.84	1.00	0.38
P101	*	0.00	14.09	-	14.09	0.00	0.00	116.24	1.00	0.12
P102	*	0.01	6.80	-	6.80	0.01	0.01	45.25	1.00	0.15
P103	9	0.01	18.78	28.50	47.28	0.01	0.01	84.27	1.00	0.56
P104	2	0.00	14.05	30.70	44.75	0.00	0.00	68.13	1.00	0.66
P105	4	0.00	24.19	75.65	99.84	0.00	0.00	278.53	1.00	0.36
P106	2	0.55	15.23	55.62	70.85	0.00	0.00	174.53	1.01	0.41
P107	10	0.00	42.20	16.57	58.77	0.00	0.00	377.98	1.00	0.16
P108	*	0.00	21.17	-	21.17	0.00	0.00	161.67	1.00	0.13
P109	9	0.33	49.29	40.86	90.15	0.00	0.00	469.17	1.00	0.19
P110	6	0.00	19.91	40.57	60.48	0.00	0.00	103.44	1.00	0.58
P111	1	0.00	73.16	155.21	228.37	0.00	0.00	296.59	1.00	0.77
P112	6	0.00	21.69	22.35	44.04	0.00	0.00	91.19	1.00	0.48
P113	4	0.00	55.70	79.50	135.21	0.00	0.00	403.91	1.00	0.33
P114	1	0.00	41.00	75.02	116.01	0.00	0.00	70.11	1.00	1.65
P115	1	0.00	55.55	115.76	171.31	0.00	0.00	353.44	1.00	0.48
Average		2.77	36.17	220.51	202.79	0.53	1.17	1718.09	-	-

Table 14: Results obtained for instances in set 3 (all gaps in % and all CPU times in seconds)

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