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Article

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Two-echelon distribution with a single capacitated city hub

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ABSTRACT

In this paper, we investigate the synchronization between the two echelons in two-echelon urban distribution systems. The first echelon aims at transferring goods from a warehouse to a (single) city hub located in the city center. The second echelon, managed with a fleet of environmentally friendly vehicles, delivers goods to final customers, from the city hub. The two echelons are synchronized in time but also with regards to the capacity of the city hub. As far as we know, this is the first study considering the latter issue in the context of two-echelon distribution. To deal with the synchronization while optimizing the distribution, we propose a three-phase heuristic solution approach. At first, our approach optimizes the distribution for the second echelon. Then, it manages the synchronization. Finally, it optimizes the distribution for the first echelon. Population-based metaheuristics and integer programs are used. Results show the effectiveness of the method and permit to derive managerial insights on the distribution.

1. Introduction

The United Nations' Department of Economic and Social Affairs states that more people currently live in urban areas than in rural areas. While 30% of the world's population was urban by 1950, 66% are projected to live in cities by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2014). This urbanization trend is enforced by the overall human population growth.

As urban communities grow, basic needs have to be fulfilled efficiently for an increasing number of inhabitants in cities. Basic needs do not only incorporate food or drinking water, but also environmental requirements, such as clean air for breathing. Moving a larger quantity of people and goods, however, leads to traffic growth, congestion and environmental nuisance. Aware of this, governments constantly inflict traffic regulations aiming at reducing the negative effects of transport. These regulations, for example, might forbid access to inner-city areas for conventionally fueled vehicles, forcing them to load and unload at specified zones. Otherwise, cities might establish rush hour policies, forbidding the access of delivery vehicles to the most central and congested urban areas during predefined periods of the day. Generally, the

use of environmentally friendly vehicles instead of conventionally fueled vehicles is encouraged (Crainic et al. (2009)).

Driven by the mentioned trends and regulations, companies need to adapt to new challenges in order to stay competitive in an ever changing environment. Aiming to fulfill customer requests while obeying the rules given by policy-makers, companies are required to redesign their traditional distribution schemes in urban areas.

A scheme that has received a lot of attention by local authorities, companies and academics, is to organize distribution in two echelons. In a two-echelon distribution scheme, goods are not transported directly from their origin (a depot or a warehouse) to their final destination (end customers), but are initially moved into an intermediate platform (a city hub), from where their final distribution is performed. City hubs will be located near the city center, close to the final destination of the goods, allowing both consolidated flows up to the city center and a more efficient and environmentally friendly last mile transport. Many cities have implemented different variants of this scheme (e.g., La Rochelle, Monaco, Padua). A company like Geodis has developed a two-echelon distribution system, called Distripolis, that has been declined in many French cities. In the scientific literature however, some important gaps still exist.

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More specifically, the issue of synchronization between the two echelons still raises important questions. Going through the literature, several papers address long-term design decisions and neglect this aspect. Conversely, some papers impose a strict synchronization between first-level and second-level vehicles. The assumption behind the latter is that no real facility is installed in the city; for example, transfers between vehicles are operated on parking lots. A last category of papers introduce city hubs but assume that the capacity of these hubs is unlimited. In this paper, we investigate the fact that they have a limited capacity. This research being conducted with a company, we address this issue in the specific context of this company. The company performs parcel deliveries and is settled in the urban area of Vienna. Dealing with this specific setting has some consequences on the possible generalization of our results. This issue will be discussed in the conclusions. The distribution scheme can be described as follows.

On the first level, a single truck transports goods, i.e. parcels, from the depot outside the city to a single city hub, where goods are transferred to cargo bikes, operating on the second level between the city hub and the final customers. Cargo bikes are able to access narrow streets, are not exposed to the problem of limited parking space and decrease the amount of emissions produced through delivery operations inside city centers. However, since not all parcels fit the cargo space of a cargo bike, the truck is allowed to visit a final customer in some cases.

All parcels are present at the depot in the morning, when the truck can pick up a certain amount of goods and deliver them to the final customers and the city hub. Being located in the inner-city area, the storage capacity of the city hub is limited, which implies that not all goods can be transported from the depot to the city hub at once. Instead, the truck is obliged to transfer parcels on the first level performing multiple trips, while respecting the capacity of the city hub and the final customer time windows. On the second level, cargo bikes can only start their delivery tours as soon as the goods have arrived to the city hub, thus freeing city hub capacity as parcels are picked up on multiple trips.

We specify time windows (TWs) to indicate the earliest and latest time a final customer demands to receive an order (this trend has become very popular in restaurants or small stores, where the availability of goods at a specific time is crucial for their operation). Nonetheless, TWs can also be used to regulate the access to certain areas at specific times due to public regulations (Muñuzuri et al. (2005)).

Organizing the described distribution scheme is a challenging task, since the coordination of first and second level trips is necessary: all second-level trips depend on the delivery of goods on the first level, which is limited by the city hub capacity. As detailed in Drexler (2012), solution approaches for problems with synchronization are generally overly technical and difficult to implement. One of our objectives in this paper is to find a way to decouple first-level and second-level decisions, so that the two levels can be addressed separately as standard vehicle routing problems.

The main contributions of this paper are thus to:

1. Investigate two-echelon distribution taking account of hub capacity;
2. Give insights on the implications of this capacity to the model;
3. Propose a decomposition method able to efficiently optimize the two echelons separately.
4. Propose a lower bounding scheme to fairly evaluate the effectiveness of the method.
5. Based on the case study proposed by our partner, provide insights on how some parameters of the system impact the distribution.

The remainder of the paper is organized as follows. In Section 2, a literature review of relevant routing problems is presented. Section 3 provides a mathematical formulation of the studied problem. In Section 4, a solution method for our routing problem is developed, and in Section 5, experimental results are reported. Finally, concluding remarks and a future outlook are given.

2. Literature review

In response to the arising sustainability issues, new distribution schemes have been proposed in the literature. These schemes consider indirect delivery from one or more depots to customers. Merchandise passes through several levels of distribution using intermediate depots for freight consolidation purposes. In the literature, these schemes are called multi-level distribution systems (Cattaruzza et al. (2017)). In the vehicle routing literature, problems dealing with such systems are usually called multi-echelon vehicle routing problems (González-Feliu, 2008). When the distribution scheme is reduced to two levels of distribution, the related problem is called *two-echelon vehicle routing problem* (2E-VRP, Cuda et al. (2015)).

This architecture of the distribution network is strongly connected to the design of City Logistics systems for large cities. Such schemes provide the means to efficiently keep big trucks out of the city center and propose the use of small and environment-friendly vehicles for the last leg of the distribution activities (Crainic et al. (2009)).

Several algorithms have been developed for the 2E-VRP. Math based heuristics can be found in González-Feliu, 2008 and Perboli et al. (2011), greedy randomized adaptive search procedures (GRASP) can be found in Crainic et al. (2013). Crainic et al. (2011) proposed a multi-start heuristic based on the cluster-first route-second paradigm, while large neighborhood search procedures are proposed in Hemmelmayr et al. (2012) or Breunig et al. (2016). Baldacci et al. (2013) propose an exact algorithm that decomposes the 2E-VRP into a limited set of multi-depot capacitated vehicle routing problems. The interested reader is referred to the survey of Guastaroba et al. (2016) on different models for indirect freight transportation planning. It provides an overview of three classes of problems with intermediate facilities: vehicle routing problems, transshipment problems, and service network design problems. For each class of problems the survey identifies the main problem variants, surveys the solution methods and indicates open research directions.

Note that the most studied problem is the two-echelon capacitated vehicle routing problem (2E-CVRP), where constraints on the maximum capacity of the vehicles and the intermediate depots are considered. However, most of the articles ignore the timing of the deliveries and the coordination of the delivery trips of the different distribution levels.

Anderluh et al. (2017) presented a two-echelon city distribution scheme with temporal and spatial synchronization between cargo bikes and vans. They assumed that satellites do not provide storage facilities but are pure meeting points for vehicles of both echelons. Therefore, first echelon vehicles and second echelon vehicles have to be synchronized in space and time. The authors developed a heuristic based on a greedy randomized adaptive search procedure with path relinking.

Grangier et al. (2016) studied a two-echelon multiple-trip vehicle routing problem with satellite synchronization. Characteristics, such as time windows, vehicle synchronization, and multiple delivery trips are taken into account. They propose an ALNS procedure evaluated on modified benchmarks of instances for the VRP with time windows. Goods are transported from a depot to several satellites located close to the city center. Second-level vehicles carry requests from the satellites to customers. In contrast to the problem that we consider in this paper, Grangier et al. (2016) focus on the satellite synchronization, assuming the satellites will more likely refer to a parking lot or other kind of public space, where usually very tight or no capacity is available. Therefore, the transfer of goods between the two levels needs to be synchronized.

Mirhedayatian et al. (2020) or Dellaert et al. (2018) consider two-echelon schemes where facilities are actually introduced for the transfer. Imposing a strict synchronization between vehicles is indeed very difficult to achieve in practice, seeing the variability of urban traffic and uncertainties on service times. In both papers however, the capacity of the facilities is assumed to be unlimited. Mirhedayatian et al. (2020) proposes a decomposition-based heuristic. Dellaert et al. (2018) investigate path-based formulations and branch-and-price solution algorithms.

Our problem assumes a storage facility at the city hub, thus an immediate transfer is not crucial, but also takes account of the limited capacity of this facility. The first-level vehicle needs to know at what time it should visit the hub in order to respect its capacity constraint, and to ensure that the second-level vehicles are on time at customer locations, respecting the time window constraints.

To the best of our knowledge, there is no routing problem in the literature seeking to optimize the two levels of distribution, while considering customers' time windows, different fleet sizes, inventory management for the intermediate depot, all at the same time. The routing problem that we present throughout this paper deals with these variants.

3. Problem definition and mathematical model

Let us assume a two-echelon distribution scheme, where a single truck is in charge of performing several first-level trips between a depot and a city hub, while cargo bikes do multiple trips on the second level between the city hub and the final customers. Since not all customer demands can be fulfilled by cargo bikes because of their limited cargo space, the truck is allowed to visit some final customers if necessary.

We call the problem of optimizing vehicle routes in this distribution scheme the Capacitated Two-Echelon Vehicle Routing Problem with Time Windows (C2E-VRPTW). The C2E-VRPTW is formally defined on two complete directed graphs $G_1 = (\mathcal{V}_1, \mathcal{A}_1)$ and $G_2 = (\mathcal{V}_2, \mathcal{A}_2)$, respectively introduced for the first and second levels of distribution. In the first-level graph G_1 , \mathcal{V}_1 is composed of a depot 0, a city hub H and a set of first-level customers \mathcal{N}_1 : $\mathcal{V}_1 = \{0, H\} \cup \mathcal{N}_1$. The set of vertices \mathcal{V}_2 of the second-level graph G_2 also contains the city hub H , plus the set of second-level customers \mathcal{N}_2 : $\mathcal{V}_2 = \{H\} \cup \mathcal{N}_2$.

A time horizon is given and establishes the duration of the working day, on which optimization is carried out. It can be considered as a time-window $[E, L]$ during which all operations have to be performed. Traveling on arc $(i, j) \in \mathcal{A}_1 \cup \mathcal{A}_2$ induces a traveling time T_{ij} and a cost (distance) D_{ij} . Each customer $i \in \mathcal{N}_1 \cup \mathcal{N}_2$ has a demand Q_i that has to be delivered during a time-window indicated by $[E_i, L_i]$ and with a service time S_i . E_i is the earliest time of service at customer i . A vehicle can arrive to customer i earlier than E_i , but it has to wait until its respective E_i to start the service. Arriving to a customer i after L_i is forbidden.

First-level distribution is organized with a single vehicle (truck) of capacity Q_{1L} . The vehicle is initially located at the depot 0 at time E and must be returned to the depot at time L . It has to serve all customers in \mathcal{N}_1 and to deliver to the city hub H all goods required by customers in \mathcal{N}_2 . For that matter, its tour can be organized with multiple trips, each trip starting and ending at the depot. Customers in \mathcal{N}_1 can only be visited once: no split delivery is allowed. On the contrary, the city hub H can be visited as many times as needed, but split delivery is not allowed in the sense that it is not possible to split the delivery to the city hub of the demand Q_i of a customer $i \in \mathcal{N}_2$. Loading and unloading times at the depot and the hub do not depend on the load. Without loss of generality, they are set to 0: $S_0 = S_H = 0$.

Second-level distribution is organized with a fleet $\mathcal{S}\mathcal{L}$ of second level vehicles (cargo bikes) of capacity Q_{2L} . These vehicles are initially located at the city hub H at time E and must be returned to the city hub at time L . They have to serve all customers in \mathcal{N}_2 with multi-trips and without split delivery.

Synchronization is needed between the first-level vehicle and the cargo bike fleet $\mathcal{S}\mathcal{L}$ because the goods to be delivered to a customer in \mathcal{N}_2 are only available at the city hub when they have been delivered by the first-level vehicle. Additionally, the city hub is subject to a capacity limit Q_{CH} : the amount of goods located simultaneously at the city hub is not allowed to exceed Q_{CH} .

The capacity limit of the city hub opens an important issue regarding the possible use of vehicles as an additional capacity. Typically, the truck could be parked at the city hub for a long time to artificially increase the capacity of the city hub. The same holds for second-level vehicles, which

could be loaded partially and kept parked at the city hub. We do not want to allow that in our model (as a matter of fact, it is not considered as acceptable by our company partner). We propose to counter it with the following rules:

1. When a trip of the first-level vehicle includes several visits to the city hub, these visits cannot be consecutive. In other words, it means that when the truck arrives to the city hub, it has to unload what is expected in one shot and continue to the next customer (or the depot).
2. Waiting is however allowed before reaching the city hub with the first-level vehicle. A few words about waiting times in general are provided here. As explained above, it is allowed for a vehicle to reach a customer before the opening of its time window and wait (before starting the service). With this claim, one tends to imagine that the vehicle parks in front of the customer and waits for the opening. Actually, it does not necessarily refer to this behaviour in practice. It rather means that the schedule gives some free time to the drivers: they can drive slowly, or park somewhere on the way before reaching the customer and starting the service. We consider that drivers are allowed to follow the same behaviour when driving to the hub. Thus, if the available capacity in the city hub is too limited, it might be necessary in the schedule to delay the arrival of the first-level vehicle.
3. For second-level vehicles, all the goods to be delivered in a trip have to be loaded simultaneously at the hub. In other words, it is not possible to start loading some goods and wait for the arrival of the first-level vehicle before completing the loading with additional goods that just arrived.

In addition, we want to make sure that the planning is somewhat robust with regards to travel-time uncertainties. In particular, we do not allow to transfer goods directly between first- and second-level vehicles, which would necessitate the simultaneous presence of two vehicles at the city hub. In order to deal with that constraint, we impose that when a first-level vehicle arrives at the hub there is always enough remaining capacity in the hub, even if the plan is to start a second-level vehicle at the same period and, so, a direct transfer could be realized in practice.

The goal of the C2E-VRPTW is to properly determine a set of vehicle routes, so as to satisfy customer demands at a minimum travel cost, while respecting capacity and timing constraints. Notation is summarized in Table 1.

The C2E-VRPTW can be described with a mixed integer linear programming formulation, using notation and decision variables introduced in Tables 1 and 2. The model requires introducing index sets Π and π respectively for the trips of the first-level and second-level vehicles. Upper bounds on the cardinality of these sets can easily be determined:

Table 1
Notation.

Data sets	
\mathcal{V}_1	Set of vertices in graph G_1 : $\mathcal{V}_1 = \{0, H\} \cup \mathcal{N}_1$
\mathcal{N}_1	Set of first-level customers
\mathcal{V}_2	Set of vertices in graph G_2 : $\mathcal{V}_2 = \{H\} \cup \mathcal{N}_2$
\mathcal{N}_2	Set of second-level customers
\mathcal{A}_1	Set of arcs in complete graph G_1
\mathcal{A}_2	Set of arcs in complete graph G_2
$\mathcal{S}\mathcal{L}$	Set of second-level vehicles
Data	
Q_{1L}	Capacity of the first-level vehicle
Q_{2L}	Capacity of the vehicles composing $\mathcal{S}\mathcal{L}$
Q_{CH}	Capacity of the city hub
Q_i	Quantity requested by customer $i \in \mathcal{N}_1 \cup \mathcal{N}_2$
S_i	Service time for vertex $i \in \mathcal{V}_1 \cup \mathcal{V}_2$
D_{ij}	Cost (distance) of arc $(i, j) \in \mathcal{A}_1 \cup \mathcal{A}_2$
T_{ij}	Travel time on arc $(i, j) \in \mathcal{A}_1 \cup \mathcal{A}_2$
$[E_i, L_i]$	TW of customer $i \in \mathcal{N}_1 \cup \mathcal{N}_2$
$[E, L]$	Time horizon (expressed as a TW)

Table 2
Notation and variables introduced in the model.

Sets introduced for the model	
Π	Set of first-level trips: $\Pi = \{1, \dots, \Pi \}$
π	Set of second-level trips: $\pi = \{ \Pi + 1, \dots, \Pi + \pi \}$
\mathcal{T}	Set of periods: $\mathcal{T} = \{E, \dots, L\}$
\mathcal{H}	Set of copies of the city hub in a first-level trip. H_h indicates copy h of the hub, $h \in \mathcal{H}$
$\tilde{\mathcal{V}}_1$	Vertex set for the first level with the city hub duplications
$\tilde{\mathcal{A}}_1$	Arc set for the first level with the city hub duplications
Variables	
x_{ij}^w	1 if arc $(i, j) \in \tilde{\mathcal{A}}_1$ is assigned to trip $w \in \Pi$, or if arc $(i, j) \in \mathcal{A}_2$ is assigned to trip $w \in \pi$, 0 otherwise;
y_i^w	1 if vertex $i \in \tilde{\mathcal{V}}_1$ is present in trip $w \in \Pi$, or if vertex $i \in \mathcal{V}_2$ is present in trip $w \in \pi$, 0 otherwise;
y_i^{wh}	1 if the goods requested by final customer $i \in \mathcal{N}_2$ are delivered to the copy $h \in \mathcal{H}$ of the city hub in trip $w \in \Pi$, 0 otherwise;
t_i^w	Time at which trip $w \in \Pi$ visits vertex $i \in \tilde{\mathcal{V}}_1$ if it is present in the trip (for the depot 0, t_0^w is the starting time of the trip),
t_i^w	Time at which trip $w \in \pi$ visits vertex $i \in \mathcal{V}_2$ if it is present in the trip (for the city hub H , t_H^w is the starting time of the trip);
t_f^w	Finishing time of trip $w \in \Pi \cup \pi$;
$z_{ww'}$	1 if trip $w \in \pi$ is followed by trip $w' \in \pi$ on the same second-level vehicle, 0 otherwise;
γ_t^{wh}	1 if first-level trip $w \in \Pi$ visits copy $h \in \mathcal{H}$ of the city hub at period $t \in \mathcal{T}$, 0 otherwise;
σ_t^w	1 if second-level trip $w \in \pi$ starts (from the city hub) at period $t \in \mathcal{T}$, 0 otherwise;
α_{it}^{wh}	1 if first-level trip $w \in \Pi$ delivers the goods demanded by customer $i \in \mathcal{N}_2$ to the copy $h \in \mathcal{H}$ of the city hub at period $t \in \mathcal{T}$, 0 otherwise;
δ_{it}^w	1 if the second-level trip $w \in \pi$ visits customer $i \in \mathcal{N}_2$ and leaves the city hub at period $t \in \mathcal{T}$, 0 otherwise;
l_t	stock level in the city hub at period $t \in \mathcal{T}$.

$|\mathcal{N}_1 \cup \mathcal{N}_2|$ for Π (one trip to serve a customer in \mathcal{N}_1 plus a trip per customer in \mathcal{N}_2 to bring its merchandise to the hub) and $|\mathcal{N}_2|$ for π . For the management of the city hub inventory in the model, time is discretized in a set \mathcal{T} of periods. This discretization is assumed to be consistent with the time granularity of temporal data (that is, values $E, L, E_i, T_i, S_i, T_{ij}$). M is a large number (e.g., $M = L - E$). Also, copies of the city hub are introduced for the first-level distribution. The set \mathcal{H} represents these copies and each individual occurrence of the city hub in a trip is denoted H_h with $h \in \mathcal{H}$. New sets $\tilde{\mathcal{V}}_1$ and $\tilde{\mathcal{A}}_1$ are introduced to include these copies. $\tilde{\mathcal{V}}_1 = \mathcal{N}_1 \cup \{0\} \cup \{H_h : h \in \mathcal{H}\}$. $\tilde{\mathcal{A}}_1$ is built accordingly, except that arcs between two copies of the city hub are not added to $\tilde{\mathcal{A}}_1$ (remind that consecutive visits to the city hub are not allowed). The size of \mathcal{H} can be fixed with a simple upper bound on the maximal number of visits to the city hub in a trip.

The proposed integer linear programming formulation for the C2E-VRPTW is:

$$\text{minimize } \sum_{w \in \Pi} \sum_{(i,j) \in \tilde{\mathcal{A}}_1} D_{ij} \times x_{ij}^w + \sum_{w \in \pi} \sum_{(i,j) \in \mathcal{A}_2} D_{ij} \times x_{ij}^w \quad (1)$$

subject to:
(First-level distribution)

$$\sum_{w \in \Pi} y_i^w = 1 \quad (i \in \mathcal{N}_1), \quad (2)$$

$$\sum_{w \in \Pi} \sum_{h \in \mathcal{H}} y_i^{wh} = 1 \quad (i \in \mathcal{N}_2), \quad (3)$$

$$\sum_{i \in \mathcal{N}_2} y_i^{wh} \leq |\mathcal{N}_2| \times y_{H_h}^w \quad (w \in \Pi, h \in \mathcal{H}), \quad (4)$$

$$\sum_{j \in \tilde{\mathcal{V}}_1 \setminus \{i\}} x_{ji}^w = \sum_{j \in \tilde{\mathcal{V}}_1 \setminus \{i\}} x_{ij}^w = y_i^w \quad (i \in \tilde{\mathcal{V}}_1, w \in \Pi), \quad (5)$$

$$\sum_{i \in \mathcal{N}_1} Q_i \times y_i^w + \sum_{i \in \mathcal{N}_2} \sum_{h \in \mathcal{H}} Q_i \times y_i^{wh} \leq Q_{1L} \quad (w \in \Pi), \quad (6)$$

$$t_i^w + S_i + T_{ij} \leq t_j^w + M \times (1 - x_{ij}^w) \quad ((i, j) \in \tilde{\mathcal{A}}_1 : j \neq 0, w \in \Pi), \quad (7)$$

$$t_i^w + S_i + T_{i0} \leq t_f^w + M \times (1 - x_{i0}^w) \quad (i \in \tilde{\mathcal{V}}_1 \setminus \{0\}, w \in \Pi), \quad (8)$$

$$E_i \times y_i^w \leq t_i^w \leq L_i \times y_i^w \quad (i \in \mathcal{N}_1, w \in \Pi), \quad (9)$$

$$t_0^w \leq t_f^w \leq t_0^{w+1} \quad (w \in \{1, \dots, |\Pi| - 1\}), \quad (10)$$

$$E \leq t_0^1, \quad (11)$$

$$t_f^{\Pi} \leq L, \quad (12)$$

(Second-level distribution)

$$\sum_{w \in \pi} y_i^w = 1 \quad (i \in \mathcal{N}_2), \quad (13)$$

$$\sum_{j \in \mathcal{V}_2 \setminus \{i\}} x_{ji}^w = \sum_{j \in \mathcal{V}_2 \setminus \{i\}} x_{ij}^w = y_i^w \quad (i \in \mathcal{V}_2, w \in \pi), \quad (14)$$

$$\sum_{i \in \mathcal{N}_2} Q_i \times y_i^w \leq Q_{2L} \quad (w \in \pi), \quad (15)$$

$$t_i^w + S_i + T_{ij} \leq t_j^w + M \times (1 - x_{ij}^w) \quad ((i, j) \in \mathcal{A}_2 : j \neq H, w \in \pi), \quad (16)$$

$$t_i^w + S_i + T_{iH} \leq t_f^w + M \times (1 - x_{iH}^w) \quad (i \in \mathcal{V}_2 \setminus \{H\}, w \in \pi), \quad (17)$$

$$E_i \times y_i^w \leq t_i^w \leq L_i \times y_i^w \quad (i \in \mathcal{V}_2 \setminus \{H\}, w \in \pi), \quad (18)$$

$$t_f^w \leq L, \quad (w \in \pi), \quad (19)$$

$$t_f^w \leq t_H^{w'} + M \times (1 - z_{ww'}) \quad (w \in \pi, w' \in \pi : w < w'), \quad (20)$$

$$|\pi| - \sum_{w \in \pi} \sum_{w' \in \pi, w < w'} z_{ww'} \leq |\mathcal{S} \mathcal{L}|, \quad (21)$$

$$\sum_{w \in \pi, w < w'} z_{ww'} \leq 1, \quad (w' \in \pi), \quad (22)$$

$$\sum_{w \in \pi, w < w'} z_{w'w} \leq 1, \quad (w' \in \pi), \quad (23)$$

(Synchronization)

$$t_{H_h}^w \leq t_H^{w'} + M \times (2 - y_i^{wh} - y_i^{w'}) \quad (w \in \Pi, h \in \mathcal{H}, w' \in \pi, i \in \mathcal{N}_2), \quad (24)$$

(Hub capacity management)

$$t_{H_h}^w = \sum_{t \in \mathcal{T}} t \times \gamma_t^{wh} \quad (w \in \Pi, h \in \mathcal{H}), \quad (25)$$

$$\sum_{t \in \mathcal{T}} \gamma_t^{wh} = y_{H_h}^w \quad (w \in \Pi, h \in \mathcal{H}), \quad (26)$$

$$t_0^w = \sum_{t \in \mathcal{T}} t \times \sigma_t^w \quad (w \in \pi), \quad (27)$$

$$\sum_{t \in \mathcal{T}} \sigma_t^w = 1 \quad (w \in \pi), \quad (28)$$

$$1 + \alpha_{it}^{wh} \geq \gamma_t^{wh} + y_i^{wh} \quad (t \in \mathcal{T}, w \in \Pi, h \in \mathcal{H}, i \in \mathcal{N}_2), \quad (29)$$

$$2 \alpha_{it}^{wh} \leq \gamma_t^{wh} + y_i^{wh} \quad (t \in \mathcal{T}, w \in \Pi, h \in \mathcal{H}, i \in \mathcal{N}_2), \quad (30)$$

$$1 + \delta_{it}^w \geq \sigma_t^w + y_i^w \quad (t \in \mathcal{T}, w \in \pi, i \in \mathcal{N}_2), \quad (31)$$

$$2 \delta_{it}^w \leq \sigma_t^w + y_i^w \quad (t \in \mathcal{T}, w \in \pi, i \in \mathcal{N}_2), \quad (32)$$

$$l_E = 0, \quad (33)$$

$$l_t = l_{t-1} + \sum_{w \in \Pi} \sum_{h \in \mathcal{H}} \sum_{i \in \mathcal{N}_2} Q_i \times \alpha_{it}^{wh} - \sum_{w \in \pi} \sum_{i \in \mathcal{N}_2} Q_i \times \delta_{it}^w \quad (t \in \mathcal{T} \setminus \{E\}), \quad (34)$$

$$l_{t-1} + \sum_{w \in \Pi} \sum_{h \in \mathcal{H}} \sum_{i \in \mathcal{N}_2} Q_i \times \alpha_{it}^{wh} \leq Q_{CH} \quad (t \in \mathcal{T}), \quad (35)$$

(Decision variables)

$$x_{ij}^w \in \{0, 1\} \quad ((i, j) \in \tilde{\mathcal{A}}_1, w \in \Pi), \quad (36)$$

$$y_i^w \in \{0, 1\} \quad (i \in \tilde{\mathcal{V}}_1, w \in \Pi), \quad (37)$$

$$y_i^{wh} \in \{0, 1\} \quad (i \in \mathcal{N}_2, w \in \Pi, h \in \mathcal{H}), \quad (38)$$

$$t_i^w \geq 0 \quad (i \in \tilde{\mathcal{V}}_1, w \in \Pi), \quad (39)$$

$$t_f^w \geq 0 \quad (w \in \Pi), \quad (40)$$

$$x_{ij}^w \in \{0, 1\} \quad ((i, j) \in \mathcal{A}_2, w \in \pi), \quad (41)$$

$$y_i^w \in \{0, 1\} \quad (i \in \mathcal{V}_2, w \in \pi), \quad (42)$$

$$t_i^w \geq 0 \quad (i \in \mathcal{V}_2, w \in \pi), \quad (43)$$

$$t_f^w \geq 0 \quad (w \in \pi), \quad (44)$$

$$z_{ww'} \in \{0, 1\} \quad (w \in \pi, w' \in \pi : w < w'), \quad (45)$$

$$\gamma_t^{wh} \in \{0, 1\} \quad (w \in \Pi, h \in \mathcal{H}, t \in \mathcal{T}), \quad (46)$$

$$\sigma_t^w \in \{0, 1\} \quad (w \in \pi, t \in \mathcal{T}), \quad (47)$$

$$\alpha_{it}^{wh} \in \{0, 1\} \quad (i \in \mathcal{N}_2, w \in \Pi, h \in \mathcal{H}, t \in \mathcal{T}), \quad (48)$$

$$\delta_{it}^w \in \{0, 1\} \quad (i \in \mathcal{N}_2, w \in \pi, t \in \mathcal{T}), \quad (49)$$

$$l_t \geq 0 \quad (t \in \mathcal{T}). \quad (50)$$

The objective function (1) aims at minimizing the total travel cost. Constraints (2)–(12) define the first-level distribution scheme. The formulation is based on a four-index formulation for the multi-trip VRPTW (MTVRPTW), as presented in Cattaruzza et al. (2016b), with the simplification that with a single first-level vehicle the vehicle index is not introduced. Constraints (2) and (3) ensure that the demand of every customer (first or second level) is loaded in exactly one trip. With Constraints (4) they also force to unload goods of a second-level customer in

exactly one copy of the city hub and to visit this copy. Constraints (5) are for flow conservation. Constraints (6) are vehicle capacity constraints. Constraints (7)–(12) evaluate time variables from flow variables, taking time constraints into account. In addition, they prevent from subtours and force starting and finishing trips at the depot.

Constraints (13)–(23) define the second-level distribution scheme. The formulation is based on a three-index formulation for the MTVRPTW, as presented in Cattaruzza et al. (2016b). Constraints (13) impose the service of all second-level customers. Constraints (14) are for flow conservation and Constraints (15) for vehicle capacity. Constraints (16)–(19) with Constraints (20)–(23), fix time variables, forbid subtours and force starting and finishing trips at the city hub. The role of Constraints (20)–(23) is to manage the sequencing of trips in vehicle routes. Variables $z_{ww'}$ are introduced to fix these decisions. A difficult point, solved thanks to Constraints (21), is to limit the fleet size. The validity of the constraints is explained by the fact that the number of vehicles used is given by the number of trips minus the number of consecutive trips. Note that empty trips can be considered part of any vehicle schedule.

Constraints (24) synchronize the two levels of distribution. A second-level trip delivering goods to a customer $i \in \mathcal{N}_2$ has to start after the arrival to the city hub of the first-level trip carrying goods required by customer i .

Constraints (25)–(26) allow fixing variables γ_t^{wh} (arrival time of first-level trip w at copy h of the city hub). Constraints (27)–(28) are equivalent for variables σ_t^w (departure time of second-level trip w from the city hub). Constraints (29)–(30) and (31)–(32) linearize logical constraint $\alpha_{it}^{wh} = \gamma_t^{wh} \wedge y_i^{wh}$ and $\delta_{it}^w = \sigma_t^w \wedge y_i^w$, respectively. They allow introducing standard inventory balance constraints (34) for the city hub. Finally, Constraints (33) and (35) bound the inventory. Note that hub capacity constraints have to hold before goods are loaded into second-level vehicles. It limits the needs to synchronize vehicles, as explained in Section 3.

Constraints (36)–(50) define the decision variables, as explained in Table 2.

4. Solution method

4.1. Intuition and motivation in the design of the solution method

A very standard approach in combinatorial optimization is to decompose problems and address successively different families of decisions. In our context, it would be very natural to desynchronize the two levels of distribution and optimize separately these two levels. Unfortunately, the literature does not show any easy way to achieve this when synchronization constraints are binding. In this section, we propose an original decomposition mechanism that allows tackling separately the two levels of distribution.

The whole algorithm is based on the following observation. At the second level, the fact that small vehicles are used implies short trips. Then, given a customer and the trip that visits this customer, a rough estimation of the starting time of the trip can be deduced from the customer's time window.

Let us assume temporarily that this starting time is exactly known for all customers and that the hub has no capacity, i.e., first- and second-level vehicles have to be perfectly synchronized. In this case, the problem naturally decomposes: second-level distribution is optimized based on trip starting times, first-level distribution is optimized so that goods arrive exactly on time at the city hub.

Of course, the above assumption is too strong. On one hand, trip starting times cannot be known exactly, i.e., there is some uncertainty on these values. But, on the other hand, the city hub is capacitated, which means that there is some possibility to absorb the uncertainty through inventory. Based on this key analysis, we propose a solution approach in three phases:

1. Optimize the second-level distribution without considering synchronization, i.e., assuming that all goods are available at the city hub at second-level convenience. This first phase provides second-level trips and a schedule for these trips.
2. Using this schedule, taking account of hub capacity and approximating the first-level distribution, deduce arrival times for first-level trips. At the end of this phase, all the operations at the city hub (goods arrivals and departures) are fixed.
3. Optimize the first-level distribution based on these values.

4.2. More details on the three phases of the method

In the first phase, we compute a population of solutions for the delivery of second-level customers from the city hub (phase 1). Phases 2 and 3 are applied to each one of these solutions, independently. The output of the algorithm is the best solution among all the solutions found.

The problem of phase 1 corresponds to a MTRVPTW. Each solution provides a set of cargo bike trips that visit all second-level customers. To solve this problem, we use the algorithm proposed by Cattaruzza et al. (2016a). The output of the algorithm is a population of good and dispersed solutions. The algorithm proposed by Cattaruzza et al. (2016a) considers infeasibility with respect to TW violation. As a result solutions in the final population may be infeasible. Consequently, phases 2 and 3 are applied to at most the best-ranked φ feasible solutions. The method proposed in Cattaruzza et al. (2016a) is a population-based algorithm using the giant tour decomposition scheme introduced by Prins (2004) and applying the techniques developed in Vidal et al., 2013. For a deeper overview of the algorithm, the interested reader is referred to Cattaruzza et al. (2016a).

For each solution, the second phase (phase 2) solves a simplified version of the integrated first-level-distribution and city-hub-inventory-management problems. In this phase, first-level customers are ignored and first-level distribution is thus limited to back-and-forth trips between the depot and the city hub. These trips have to be organized such that goods arrive on time for the second-level deliveries, as they are planned in phase 1. Also, the constraint on hub capacity has to be satisfied. For this phase, we propose several integer programming formulations. At the end of this phase, the delivery schedule to the city hub is fixed.

The last phase (phase 3) considers this schedule and optimizes accordingly the trips of the first-level vehicle, considering first-level customers. In phase 3, we face again a MTRVPTW, but with a single vehicle. It is again solved with the algorithm of Cattaruzza et al. (2016a).

Not all the solutions obtained at the end of phase 1 can be feasibly completed with phases 2 and 3. The output of the algorithm is the best solution among those for which phases 2 and 3 succeeded. To maximize the chances of finding a feasible solution at phase 3, the objective of the integer programs of phase 2 is to minimize the number of back-and-forth trips for the first-level vehicle. This should indeed leave a maximal amount of idle time for this vehicle to manage the first-level customers. It should also tend to minimize costs.

An interesting property of this algorithm is that the second-level distribution costs (phase 1) should be very well optimized, since optimization is done with a heuristic that demonstrated its effectiveness and without considering any constraint related to first-level distribution or hub capacity. Also, first-level distribution costs should be rather well minimized as long as the number of visits to the city hub is indeed minimized. The issue at stake is then to see if a feasible solution will be found, despite the sequential execution of the three phases. We believe that it is possible thanks to the dispersion of the population of solutions provided by the algorithm after phase 1. Experiments presented in Section 5 confirm this intuition and give more insights on the behaviour of the algorithm.

The three phases of the proposed heuristic are detailed in the following sections.

4.3. First phase: Optimize the second-level distribution

The second-level problem corresponds to the final leg of distribution made by the cargo bikes. In our characterization, the cargo bikes cannot start their trips before the goods of customers to be served by those trips arrive to the city hub. However, for this phase we assume that all goods are available in the city hub. This means that the cargo bikes can start their trips without waiting for the goods to arrive. Hence, the problem is seen as a MTRVPTW. The first-level distribution part of the problem and the hub capacity constraint are not yet considered.

To solve this subproblem, the population-based algorithm developed by Cattaruzza et al. (2016a) is used. The input to the algorithm is constructed as follows. The customer set is the set \mathcal{N}_2 of second-level customers, with their respective demand, service times and time windows. The fleet is the fleet \mathcal{SL} of cargo bikes, based at the city hub. The beginning of the time horizon is set to $E + T_{OH}$, because it corresponds to the earliest possible arrival time of the goods to the city hub. Other input data (time matrix, distance matrix, end of the time horizon) is defined as in the C2E-VRPTW.

The output of this algorithm is a population of solutions. The algorithm embeds a diversity management technique for the population, which ensures that the final population respects a good compromise between quality and diversity. To ensure diversity of the population the fitness of each solution is calculated as a linear combination of its cost and diversity contribution to the population. The diversity contribution is a measure of dissimilarity among the current solution and the solutions already in the population. This measure may be the number of arcs that are not shared by the solutions. For further details the reader is referred to Vidal et al., 2013.

4.4. Second phase: Define the visits to the city hub

In this phase, each second-level solution obtained from phase 1 is completed with back-and-forth trips of the first-level vehicle, to transfer goods from the depot to the city hub. The addition of these trips is subject to several constraints. First, goods of second-level customers have to keep being delivered on time. Second, the capacity constraint of the first-level vehicle has to be satisfied. Third, the city hub capacity has to be respected. Finally, the first-level truck has to return on time to the depot. In this phase, first-level customers are ignored.

To obtain these back-and-forth trips, we propose three alternative mathematical formulations (integer programs). In the first model, departure times of second-level vehicles are fixed. Customer demands of each second-level trip are consolidated at the depot and delivered together to the city hub. In the second model, departure times of second-level vehicles are not fixed. They can start later than the departure times indicated after the first phase. Customer demands are still consolidated at the depot. The third model does not fix departure times for second-level vehicles and does not consolidate demands at the depot: Demands of second-level customers belonging to the same second-level trip are not necessarily delivered to the city hub within the same first-level trip. In all cases, the objective is to minimize the number of back-and-forth trips.

From a combinatorial point of view, the first model necessitates less binary decision variables than the other ones and should be easier to solve, but offers less flexibility in the deliveries to the city hub. The second model is intermediate. The third model necessitates the largest number of binary decision variables and probably is the most complex to solve. However, it offers maximal flexibility.

Before presenting the three models we introduce specific notation. The set of second-level trips provided by phase 1 is denoted \mathcal{W} . The black box algorithm used to solve the second level provides for each trip $w \in \mathcal{W}$ the amount of goods Q_w delivered in the trip, a time window $[E_w, L_w]$ and a duration T_w . If the trip starts during $[E_w, L_w]$ its duration is minimal and equals T_w . If the trip starts at $t < E_w$ duration of the trip is

increased by $E_w - t$. If the trip starts at $t > L_w$ it is infeasible. Thus, given a time instant $t \leq L_w$, the exact duration of a trip is $T_w(t) = T_w + \max\{0, E_w - t\}$. Given two trips w and w' , $\delta_{ww'} = 1$ if trip w' follows trip w on the same second-level vehicle, $\delta_{ww'} = 0$ otherwise.

We denote by \mathcal{T}_{1H} the time horizon restricted to the possible arrival times of the first-level truck to the city hub: $\mathcal{T}_{1H} = \{E + T_{0H}, \dots, L - T_{0H}\}$. \mathcal{T}_w is the time horizon restricted to the possible starting times of trip $w \in \mathcal{W}$: $\mathcal{T}_w = \{E + T_{0H}, \dots, L_w\}$. Finally, $w(i)$ provides the trip that contains customer i .

The three proposed models are detailed in the following sections.

4.4.1. Model 1: Trip-based model with fixed departure times

In this first model, the starting time of the second-level trips is imposed and fixed to their latest allowed starting time L_w . This is done to provide the largest flexibility to the first-level vehicle while ensuring feasibility. Goods to be delivered in a trip w are assumed to be consolidated at the depot and delivered simultaneously to the city hub. We introduce the following binary decision variables:

- $x_w^t = 1$ if goods to be delivered with trip w arrive at the city hub at time t , 0 otherwise ($w \in \mathcal{W}, t \in \mathcal{T}_w$);
- $x^t = 1$ if the first-level vehicle arrives at the city hub at time t , 0 otherwise ($t \in \mathcal{T}_{1H}$).

The first model is given as follows:

$$\text{minimize } \sum_{t \in \mathcal{T}_{1H}} x^t \quad (51)$$

subject to

$$\sum_{t \in \mathcal{T}_w} x_w^t = 1 (w \in \mathcal{W}), \quad (52)$$

$$\sum_{\{w \in \mathcal{W} : t \leq L_w\}} \sum_{t' \in \{E+T_{0H}, \dots, t\}} Q_w \times x_w^{t'} \leq Q_{CH} (t \in \mathcal{T}_{1H}), \quad (53)$$

$$\sum_{\{w \in \mathcal{W} : t \leq L_w\}} Q_w \times x_w^t \leq Q_{1L} \times x^t (t \in \mathcal{T}_{1H}), \quad (54)$$

$$\sum_{t' \in \{t, \dots, t+2 \times T_{0H}-1\}} x^{t'} \leq 1 (t \in \{E + T_{0H}, \dots, L - 3 \times T_{0H} + 1\}), \quad (55)$$

$$x_w^t \in \{0, 1\} (w \in \mathcal{W}, t \in \mathcal{T}_w), \quad (56)$$

$$x^t \in \{0, 1\} (t \in \mathcal{T}_{1H}). \quad (57)$$

The objective (51) is to minimize the number of deliveries to the city hub with the first-level vehicle. Constraints (52) enforce the arrival of goods to the city hub. Constraints (53) ensure that the amount of goods stored in the city hub does not exceed the city hub capacity. Constraints (54) limit the amount of goods transported simultaneously in the first-level vehicle. They also link the two families of variables, i.e., the arrival to the city hub of goods and of the first-level vehicle. Constraints (55) impose a feasible schedule for the first-level vehicle: two arrivals to the city hub are at least separated by the time taken for a back-and-forth trip.

4.4.2. Model 2: Trip-based model with flexible departure times

In this model, goods to be delivered in a trip w are assumed to be consolidated at the depot and delivered simultaneously to the city hub. The starting times of the second-level trips are not imposed anymore. We introduce the following additional binary decision variables:

- $y_w^t = 1$ if trip w starts at time t , 0 otherwise ($w \in \mathcal{W}, t \in \mathcal{T}_w$).

This model is defined by the objective function (51), Constraints (52), (54)–(57) plus the following ones:

$$\sum_{t \in \mathcal{T}_w} y_w^t = 1 (w \in \mathcal{W}), \quad (58)$$

$$\sum_{t'=E+T_{0H}} (x_w^{t'} - y_w^{t'}) \geq 0 (w \in \mathcal{W}, t \in \mathcal{T}_w), \quad (59)$$

$$\sum_{\{w \in \mathcal{W} : t \leq L_w\}} \left(\sum_{t'=E+T_{0H}} Q_w x_w^{t'} - \sum_{t'=E+T_{0H}} Q_w y_w^{t'} \right) \leq Q_{CH} (t \in \mathcal{T}_{1H}), \quad (60)$$

$$\sum_{t=t}^{L_w} y_w^t + \sum_{t'=E+T_{0H}} y_{w'}^{t'} \leq 1 (w, w' \in \mathcal{W} : \delta_{ww'} = 1, t \in \mathcal{T}_w), \quad (61)$$

$$y_w^t \in \{0, 1\} (w \in \mathcal{W}, t \in \mathcal{T}_w). \quad (62)$$

Constraints (58) enforce that all trips are executed. With Constraints (59), a trip cannot start before the arrival of the associated goods to the city hub. Constraints (60) handle the city hub capacity and are adapted from (53) and (35). Constraints (61) manage the feasibility of the second-level vehicle schedule: if trip w does not start before time t , trip w' cannot start before time $t + T_w(t)$. Note that the schedule may be overconstrained here because the actual duration of trip w could be less than $T_w(t)$.

4.4.3. Model 3: Second-level customers-based model

In this model, goods associated with the second-level trips are not consolidated at the depot. This means that they can be delivered separately to the city hub. Also, the starting time of these trips is still not imposed. We change variables x_w^t to the following binary decision variables:

- $x_i^t = 1$ if goods of the second-level customer i arrive to the city hub at time t , 0 otherwise ($i \in \mathcal{N}'_2, t \in \mathcal{T}_{w(i)}$).

This model is defined by the objective function (51), Constraints (55), (57), (58), (61), (62) plus the following ones:

$$\sum_{t \in \mathcal{T}_{w(i)}} x_i^t = 1 (i \in \mathcal{N}'_2), \quad (63)$$

$$\sum_{\{i \in \mathcal{N}'_2 : t \leq L_{w(i)}\}} Q_i x_i^t \leq Q_{1L} x^t (t \in \mathcal{T}_{1H}), \quad (64)$$

$$\sum_{t'=E+T_{0H}} (x_i^{t'} - y_{w(i)}^{t'}) \geq 0 (i \in \mathcal{N}'_2, t \in \mathcal{T}_{w(i)}), \quad (65)$$

$$\sum_{\{i \in \mathcal{N}'_2 : t \leq L_{w(i)}\}} \sum_{t'=E+T_{0H}} Q_i x_i^{t'} - \sum_{\{w \in \mathcal{W} : t \leq L_w\}} \sum_{t'=E+T_{0H}} Q_w y_w^{t'} \leq Q_{CH} (t \in \mathcal{T}_{1H}), \quad (66)$$

$$x_i^t \in \{0, 1\} (i \in \mathcal{N}'_2, t \in \mathcal{T}_{w(i)}). \quad (67)$$

Constraints (63) to (66) are straightforwardly adapted from Constraints (52), (54), (59) and (60), respectively.

4.5. Third phase: Optimize the first-level distribution

The goal of the third phase of our algorithm is to organize the trips of the first-level vehicle. These trips include demands of second-level customers to be delivered to the city hub as well as demands of first-level customers.

As in the first phase, we address this problem as a MTRVPTW and use the algorithm developed by Cattaruzza et al. (2016a). The input data is constructed as follows. For each back-and-forth trip resulting from the

second phase, a dummy customer is created. The location of this dummy customer is the city hub location, its demand is equal to the transported goods within the corresponding trip, its service time is zero and its time window is exactly equal to the visit time fixed by the second phase. All first-level customers with their associated time windows, service times and demands are also considered. A single vehicle, the truck of capacity Q_{1L} , based at the depot, is used. The time horizon, time matrix and distance matrix are those defined for the C2E-VRPTW, with the sole exception that the distance (cost) and travel time between two dummy customers are set to $2 \times D_{OH}$ and $2 \times T_{OH}$ respectively. Indeed, the algorithm used in this phase allows successive visits of dummy customers in a trip, while consecutive visits of the city hub are not allowed in the problem definition. With these costs, successive visits of dummy customers amount to adding a back-and-forth trip to the depot. Note that Constraints (55) ensure that enough time is available for that trip.

5. Computational experiments

This section reports the computational results for the C2E-VRPTW obtained with the proposed three-phase solution procedure. The algorithm is coded in C++ and is compiled with the Visual Studio 2012 environment. Experiments are run on an Intel(R) Core(TM) i7-5600U CPU 2.60 GHz machine with 8 Gb of RAM memory.

5.1. Test instances

We developed a set of real-world test instances with data from the city of Vienna. These instances are based on historic GPS data from an Austrian parcel delivery company capturing deliveries in May 2015. The focal area is next to the largest shopping street in the city of Vienna, which hosts a large number of shops, but also final customers living in this area. GPS trajectories were used to identify delivery stops, which were then categorized as first or second level customers referring to their ability of being serviced by a cargo bike depending on the required transport capacity. Twenty networks were then generated by randomly selecting a subset of first and second level customers. Details on the number of customers in each network are presented in Table 3.

Time windows for customers are calculated as follows. The opening hour of the TW is uniformly drawn in $\{1, 2, \dots, 7\}$, while the closing of the TW is obtained from the opening time plus the 3 h width. The time windows for the depot and the city hub equal the time horizon that is 10 h long.

Service times are generated based on uniform distributions. The service times of first-level customers are between 7 and 15 min while the service times of second-level customers are between 3 and 15 min.

Customer demands are randomly generated based on uniform distributions. The demand of first-level customers is uniformly distributed with a weight between 101 and 120 kg. The demand of second-level customers is uniformly distributed with a weight between 1 and 22 kg.

The first-level vehicle is a truck with a capacity of 700 kg. We introduce two variants of second-level vehicles. They can either be cargo bikes with a capacity of 100 kg or electric vans with a capacity of 300 kg (see Table 4).

Table 3
Number of customers on each level of the distribution on the different networks.

network	1	2	3	4	5	6	7	8	9	10
first-level customers	10	9	9	8	7	9	10	9	11	7
second-level customers	72	65	64	71	65	63	69	62	68	70
network	11	12	13	14	15	16	17	18	19	20
first level customers	6	5	5	6	7	7	5	5	5	7
second level customers	65	73	72	78	69	69	78	77	69	74

Table 4
Characteristics of the different fleets of vehicles.

variant	first level		second level	
	vehicle fleet	capacity (kg)	vehicle fleet	capacity (kg)
variant bikes	truck	700	bikes	100
variant e-vans	truck	700	electric vans	300

We use different sources of data to compute travel times for the different types of vehicles, based on the real street network in Vienna. To calculate travel times for the truck and electric vans, we take Floating Car Data (FCD) from FLEET, an FCD system continuously working since 2003 and collecting data from about 3000 taxis in Vienna. Out of this data, the system estimates the average speed per road element and time interval (cf. (Graser et al., 2012)). We use the average speed-per-road element at 4:00 a.m. on a typical weekday. For bikes, the routes currently taken by the majority of cyclists are of great interest. We use routes for cyclists which are not merely based on shortest travel time or cycle-friendly infrastructure, but contain a route popularity measure from GPS trajectories of real trips that include subjective or difficult to measure factors of influence (cf. (Straub and Graser, 2015)). As a consequence, given two locations i and j in one of the considered networks, the shortest path that links i and j does not correspond for bikes and vans, usually both in terms of travel time and distance.

All time values are integers expressed in seconds, while distances are floating values with one decimal digit expressed in meters.

Three scenarios are investigated with different potential locations for the city hub, each with a different capacity and distance to the final customers and to the depot, as indicated in Table 5. Based on discussions with practitioners, we assume that the inner city hub has the smallest capacity, since the available storage area in the city center is scarce. The city hub at the boundaries of the city has a middle capacity, while the city hub at the outskirts is equipped with a comparatively large storage area. For each scenario, the depot is placed outside the city.

Each scenario is combined with the two variants for the vehicle fleet and tested on the 20 networks. In total, this gives a set of 120 realistic test instances for the city of Vienna.

5.2. Experimental results

To evaluate the quality of the results, we investigated different aspects on three dimensions. The first dimension refers to the location and size of the city hub, which is assessed with cost incurred at the first and second level. The second dimension refers to the vehicle fleet and is assessed with the number of trips, vehicles, visits and capacity usage at the first and second level. The last dimension is related to the used IP model, as presented in Section 4.4. Detailed results for all test instances can be found in Appendix A.1.

In all experiments, phase 1 returns up to five solutions. Time limits of the first and third phase are fixed to 120 and 20 s, respectively. In the second phase, mathematical models are solved optimally using the standard solver CPLEX 12.6 with a time limit of 20 s. To speed up the resolution of the models the time granularity considered in phase 2 is reduced. We recall that the instances have a horizon of 10 h with a granularity of one second. Keeping the same granularity would lead to a large number of variables in each model. Thus, in phase 2, a granularity of 12 s is considered. Consequently, all time quantities involved in the model definitions are normalized to the same granularity.

Table 5
Characteristics of the different scenarios that are considered for each network.

scenario	city hub location	city hub capacity	distance city hub - depot
scenario 1	inner city	small (300 kg)	long (20 km)
scenario 2	city boundaries	middle (500 kg)	middle (18 km)
scenario 3	outskirts	large (700 kg)	short (13 km)

Impact of variants and scenarios

First, we analyze impacts of the location and size of the city hub (see Table 5) as well as the used vehicle fleet (see Table 4) on the performance of the system. In these experiments, the three proposed IP models are solved in phase 2, and phase 3 is applied on every solution that is found. The best feasible solution is kept for the result table.

Table 6 shows the average cost of each level and the average total cost on the different scenarios and variants. From Table 6, we notice that the location and the size of the city hub influence the cost of each level, depending on the vehicle fleet.

As expected, first-level costs are only slightly modified if bikes or vans are used for the second-level: the maximal difference is observed for scenario 1 which is approximately 5%. Also, these costs are relatively similar for the first two scenarios. A large decrease is observed for the third scenario, where the distance between the city hub and the depot has been reduced by a third and the city hub capacity has more than doubled (compared to scenario 1). However, by computing the ratio between first-level costs and the hub-to-depot distance (not reported in the table), one can see a large increase for scenarios 2 and 3. This is easily explained by the fact that the first-level vehicle not only travels between the depot and the city hub, but also performs deliveries to first-level customers.

Regarding second-level costs for the bike variant, a strong increase can be observed when the hub is distant to the city center. This increase is not compensated by the decrease in first-level costs and scenario 1 is by far the most effective. For vans, the situation is more complex. Second-level costs still increase with the distance between the hub and the depot, but the slope is weaker. Eventually, the benefits at the first level are (almost) enough to compensate this increase: scenario 1 and scenario 2 show relatively similar performances.

Finally, comparing bikes and vans, bikes should clearly be preferred for scenario 1. When the city hub is located outside the city center, vans quickly become more effective. At the end, the best option is found with scenario 1, using bikes for second-level deliveries.

Table 7 underlines these findings with detailed results for the different scenarios and variants on all the networks and at each level. Table 7 shows the average number of visits of the truck to the city hub at the first level (nb. hub visits) and the average number of vehicles used at the second level (nb. 2L vehicles). It also shows the average number of performed trips (nb. trips) for the first level (1L) and the second level (2L). In this Table we also report the average percentage of usage of vehicles (%usage) on the first level (1L) and the second level (2L). It is computed as the average demand delivered with each trip divided by vehicle capacity.

Obviously, since the capacity of cargo bikes is lower than the capacity of electric vans, more vehicles and more trips are needed on the second level when bikes are used. However, the capacity usage of cargo bikes is higher compared with the capacity usage obtained when electric vans are considered. This means that available resources are more efficiently used.

Analysis of the proposed IP models

Table 8 compares the performance of the different IP models. The Table reports, for each model and after phase 3 is applied, the number of fails to obtain a feasible solution (nb. infeasibilities), i.e., the number of times when either phase 2 or phase 3 fails to complete the execution. When phase 2 or 3 fails, it means that it is not capable to provide a

Table 6 Cost overview.

variant	costs	scenario 1	scenario 2	scenario 3
variant bikes	first level cost	2 232 980.8	2 262 549.0	1 807 134.8
	second level cost	504 488.1	772 535.7	1 290 067.3
	total cost	2 737 468.9	3 035 084.7	3 097 202.1
variant e-vans	first level cost	2 353 041.2	2 218 365.5	1 808 966.7
	second level cost	635 816.1	745 935.6	999 114.3
	total cost	2 988 857.3	2 964 301.1	2 808 081.0

Table 7 Experimental results.

	nb. hub visits	nb. 2L vehicles	nb. trips		%usage	
			1L	2L	1L	2L
variant bikes						
scenario 1	3.05	8.25	4.95	8.95	0.24	0.89
scenario 2	2.05	7.75	4.25	8.70	0.27	0.91
scenario 3	1.80	7.45	2.90	8.65	0.40	0.92
variant e-vans						
scenario 1	3.40	4.70	5.10	4.85	0.23	0.55
scenario 2	2.10	3.95	4.25	3.95	0.27	0.68
scenario 3	1.80	4.15	2.95	4.15	0.40	0.65

Table 8 Performance of the models on the five best solutions.

	nb. infeasibilities	nb. best	av. gap to best (%)	av. CPU time (sec)
model 1	87	222	2.75	0.32
model 2	53	207	2.57	8.02
model 3	52	295	1.37	10.39

feasible solution for the sub-problem it is solving. It follows that a solution for the whole problem cannot be provided in that specific run.

Table 8 also reports the number of obtained best solutions (nb. best), the average percentage gap to the best solution (av. gap to best) when a solution is found, and the average CPU Time expressed in seconds (av. CPU time). Let us indicate with $c(s)$ the cost of a solution s . Its percentage gap with respect to the best solution s^* is calculated as $100 \times \frac{c(s) - c(s^*)}{c(s^*)}$.

Model 1 is the least flexible. Starting times of second-level trips are imposed and the goods to be delivered in a second-level trip are consolidated at the depot and delivered simultaneously to the city hub. Since this model is particularly restrictive, it is not rare that it fails in finding a feasible solution. When a feasible solution is found however, it is usually as good as those found with Model 2: average gaps to the best solution (reported in column av. gap to best (%)) are of the same order. Furthermore, CPU times are significantly shorter compared to those of the two other models.

In Model 2, as in Model 1, the goods to be delivered in a trip are consolidated at the depot and delivered simultaneously to the city hub. However in Model 2 the starting times of the second-level trips are not imposed. This introduces some flexibility to the distribution process, since goods can also be transferred directly from the first to the second level, if appropriate in terms of time. More feasible solutions are found with respect to Model 1, and the increment in the CPU time is significant. Surprisingly, the number of best solutions is lower compared to Model 1, but the average gap with the best solution slightly improves.

In Model 3 goods associated with the second-level trips are not consolidated, but can be delivered separately to the city hub. This allows to better exploit capacities and available resources of the first-level vehicle and the city hub. As a consequence, computing times are the longest among the different models. This model shows the highest ability in finding best solution and provides solutions that are on average better than the solution obtained when using the other 2 models.

Table 9 is similar to Table 8 except that at the first phase of the algorithm only the best solution is kept. The three models are applied with the same parameters. The average gap is calculated according to best obtained solutions of Table 8. From Table 9, we can notice that the same conclusions can be drawn as for Table 8.

Quality of the solutions

In order to assess the quality of the solutions obtained with our algorithm, we derived two lower bounds, LB1 and LB2. Both LBs are obtained by relaxing the capacity constraints at the city hub and the time dependency of the two distribution levels. Thus, LBs are obtained by

Table 9
Performance of the models with respect to the best solution.

	nb. infeasibilities	nb. best	av. gap to best (%)	av. CPU time (sec)
model 1	22	33	3.52	0.30
model 2	11	16	2.90	7.69
model 3	11	71	1.84	10.13

separately solving the first and the second level of the system without having to consider the capacity management at the hub nor synchronization aspects. LB1 and LB2 are obtained by the sum of routing delivery costs at the first (LB1₁, LB2₁) and second (LB1₂, LB2₂) level. Thus LB1 = LB1₁ + LB1₂ and LB2 = LB2₁ + LB2₂.

LB1 represents the minimal delivery costs necessary to serve all first- and second-level customers and to bring the required merchandise to the city hub. Thus, when solving the first level of the distribution to compute LB1₁, all the second-level customers are supposed to be located at the city hub and are associated with a TW that equals the horizon, namely $[E, L]$. LB1₂ is obtained by assuming that all the goods are available at the city hub at the beginning of the planning horizon.

LB2 is as LB1 but trivially takes into account the interplay between the two levels. To this end, to calculate LB2₁ we suppose all the second-level customers are located at the city hub and are associated with a TW that is equal to $[E, L_i - T_{Hi}]$. That means the TWs do not have a restrictive lower bound, while the upper bound is obtained as the difference between the original L_i and the travel time to reach the customer from the city hub. If the merchandise is not available at the city hub before $L_i - T_{Hi}$, the service of customer i will not meet the associated TW.

To calculate LB2₂ we suppose that goods are available at the city hub at T_{0H} , namely the travel time necessary to go from the depot to the city hub. This is an obvious lower bound on the availability time of merchandise at the city hub.

The problems to solve to calculate the lower bounds are again MTRVPTW, for which the algorithm developed in Cattaruzza et al. (2016a) can be used. Due to the heuristic nature of the algorithm proposed in Cattaruzza et al. (2016a), the bounds are only *heuristic*. However, the algorithm in Cattaruzza et al. (2016a) has proven to provide near-optimal solutions for instances of the size of the considered network. Thus, insights on the quality of the solutions can still be drawn.

Table 10 reports some metrics to evaluate the quality of the lower bounds and the solutions.

The Table reports the average percentage gap between the cost of the best solution and the lower bound calculated on all the networks (column cost), the average percentage gap of the number of visits of the first-level vehicle to the city-hub (nb. hub visits), the average percentage gap of the number of trips (nb. trips) of the first level (L1) and of the second level (L2), the average percentage gap to used capacity (usage) of the first-level vehicle (L1) and of the second-level vehicles (L2), and the average percentage gap to the number of used vehicles in the second level (nb. L2 vehicles).

From Table 10 we can clearly see that LB2 outperforms LB1. A lower average percentage gap of the best solutions with the lower bounds means an averagely higher value of the bounds that is, consequently, tighter. We can notice that the solutions we obtain are about 2.5% from the bounds, assessing the good quality of the solutions. However, we recall that the bounds are heuristics. We can also notice that solutions

Table 10
Average percentages of the best solutions with respect to the lower bounds LB1 and LB2.

	cost	nb. hub visits	nb. trips		usage		nb. L2 vehicles
			L1	L2	L2	L1	
LB1	2.58	-6.67	30.28	5.11	-59.78	-1.74	1.26
LB2	2.32	-9.58	28.61	6.53	-59.46	-3.08	3.71

behave the same way with respect to the lower bounds: in the first level, the vehicle performs less visits to the city hub, it performs more trips and, consequently, the capacity resource is less exploited. In the second level, more vehicles are used, more trips are performed and the capacity is less exploited.

5.3. Allowing direct transfers from first to second level vehicles

All along this paper we made the assumption that direct transfer of goods from first-to second-level vehicles is not allowed. This assumption prevents vehicles of the two fleets to wait for each other at the city hub. As a consequence, the first-level vehicle fleet does not have to wait at the city hub as long as enough free space is present to unload the merchandise. The second-level vehicles do not have to wait at the city hub as long as goods they need to carry in the next trip are available for loading operations. This modus operandi may be more robust in practical life than allowing direct transfer among vehicles that impose their simultaneous presence. However, one may be interested in analysing the solutions that are obtained if direct transfer is permitted. This is the objective of this section.

First, from a theoretical point of view, the model (1)–(50) that describes the C2E-VRPTW only requires the modification of Constraints (35), that become:

$$I_{t-1} + \sum_{w \in \Pi} \sum_{i \in \mathcal{I}_2} Q_i \times \alpha_i^{wh} - \sum_{w \in \Pi} \sum_{i \in \mathcal{I}_2} Q_i \times \delta_i^w \leq Q_{CH} \quad (t \in \mathcal{T}). \quad (68)$$

Constraints (68) impose that the stock at the city hub at period t equals the stock at the previous period plus what is brought at period t minus what is loaded into second-level vehicles, thus allowing for transfer.

The algorithm described in Section 4 is slightly modified in order to allow transfers. In particular, we modify the mathematical models involved in the second phase of the algorithm. Models 2 and 3, presented in Sections 4.4.2 and 4.4.3 respectively, allow to determine the starting time of trips involved in the second level of the distribution system. This is done by variables y_w^t . To allow transfers, Constraints (60) in Model 2 are modified as follows:

$$\sum_{\{w \in \mathcal{W} : t \leq L_w\}} \left(\sum_{t'=E+T_{0H}}^t Q_w x_w^{t'} - \sum_{t'=E+T_{0H}}^t Q_w y_w^{t'} \right) \leq Q_{CH} \quad (t \in \mathcal{T}_{1H}), \quad (69)$$

while Constraints (66) in Model 3 are modified as follows:

$$\sum_{\{i \in \mathcal{I}_2 : t \leq L_{w(i)}\}} \sum_{t'=E+T_{0H}}^t Q_i x_i^{t'} - \sum_{\{w \in \mathcal{W} : t \leq L_w\}} \sum_{t'=E+T_{0H}}^t Q_w y_w^{t'} \leq Q_{CH} \quad (t \in \mathcal{T}_{1H}). \quad (70)$$

In both cases the last sum over t' goes from $t' = E + T_{0H}$ until t and not until $t - 1$. This allows to respect the city hub capacity even if there is not enough space to store the goods at time t . Capacity constraints at the city hub are satisfied by directly transferring goods from the truck to the second-level vehicles. This is obtained by scheduling the arrival of the truck at the city hub exactly as the departure of one or several second-level vehicles from the city hub. We recall that the phase 1 of the algorithm determines a set of delivery trips each associated with a departure time window, $[E_w, L_w]$ that represents the set of all feasible departure times of trip w that minimize the trip duration. Variables y_w^t determine the exact starting time of trip w and can be one only for $t \in [E_w, L_w]$. If the solution provided by Model 2 is such that it exists t^* such that $x_w^{t^*} = y_w^{t^*} = 1$ a direct transfer is performed: the truck arrives at the city hub at t^* , goods are loaded in the second-level vehicles that immediately leave the city hub. Model 3 behaves similarly.

To evaluate the impact of the transfers in the solutions, we run again, on all the instances, the procedure described in Section 4 where the models involved in phase 2 are modified as described above. Results are reported in Tables 11 and 12. The headers of these two tables are as in

Tables 6 and 7, respectively.

Table 11 reports the average costs on all the instances when transfers are allowed. The upper part of the Table reports absolute cost values on the different levels of the distribution system for the different scenarios. The lower part of the Table reports percentage gaps with respect to the costs obtained when transfers are not allowed (i.e., values reported in Table 6). We may notice that gaps related to the second level of the distribution are close to zero. This is explained by the fact that the resolution phase that computes distribution routes for this level is not impacted by the modifications that allow transfers. The variations are due to the fact that the best overall solution may not correspond to the same second-level solution when transfers are allowed or not. However, costs associated with the first level of the distribution significantly decrease in Scenarios 1 and 2 lowering the overall operational costs. This is not the case for Scenario 3, where total costs are practically equivalent in the two cases. This may be further explained by looking at Table 12 that reports insights on the solutions with transfers. Here we can notice that the visits scheduled at the city hub are, in Scenario 1 and 2 on average lower which allows for more flexibility in the determination of the distribution planning for the first level. For Scenario 3, the average number of visits to the hub remains unchanged.

6. Conclusions

In this paper we addressed the optimization of a two-echelon distribution system with a capacitated intermediate hub. Goods are first delivered from the depot to the city hub, then from the city hub to final customers. Some customers are visited directly from the depot. The main originality of this problem comes from the storage capacity offered by the city hub, which serves as a buffer and limits the synchronization between the two delivery levels. It is an important contribution compared to the literature that either imposes a perfect synchronization between vehicles of the two levels or assumes an infinite capacity at the city hub.

To solve the problem we developed a three-phase heuristic coupling a genetic algorithm, local search and integer programming. We proposed and compared several variants of the algorithm. We also derived two lower bounds to assess the quality of solutions. An interesting feature of this heuristic is to tackle separately the first-level and second-level decisions. The advantage is to manage synchronization with much more simplicity than methods that would consider all decisions simultaneously. The price to pay is certainly a loss in solution quality, but experiments on realistic instances from the city of Vienna and comparisons to lower bounds tended to show an excellent effectiveness for the heuristic. In addition, these experiments permitted to derive some important insights on the two-echelon distribution system at hand.

Table 11
Cost overview with transfers.

variant	costs	scenario 1	scenario 2	scenario 3
variant bikes	first level cost	2 162 466.4	2 194 108.4	1 808 255.4
	second level cost	504 340.4	773 064.9	1 290 132.6
	total cost	2 666 806.8	2 967 173.3	3 098 388.0
variant e-vans	first level cost	2 177 264.5	2 151 635.9	1 812 520.0
	second level cost	634 852.0	745 109.1	999 206.1
	total cost	2 812 116.5	2 896 745.0	2811726.1
variant	gaps (%)	scenario 1	scenario 2	scenario 3
variant bikes	first level gap	-3.26	-3.12	0.06
	second level gap	-0.03	0.07	0.01
	total gap	-2.65	-2.29	0.04
variant e-vans	first level gap	-8.07	-3.10	0.20
	second level gap	-0.15	-0.11	0.01
	total gap	-6.28	-2.33	0.13

Table 12
Experimental results with transfers.

	nb. hub visits	nb. 2L vehicles	nb. trips		%usage	
			1L	2L	1L	2L
variant bikes	absolute values					
scenario 1	2.05	8.10	4.00	8.95	0.30	0.88
scenario 2	1.85	7.70	3.90	8.70	0.30	0.91
scenario 3	1.80	7.45	2.95	8.65	0.39	0.92
variant e-vans	absolute values					
scenario 1	1.95	4.85	3.85	4.90	0.31	0.54
scenario 2	1.80	3.95	3.85	3.95	0.30	0.68
scenario 3	1.80	4.15	2.95	4.15	0.40	0.65
variant bikes	gaps (%)					
scenario 1	-48.78	-1.85	-23.75	0.00	20.00	-1.14
scenario 2	-10.81	-0.65	-8.97	0.00	10.00	0.00
scenario 3	0.00	0.00	1.69	0.00	-2.56	0.00
variant e-vans	gaps (%)					
scenario 1	-74.36	3.09	-32.47	1.02	25.81	-1.85
scenario 2	-16.67	0.00	-10.39	0.00	10.00	0.00
scenario 3	0.00	0.00	0.00	0.00	0.00	0.00

As a perspective to this work, it will be interesting to extend the approach to multiple city hubs and/or to multiple vehicles at the first level. In the setting of our two-echelon distribution schemes we indeed copied the characteristics our partner distribution scheme and considered a single city hub and a single first-level vehicle. Relaxing these two assumptions might have important consequences on the solution algorithm.

With several city hubs, our decomposition technique would impose to assign second-level customers to city hubs while optimizing second-level trips (phase 1). The possible compromise between the quality of these assignments and the additional cost that more distant city hubs could add to first-level distribution would then be totally ignored. Probably, some mechanisms would be needed to give more priority to the hubs that are the less distant to the depot. Also, in phase 2, trips visiting successively several city hubs would have to be considered. More complex integer programs would be needed, with the risk that these programs become intractable if the number of hubs becomes too large (which, fortunately, is probably not the case in practice).

Generalizing to multiple first-level vehicles seems easier. The only consequence should be to make the integer programs of phase 2 more complex. The algorithm used in phase 3 is indeed already designed to manage a fleet of vehicles.

Another interesting perspective would be to compute lower bounds exactly and obtain a more accurate estimation of the heuristic. This could be possible implementing the exact solution method proposed in [Paradiso et al., 2020](#) for the MTRPTW.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

A Appendix.

A.1. Detailed results

Table 13 reports detailed results on all instances. The column "Instance" describes the name. The name of the instances is composed of

three parts: the first relates to the network index, the second to the scenario (see Table 5), the third to the type of vehicle in the second level of the delivery system (“b” for bikes, “e” for electric vans.) Column “cost” reports the total cost of the corresponding solution. Columns 3 to 6 report information about the second-level solution, that is the cost (column “cost”), the number of vehicles that are used (“nb.v”), the number of trips that are performed (“nb.t”), the capacity usage of the vehicles (“cap”). Columns 7 to 9, 10 to 12, 13 to 15 report information on the first level, respectively using Model 1 (“1L - M1”), Model 2 (“1L - M2”), Model 3 (“1L - M3”). Each sub set of columns reports the cost of the first-level

solution (“cost”), the number of trips used (“nb.t”) and the capacity usage (“cap”). Blanks indicate that a feasible solution could not be obtained.

For each instance at most five rows are reported. These rows correspond to the best five feasible solutions found by the population-based algorithm ran during phase 1 of the algorithm. Since the algorithm used for phase 1 does consider infeasible solutions with respect to TW and capacity violation, it may happen that the final population of solutions does contain less than five feasible solutions. In this case the rows reported in the Table will be as many as the feasible solutions.

Table 13
Detailed results on all instances

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
network00_1_b	143705.7	24524.7	9	10	0,92				155746.0	6	0,26	119181.0	5	0,31
	177162.4	24462.4	10	10	0,92				155746.0	6	0,26	152700.0	6	0,26
	177224.7	24524.7	10	10	0,92				152700.0	6	0,26	152700.0	6	0,26
	180270.7	24524.7	10	10	0,92				155746.0	6	0,26	156338.0	6	0,26
network00_1_e	182298.9	29598.9	5	5	0,61				155746.0	6	0,26	152700.0	6	0,26
	182324.2	29624.2	6	6	0,51				155746.0	6	0,26	152700.0	6	0,26
	182324.3	29624.3	6	6	0,51				156096.0	6	0,26	152700.0	6	0,26
	185359.2	29613.2	5	5	0,61				156709.0	6	0,26	155746.0	6	0,26
	X	29624.2	5	6	0,51									
network00_2_b	158208.3	39534.3	9	10	0,92	154455.0	5	0,31	153872.0	6	0,26	118674.0	4	0,39
	158231.3	39534.3	10	10	0,92	154095.0	5	0,31	118697.0	4	0,39	154078.0	5	0,31
	191740.3	39534.3	9	10	0,92	152206.0	5	0,31	154315.0	6	0,26	154078.0	5	0,31
	192713.3	39534.3	9	10	0,92	153179.0	6	0,26						
	193034.3	39534.3	9	10	0,92	153500.0	4	0,39						
network00_2_e	153393.7	34719.7	4	4	0,77	153326.0	5	0,31	118674.0	4	0,39	153537.0	5	0,31
	153393.8	34719.8	4	4	0,77	154937.0	5	0,31	118674.0	4	0,39	154095.0	5	0,31
	186902.8	34719.8	4	4	0,77				152183.0	5	0,31	152464.0	5	0,31
	187345.7	34719.7	4	4	0,77	152626.0	5	0,31	153313.0	5	0,31	152841.0	5	0,31
network00_3_b	170875.2	71230.0	9	10	0,92	136330.0	4	0,39				99645.2	3	0,52
	170875.3	71230.1	9	10	0,92	129186.0	4	0,39	128163.0	4	0,39	99645.2	3	0,52
	199214.2	71230.2	9	10	0,92	127984.0	4	0,39	128001.0	4	0,39			
	X	71229.9	9	10	0,92									
network00_3_e	150336.2	49465.2	4	4	0,77	127975.0	4	0,39	101507.0	3	0,52	100871.0	3	0,52
	150897.5	49390.5	4	4	0,77	108977.0	3	0,52	101507.0	3	0,52	101507.0	3	0,52
	150898.5	49390.5	4	4	0,77	127975.0	4	0,39	101508.0	3	0,52	101508.0	3	0,52
	153106.2	48937.2	4	4	0,77	104169.0	4	0,39	128001.0	4	0,39	127975.0	4	0,39
	158859.5	49390.5	4	4	0,77	109469.0	3	0,52	128001.0	4	0,39	128001.0	4	0,39
network01_1_b	137379.8	24850.8	8	8	0,91	112529.0	6	0,24	146756.0	7	0,21	146729.0	7	0,21
	137382.4	24853.4	8	8	0,91	112529.0	5	0,29	146729.0	6	0,24	146884.0	6	0,24
	143611.5	24853.5	6	8	0,91				118758.0	6	0,24	146887.0	6	0,24
	171578.7	24850.7	8	8	0,91	146756.0	7	0,21	146729.0	6	0,24	146728.0	6	0,24
	X	24853.6	6	8	0,91									
network01_1_e	176752.6	29996.6	4	4	0,61	148792.0	7	0,21	146756.0	7	0,21	146756.0	7	0,21
	177247.6	30491.6	4	4	0,61	146756.0	7	0,21	146756.0	7	0,21	146756.0	7	0,21
	177264.7	30508.7	4	4	0,61	148792.0	7	0,21	146887.0	7	0,21	146756.0	7	0,21
	177346.5	30590.5	4	4	0,61	146756.0	7	0,21	146756.0	7	0,21	146756.0	7	0,21
	177509.4	30781.4	5	5	0,49	148813.0	7	0,21	146756.0	7	0,21	146728.0	6	0,24
network01_2_b	149789.5	35885.5	8	8	0,91	113904.0	5	0,29	115935.0	4	0,36	146539.0	6	0,24
	149972.8	35966.8	7	8	0,91	114006.0	4	0,36	115954.0	5	0,29	115954.0	5	0,29
	151029.4	35885.4	7	8	0,91	115144.0	4	0,36	115957.0	4	0,36	115954.0	4	0,36
	151886.7	35932.7	6	8	0,91	115954.0	4	0,36	117419.0	4	0,36	115957.0	4	0,36
	186916.2	35877.2	5	8	0,91	151039.0	6	0,24						
network01_2_e	149808.3	35723.3	4	4	0,61	114085.0	4	0,36	146539.0	6	0,24	146539.0	6	0,24
	150843.6	35699.6	4	4	0,61	146539.0	6	0,24	115144.0	4	0,36	146539.0	6	0,24
	151677.3	35723.3	4	4	0,61	115954.0	5	0,29	146539.0	6	0,24	146539.0	6	0,24
	182238.6	35699.6	4	4	0,61	146539.0	6	0,24	146539.0	6	0,24	146539.0	6	0,24
	182262.4	35723.4	4	4	0,61	146668.0	5	0,29	146539.0	6	0,24	146539.0	6	0,24
network01_3_b	156498.8	60115.1	7	8	0,91	96383.7	3	0,47						
	157149.9	60115.1	7	8	0,91	97034.8	4	0,36	122474.0	5	0,29	121823.0	3	0,47
	158980.7	60115.0	6	8	0,91	98865.7	4	0,36						
	X	60115.7	6	8	0,91									
network01_3_e	143047.2	46663.5	4	4	0,61	96383.7	3	0,47				121823.0	3	0,47

(continued on next page)

Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	143559.3	47175.6	4	4	0,61	121822.0	4	0,36	96383.7	3	0,47	97034.8	3	0,47
	143719.2	47335.5	4	4	0,61	123026.0	4	0,36	96383.7	3	0,47	97034.8	3	0,47
	143798.8	47415.1	4	4	0,61	123573.0	4	0,36	96383.7	3	0,47	96383.7	3	0,47
	144072.0	47425.0	4	4	0,61	122831.0	4	0,36				96647.0	3	0,47
network02_1_b	135665.6	23444.6	8	8	0,87	117117.0	4	0,37	112221.0	5	0,3	115011.0	5	0,3
	136945.6	23444.6	6	8	0,87	117451.0	3	0,49	113731.0	5	0,3	113501.0	5	0,3
	138034.6	23444.6	7	8	0,87	115384.0	5	0,3	115036.0	5	0,3	114590.0	5	0,3
	138455.7	23444.7	7	8	0,87	119637.0	3	0,49	115083.0	5	0,3	115011.0	5	0,3
network02_1_e	143132.8	28121.8	4	4	0,58	115011.0	5	0,3	115011.0	5	0,3	115011.0	5	0,3
	143840.4	28829.4	5	5	0,46	115011.0	5	0,3	115011.0	5	0,3	115011.0	5	0,3
	144134.4	29123.4	5	5	0,46	115011.0	5	0,3	115011.0	5	0,3	115011.0	5	0,3
	144153.6	29142.6	4	4	0,58	115011.0	5	0,3	115011.0	5	0,3	115011.0	5	0,3
network02_2_b	146775.5	34396.5	6	8	0,87	113456.0	4	0,37	113456.0	4	0,37	112379.0	5	0,3
	147467.1	34011.1	6	7	0,99	113456.0	4	0,37						
	147887.5	34396.5	5	8	0,87	113491.0	4	0,37						
network02_2_e	145041.8	32662.8	3	3	0,77	112379.0	5	0,3	112379.0	5	0,3	112379.0	5	0,3
	145726.2	33347.2	4	4	0,58	112379.0	5	0,3	112379.0	5	0,3	112379.0	5	0,3
network02_3_b	157022.8	58789.0	6	8	0,87	124272.0	4	0,37	123898.0	4	0,37	98233.8	3	0,49
	157022.9	58789.1	6	8	0,87	125213.0	4	0,37	98233.8	4	0,37	98233.8	3	0,49
	182687.0	58789.0	5	8	0,87	123898.0	4	0,37						
	X	58789.0	5	8	0,87									
network02_3_e	139319.6	41085.8	3	3	0,77	98233.8	3	0,49	98233.8	3	0,49			
	139368.2	41134.4	3	3	0,77	101281.0	4	0,37	98233.8	3	0,49	98233.8	3	0,49
	139394.7	41160.9	3	3	0,77	98233.8	3	0,49	98233.8	3	0,49	98233.8	3	0,49
	139612.0	41378.2	3	3	0,77	98233.8	3	0,49	98233.8	3	0,49	98233.8	3	0,49
	140273.4	42039.6	3	3	0,77	98233.8	3	0,49	98233.8	3	0,49	98233.8	3	0,49
network03_1_b	141790.0	25274.0	8	8	0,95	116516.0	5	0,25	117151.0	4	0,31			
	142143.2	25274.2	8	8	0,95	117288.0	5	0,25	116869.0	5	0,25	116869.0	5	0,25
network03_1_e	147974.3	31105.3	5	5	0,51	116869.0	5	0,25	117151.0	4	0,31	116869.0	5	0,25
	147974.4	31105.4	5	5	0,51				116869.0	5	0,25	117151.0	4	0,31
	148092.1	31223.1	6	6	0,43	117402.0	5	0,25	116869.0	5	0,25	116869.0	5	0,25
	148374.2	31223.2	6	6	0,43	117402.0	5	0,25	117927.0	5	0,25	117151.0	5	0,25
network03_2_b	150340.0	35228.0	8	8	0,95	116734.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150400.1	35288.1	8	8	0,95	116647.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150411.1	35299.1	8	8	0,95	116958.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150415.7	35303.7	8	8	0,95	116907.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	151874.9	35227.9	8	8	0,95	116647.0	4	0,31	116647.0	4	0,31	116659.0	4	0,31
network03_2_e	150181.7	35069.7	4	4	0,64	115112.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150181.8	35069.8	4	4	0,64	115112.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150396.7	35284.7	4	4	0,64	115112.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
	150588.0	35476.0	4	4	0,64	115112.0	4	0,31	115112.0	4	0,31	116906.0	4	0,31
	150588.1	35476.1	4	4	0,64	115112.0	4	0,31	115112.0	4	0,31	115112.0	4	0,31
network03_3_b	158453.0	60122.9	8	8	0,95	105582.0	3	0,42	101004.0	4	0,31	98330.1	3	0,42
	158552.3	60222.2	7	8	0,95	105582.0	3	0,42	100164.0	3	0,42	98330.1	3	0,42
	158582.5	60252.4	7	8	0,95	98330.1	3	0,42						
	160286.8	60122.8	7	8	0,95	133920.0	4	0,31	100164.0	3	0,42	101004.0	4	0,31
	160416.4	60252.4	6	8	0,95	100164.0	3	0,42						
network03_3_e	144678.4	46348.3	4	4	0,64	105619.0	3	0,42	98330.1	3	0,42	101004.0	4	0,31
	144734.4	46348.3	4	4	0,64	129305.0	5	0,25	105619.0	3	0,42	98386.1	3	0,42
network04_1_b	140056.3	24609.3	8	9	0,91	116878.0	5	0,22	116451.0	5	0,22	115447.0	5	0,22
	140056.4	24609.4	8	9	0,91	118532.0	4	0,28	116451.0	5	0,22	115447.0	5	0,22
	141015.3	24609.3	8	9	0,91	118715.0	4	0,28	116606.0	4	0,28	116406.0	3	0,37
	141060.3	24609.3	8	9	0,91	120754.0	4	0,28	117006.0	4	0,28	116451.0	5	0,22
network04_1_e	145814.3	29363.3	4	4	0,68				117174.0	5	0,22	116451.0	5	0,22
	145975.7	29524.7	5	5	0,55				117174.0	5	0,22	116451.0	5	0,22
	145975.8	29524.8	5	5	0,55				117174.0	5	0,22	116451.0	5	0,22
network04_2_b	154201.9	39000.9	7	9	0,91	116796.0	5	0,22	116398.0	4	0,28	115201.0	4	0,28
	155429.9	39000.9	7	9	0,91	116429.0	5	0,22						
	155958.9	39000.9	7	9	0,91	116958.0	5	0,22						
	156948.5	38941.5	8	9	0,91	118007.0	4	0,28						
	160309.9	39000.9	7	9	0,91	121309.0	4	0,28						
network04_2_e	148750.4	33549.4	4	4	0,68	116398.0	4	0,28	116398.0	4	0,28	115201.0	4	0,28
network04_3_b	162968.6	66060.4	9	9	0,91	97129.8	3	0,37	97129.8	3	0,37	96908.2	3	0,37
	162968.7	66060.5	8	9	0,91	97129.8	3	0,37	97129.8	3	0,37	96908.2	3	0,37
	163190.2	66060.4	8	9	0,91	97129.8	3	0,37	97129.8	3	0,37	101543.0	3	0,37

(continued on next page)

Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	163828.0	66060.5	8	9	0,91	99362.6	3	0,37	98580.6	3	0,37	97767.5	3	0,37
network04_3_e	142752.4	45622.6	4	4	0,68	97767.5	3	0,37	97129.8	3	0,37	97129.8	3	0,37
	144798.4	46217.8	4	4	0,68	98580.6	3	0,37	123172.0	4	0,28	98580.6	3	0,37
	145330.1	48200.3	4	4	0,68	97129.8	3	0,37	97767.5	3	0,37	97767.5	3	0,37
	147531.6	50401.8	5	5	0,55	98580.6	3	0,37	97129.8	3	0,37	98580.6	3	0,37
	148751.1	50983.6	5	5	0,55	99324.9	3	0,37	97767.5	3	0,37	97767.5	3	0,37
network05_1_b	133538.1	22843.1	9	9	0,86	110747.0	5	0,29	110695.0	5	0,29	116073.0	5	0,29
	136286.2	22843.2	8	9	0,86	123008.0	4	0,37	113443.0	5	0,29	113491.0	5	0,29
	138080.2	22843.2	7	9	0,86				154128.0	6	0,25	115237.0	4	0,37
	138916.2	22843.2	8	9	0,86	117868.0	5	0,29	116073.0	5	0,29	116073.0	5	0,29
	140711.3	22843.3	7	9	0,86				120036.0	3	0,49	117868.0	3	0,49
network05_1_e	139657.9	28910.9	4	4	0,64	110747.0	5	0,29	113118.0	5	0,29	113118.0	5	0,29
	139658.9	28910.9	4	4	0,64				110748.0	5	0,29	113443.0	5	0,29
	140328.9	28910.9	4	4	0,64	111418.0	5	0,29	113118.0	5	0,29	150108.0	5	0,29
	144984.0	28911.0	4	4	0,64				116073.0	5	0,29	116073.0	5	0,29
network05_2_b	153607.9	38907.9	7	8	0,96	115391.0	4	0,37	115551.0	4	0,37	114700.0	4	0,37
	153735.5	39035.5	8	8	0,96	114700.0	4	0,37	114700.0	4	0,37	114700.0	3	0,49
	154299.4	38908.4	8	8	0,96	115391.0	4	0,37	146927.0	5	0,29	115789.0	4	0,37
	154612.3	38923.3	7	8	0,96	115689.0	4	0,37						
	185501.1	38972.1	6	8	0,96	146529.0	6	0,25						
network05_2_e	149867.8	35327.8	3	3	0,86	114540.0	4	0,37	114700.0	3	0,49	114700.0	4	0,37
	149936.9	35236.9	3	3	0,86	116661.0	4	0,37	114700.0	4	0,37	114700.0	4	0,37
	149937.0	35237.0	3	3	0,86	114993.0	4	0,37	114700.0	4	0,37	115153.0	4	0,37
	149980.6	35280.6	3	3	0,86	115173.0	4	0,37	114700.0	4	0,37	114700.0	4	0,37
	150119.0	35126.0	3	3	0,86	114993.0	4	0,37	146927.0	5	0,29	115689.0	3	0,49
network05_3_b	159572.6	62583.4	7	8	0,96	96989.2	3	0,49	96989.2	3	0,49	96989.2	3	0,49
	159721.3	62732.1	7	8	0,96	96989.2	3	0,49	122428.0	4	0,37	96989.2	3	0,49
	160043.3	63054.1	7	8	0,96	96989.2	3	0,49						
	161942.4	64953.2	9	9	0,86	96989.2	3	0,49	96989.2	3	0,49	96989.2	3	0,49
	167706.1	64953.1	7	9	0,86	102753.0	3	0,49						
network05_3_e	145481.3	48492.1	4	4	0,64	102685.0	3	0,49	96989.2	3	0,49	96989.2	3	0,49
	145481.4	48492.2	4	4	0,64	96989.2	3	0,49	96989.2	3	0,49	96989.2	3	0,49
network06_1_b	137746.6	24045.6	8	8	0,87	113701.0	4	0,41	115946.0	5	0,33	115946.0	5	0,33
	138725.6	24045.6	7	8	0,87	114680.0	3	0,54	146800.0	6	0,27	115946.0	5	0,33
	139991.6	24045.6	7	8	0,87	115946.0	4	0,41	123522.0	5	0,33	115946.0	5	0,33
	140068.7	24045.7	7	8	0,87	116355.0	4	0,41	152658.0	6	0,27	116023.0	5	0,33
network06_1_e	144488.5	30071.5	5	5	0,47	114417.0	5	0,33	115946.0	5	0,33	115946.0	5	0,33
	144488.6	30071.6	5	5	0,47	114417.0	4	0,41	116516.0	4	0,41	115946.0	5	0,33
	145136.6	30071.6	5	5	0,47	115065.0	5	0,33	123027.0	4	0,41	115946.0	5	0,33
	145474.7	30071.7	5	5	0,47	115403.0	4	0,41	115946.0	5	0,33	115946.0	5	0,33
	146776.6	30071.6	5	5	0,47	117052.0	4	0,41	148058.0	5	0,33	116705.0	5	0,33
network06_2_b	148340.9	35761.9	6	7	1	149028.0	5	0,33	147864.0	5	0,33	112579.0	5	0,33
	148383.1	35804.1	8	8	0,87	114281.0	4	0,41	112579.0	5	0,33	112579.0	5	0,33
	148428.2	35804.2	8	8	0,87	112624.0	5	0,33	114281.0	4	0,41	112624.0	5	0,33
	149788.2	35804.2	8	8	0,87				114281.0	4	0,41	113984.0	5	0,33
network06_2_e	147467.8	34888.8	4	4	0,58	113193.0	5	0,33	112579.0	5	0,33	112579.0	5	0,33
	147467.9	34888.9	4	4	0,58	114281.0	4	0,41	112579.0	5	0,33	114281.0	4	0,41
network06_3_b	157137.7	58463.1	8	8	0,87	99341.2	3	0,54	98674.6	3	0,54	99143.1	3	0,54
	157876.5	58463.1	7	8	0,87	128859.0	4	0,41				99413.4	3	0,54
	163121.4	64675.1	8	9	0,78	98446.3	3	0,54	98446.3	3	0,54	99169.1	3	0,54
	163786.1	64643.0	8	9	0,78	106963.0	3	0,54	124339.0	4	0,41	99143.1	3	0,54
network06_3_e	146273.0	47129.9	4	4	0,58	134365.0	5	0,33	99143.1	3	0,54	99143.1	3	0,54
	146915.8	48241.2	4	4	0,58	99143.1	3	0,54	99341.2	3	0,54	98674.6	3	0,54
	148257.5	49114.4	4	4	0,58	99143.1	3	0,54	99143.1	3	0,54	99143.1	3	0,54
	149132.8	49989.7	4	4	0,58	99341.2	3	0,54	99143.1	3	0,54	99143.1	3	0,54
	149886.6	50743.5	5	5	0,47	99143.1	3	0,54	99143.1	3	0,54	99143.1	3	0,54
network07_1_b	139762.6	23638.6	8	8	0,79				119340.0	5	0,29	116124.0	5	0,29
	139762.7	23638.7	8	8	0,79				119340.0	5	0,29	116124.0	5	0,29
network07_1_e	140480.5	28510.5	4	4	0,53	111970.0	5	0,29	116163.0	5	0,29	116124.0	5	0,29
	140728.5	28757.5	4	4	0,53	111971.0	5	0,29	116124.0	5	0,29	116124.0	5	0,29
	140754.6	28757.6	4	4	0,53	111997.0	5	0,29	116163.0	5	0,29	119860.0	5	0,29
	140960.2	28963.2	4	4	0,53	111997.0	5	0,29	116163.0	5	0,29	116124.0	5	0,29
	141374.2	28963.2	4	4	0,53	112411.0	5	0,29	116124.0	5	0,29	116163.0	5	0,29
network07_2_b	144419.6	34216.6	7	7	0,91	110203.0	5	0,29	113881.0	4	0,36	113881.0	4	0,36
	144481.0	34278.0	7	7	0,91	113881.0	4	0,36	110203.0	5	0,29	112366.0	5	0,29

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Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	146582.6	34216.6	6	7	0,91	113881.0	4	0,36	113881.0	4	0,36	112366.0	5	0,29
	146651.6	34285.6	7	7	0,91				112366.0	5	0,29	113881.0	4	0,36
network07_2_e	143453.2	33250.2	3	3	0,71	112366.0	5	0,29	110203.0	5	0,29	112366.0	5	0,29
	143478.2	33275.2	3	3	0,71	110203.0	5	0,29	112366.0	5	0,29	113881.0	4	0,36
	143680.6	33477.6	3	3	0,71	110243.0	5	0,29	110203.0	5	0,29	112366.0	5	0,29
	144537.6	34334.6	4	4	0,53	113881.0	4	0,36	110203.0	5	0,29	110203.0	5	0,29
network07_3_b	149629.1	53533.6	6	7	0,91	96361.0	3	0,48	98701.8	3	0,48	96095.5	3	0,48
	149629.2	53533.7	6	7	0,91	96361.0	3	0,48	96361.0	3	0,48	96095.5	3	0,48
network07_3_e	139999.7	43904.2	3	3	0,71	96095.5	3	0,48	96095.5	3	0,48	96095.5	3	0,48
	140288.4	44192.9	3	3	0,71	96095.5	3	0,48	98475.9	3	0,48	96095.5	3	0,48
	141211.3	45115.8	4	4	0,53	98475.9	3	0,48	96095.5	3	0,48	100415.0	3	0,48
network08_1_b	178356.0	26167.0	8	10	0,86				153801.0	6	0,3	152189.0	6	0,3
	182620.9	26166.9	9	10	0,86	156454.0	6	0,3						
	182728.0	26167.0	8	10	0,86	156561.0	5	0,36						
	X	26167.0	7	10	0,86									
network08_1_e	187275.7	33027.7	4	4	0,72				154248.0	6	0,3	154248.0	6	0,3
	187405.1	33157.1	4	4	0,72				155511.0	6	0,3	154248.0	6	0,3
	187592.5	33344.5	4	4	0,72				155511.0	6	0,3	154248.0	6	0,3
	187763.9	33515.9	4	4	0,72				154248.0	6	0,3	154248.0	6	0,3
	187941.5	33693.5	5	5	0,58				154248.0	6	0,3	154248.0	6	0,3
network08_2_b	189471.1	39084.1	9	9	0,96	152612.0	5	0,36	150387.0	5	0,36	151031.0	5	0,36
	190115.1	39084.1	8	9	0,96	153029.0	5	0,36	151123.0	5	0,36	151031.0	5	0,36
	190115.2	39084.2	8	9	0,96	153870.0	5	0,36	151031.0	5	0,36	151162.0	5	0,36
	190207.2	39084.2	8	9	0,96	153095.0	5	0,36	151134.0	5	0,36	151123.0	5	0,36
	193004.1	39084.1	8	9	0,96	153920.0	5	0,36						
network08_2_e	188288.9	37257.9	4	4	0,72				151123.0	5	0,36	151031.0	5	0,36
	188289.0	37258.0	4	4	0,72	152527.0	5	0,36	151134.0	5	0,36	151031.0	5	0,36
	188456.1	37425.1	4	4	0,72	151849.0	5	0,36	151031.0	5	0,36	151134.0	5	0,36
	188534.5	37372.5	4	4	0,72				151162.0	5	0,36	151162.0	5	0,36
	188611.6	37449.6	4	4	0,72				151162.0	6	0,3	151775.0	5	0,36
network08_3_b	191429.5	66015.5	7	9	0,96	127038.0	4	0,44	125517.0	4	0,44	125414.0	4	0,44
	191466.4	66015.4	7	9	0,96	125451.0	4	0,44						
	191703.4	66015.4	6	9	0,96	125688.0	4	0,44						
	196305.4	66015.4	5	9	0,96	130290.0	6	0,3						
	198137.4	66015.4	5	9	0,96	132122.0	4	0,44						
network08_3_e	173872.8	48421.8	4	4	0,72	125545.0	4	0,44	125517.0	4	0,44	125451.0	4	0,44
	173971.7	48556.7	4	4	0,72	125451.0	4	0,44	125415.0	4	0,44	125415.0	4	0,44
	173994.9	48579.9	4	4	0,72	125415.0	4	0,44	125502.0	4	0,44	125451.0	4	0,44
	174028.5	48613.5	4	4	0,72	125415.0	4	0,44	125545.0	4	0,44	125545.0	4	0,44
network090_1_b	133250.3	23196.3	8	8	0,88	110054.0	5	0,2	110495.0	5	0,2	110495.0	5	0,2
	133691.3	23196.3	8	8	0,88	110495.0	5	0,2	110495.0	5	0,2	110495.0	5	0,2
	133691.4	23196.4	8	8	0,88	110495.0	5	0,2	110495.0	5	0,2	110495.0	5	0,2
network090_1_e	141036.6	30541.6	5	5	0,47				110495.0	5	0,2	110495.0	5	0,2
	141036.7	30541.7	5	5	0,47				113711.0	5	0,2	110495.0	5	0,2
	141061.9	30566.9	6	6	0,39				110495.0	5	0,2	110495.0	5	0,2
	143996.6	30541.6	5	5	0,47				113711.0	5	0,2	113455.0	5	0,2
network090_2_b	147470.8	36015.8	7	8	0,88	111455.0	4	0,24						
	147649.6	36015.6	7	8	0,88	111634.0	4	0,24						
	147649.8	36015.8	7	8	0,88	111634.0	4	0,24						
network090_2_e	110560.3	36061.8	4	4	0,59	74498.5	4	0,24	74498.5	4	0,24	74498.5	4	0,24
	110579.6	36081.1	4	4	0,59	74498.5	4	0,24	74498.5	4	0,24	74498.5	4	0,24
network090_3_b	122143.7	59131.6	8	8	0,88	63012.1	2	0,48	63012.1	2	0,48	63012.1	2	0,48
	147808.4	59131.7	7	8	0,88	88676.7	3	0,32						
	X	59131.6	7	8	0,88									
network090_3_e	107816.3	44804.2	3	3	0,78	63027.3	3	0,32	63012.1	2	0,48	63012.1	2	0,48
	107870.4	44858.3	3	3	0,78	63012.1	2	0,48	63027.3	3	0,32	63012.1	2	0,48
	107870.5	44858.4	3	3	0,78	63012.1	2	0,48	63012.1	2	0,48	63012.1	2	0,48
	108620.0	45607.9	3	3	0,78	63027.3	3	0,32	63012.1	2	0,48	63012.1	2	0,48
	110310.7	47298.6	4	4	0,59	63012.1	2	0,48	63012.1	2	0,48	63012.1	2	0,48
network091_1_b	135408.0	26109.0	8	9	0,92				114097.0	5	0,16	109299.0	5	0,16
	135408.1	26109.1	7	9	0,92				114097.0	5	0,16	109299.0	5	0,16
	135464.0	26109.0	7	9	0,92				114097.0	5	0,16	109355.0	5	0,16
	138256.1	26109.1	8	9	0,92				114097.0	5	0,16	112147.0	5	0,16
network091_1_e	141484.2	32185.2	4	5	0,56				114097.0	5	0,16	109299.0	5	0,16
	141521.7	32222.7	5	6	0,46				115064.0	5	0,16	109299.0	5	0,16

(continued on next page)

Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	141565.5	32210.5	5	6	0,46				114097.0	5	0,16	109355.0	5	0,16
	146319.7	32222.7	5	5	0,56				114097.0	5	0,16	114097.0	5	0,16
X		32222.7	4	6	0,46									
network091_2_b	153534.3	41596.3	9	9	0,92	112246.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
	153534.4	41596.4	9	9	0,92	112246.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
	153547.3	41609.3	8	9	0,92	111938.0	5	0,16	111938.0	4	0,2	111938.0	4	0,2
	153547.5	41609.5	7	9	0,92	112588.0	5	0,16	111938.0	5	0,16	111938.0	4	0,2
network091_2_e	150454.4	38516.4	4	4	0,69	111938.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
	150461.9	38523.9	4	4	0,69	111938.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
	150462.0	38524.0	4	4	0,69	111938.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
	150493.9	38555.9	4	4	0,69	112246.0	4	0,2	111938.0	4	0,2	111938.0	4	0,2
network091_3_b	128210.6	65747.5	8	9	0,92	93084.4	3	0,26	87901.8	3	0,26	62463.1	2	0,39
	153649.3	65747.5	9	9	0,92	88995.6	4	0,2	87901.8	3	0,26	87901.8	3	0,26
network091_3_e	112982.8	50519.7	4	4	0,69	62463.1	2	0,39	68659.7	2	0,39	69753.5	3	0,26
	113300.9	50837.8	4	4	0,69	62463.1	2	0,39	68659.7	2	0,39	68659.7	2	0,39
	114394.7	50837.8	4	4	0,69	63556.9	3	0,26	87901.8	3	0,26	87901.8	3	0,26
	119555.2	50895.5	4	4	0,69				68659.7	2	0,39	68659.7	2	0,39
	138785.0	50883.2	4	4	0,69	87901.8	3	0,26	88995.6	4	0,2			
network092_1_b	104168.4	26691.2	7	9	0,94	114441.0	5	0,16	114441.0	5	0,16	77477.2	4	0,2
	136425.7	26574.7	7	9	0,94	117067.0	4	0,2	114891.0	5	0,16	109851.0	5	0,16
	138765.2	26691.2	7	9	0,94	114220.0	5	0,16	114199.0	5	0,16	112074.0	4	0,2
	140076.6	26672.6	7	9	0,94	114917.0	5	0,16	114441.0	5	0,16	113404.0	5	0,16
	140890.2	26691.2	6	9	0,94	114199.0	5	0,16	114441.0	5	0,16	114441.0	3	0,26
network092_1_e	150718.7	34239.7	5	5	0,57				116638.0	5	0,16	116479.0	5	0,16
	150730.5	34251.5	5	5	0,57				116638.0	5	0,16	116479.0	5	0,16
	150730.6	34251.6	5	5	0,57				116638.0	5	0,16	116479.0	5	0,16
network092_2_b	149955.5	39413.5	9	9	0,94	110542.0	4	0,2	113861.0	4	0,2	113152.0	4	0,2
	152071.5	39413.5	8	9	0,94	112658.0	4	0,2	114055.0	4	0,2	113152.0	4	0,2
	154410.5	39413.5	7	9	0,94	114997.0	5	0,16						
	154558.5	39413.5	7	9	0,94	115145.0	4	0,2						
network092_2_e	149839.5	39296.5	4	4	0,71	111611.0	4	0,2	113861.0	4	0,2	110543.0	4	0,2
	149840.8	39297.8	4	4	0,71	111611.0	4	0,2				110543.0	4	0,2
	150434.0	39207.0	4	4	0,71	111611.0	4	0,2	111227.0	4	0,2	113861.0	4	0,2
	150524.8	39297.8	4	4	0,71	111611.0	4	0,2	111227.0	4	0,2	113672.0	4	0,2
network092_3_b	131338.3	66626.6	7	9	0,94	95590.1	3	0,26	91020.1	3	0,26	64711.7	2	0,39
	157466.8	66460.3	8	9	0,94	96630.1	3	0,26	91006.5	4	0,2	91006.5	4	0,2
	157633.1	66626.6	7	9	0,94	95590.1	3	0,26	91006.5	4	0,2	91006.5	4	0,2
	157656.9	66650.4	7	9	0,94	95590.1	3	0,26	91020.1	3	0,26	91006.5	4	0,2
network092_3_e	114404.4	49692.7	4	4	0,71	95590.1	3	0,26	91020.1	3	0,26	64711.7	2	0,39
	114420.6	49708.9	4	4	0,71	69996.3	2	0,39	91006.5	4	0,2	64711.7	2	0,39
	140715.4	49708.9	4	4	0,71	96221.8	3	0,26	91020.1	3	0,26	91006.5	4	0,2
	140911.2	49786.9	4	4	0,71	96630.1	3	0,26	91124.3	3	0,26	91331.9	4	0,2
	141118.8	49786.9	4	4	0,71	96630.1	3	0,26	91331.9	4	0,2			
network093_1_b	137418.7	27626.7	10	11	0,83				116357.0	5	0,2	109792.0	5	0,2
	137563.6	27771.6	10	11	0,83				116357.0	5	0,2	109792.0	5	0,2
	139122.3	27584.3	10	11	0,83				114719.0	5	0,2	111538.0	5	0,2
	142345.8	27626.8	10	11	0,83				114719.0	5	0,2	116357.0	5	0,2
X		27691.4	10	11	0,83									
network093_1_e	149278.0	34688.0	5	5	0,61	114719.0	5	0,2	114590.0	5	0,2	114719.0	5	0,2
	149671.1	35081.1	6	6	0,51	114590.0	5	0,2	116357.0	5	0,2	114719.0	5	0,2
	149774.9	35055.9	5	5	0,61				114842.0	5	0,2	114719.0	5	0,2
	184627.9	34687.9	5	5	0,61				149940.0	6	0,16	149940.0	6	0,16
X		35081.2	5	6	0,51									
network093_2_b	153413.3	42732.3	10	10	0,92	110681.0	4	0,24	111042.0	4	0,24	111042.0	4	0,24
	153774.3	42732.3	9	10	0,92	111195.0	4	0,24	111195.0	4	0,24	111042.0	4	0,24
	153774.4	42732.4	9	10	0,92	111195.0	4	0,24	111195.0	4	0,24	111042.0	4	0,24
	153927.3	42732.3	9	10	0,92	111195.0	4	0,24	111195.0	4	0,24	111195.0	4	0,24
	155279.5	44237.5	10	10	0,92	111042.0	4	0,24	111195.0	4	0,24	111042.0	4	0,24
network093_2_e	151971.0	42826.0	4	4	0,77	109145.0	5	0,2	111042.0	4	0,24	111042.0	4	0,24
	152006.5	42861.5	4	4	0,77	109145.0	5	0,2				111042.0	4	0,24
	153283.5	42241.5	4	4	0,77				111042.0	4	0,24	111042.0	4	0,24
	153714.6	42672.6	4	4	0,77	111042.0	4	0,24	111042.0	4	0,24	111042.0	4	0,24
	153940.4	42898.4	4	4	0,77				111195.0	4	0,24	111042.0	4	0,24
network093_3_b	161984.7	74554.5	8	10	0,92	87430.2	3	0,32						
	161993.4	74563.2	7	10	0,92	87430.2	3	0,32						
	161993.5	74563.3	7	10	0,92	87430.2	3	0,32						

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Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	162125.9	74554.5	8	10	0,92	87571.4	3	0,32						
network093_3_e	151682.7	64252.5	6	6	0,51	87430.2	3	0,32	87430.2	3	0,32	87430.2	3	0,32
	151720.4	64290.2	6	6	0,51	87430.2	3	0,32	87430.2	3	0,32	87430.2	3	0,32
	151998.7	64568.5	6	6	0,51	87430.2	3	0,32	87430.2	3	0,32	87430.2	3	0,32
	158581.4	71151.2	7	7	0,44	88486.7	3	0,32	87430.2	3	0,32	87430.2	3	0,32
	159444.1	72013.9	7	7	0,44	87430.2	3	0,32	87571.4	3	0,32	87430.2	3	0,32
network094_1_b	134600.5	24687.5	8	9	0,89				112579.0	5	0,23	109913.0	5	0,23
	134608.6	24695.6	9	9	0,89				112579.0	5	0,23	109913.0	5	0,23
	134617.2	24704.2	9	9	0,89	113916.0	5	0,23	111301.0	5	0,23	109913.0	5	0,23
	136005.3	24704.3	9	9	0,89	113682.0	4	0,28	111301.0	5	0,23	112579.0	5	0,23
	137266.5	24687.5	9	9	0,89	115574.0	5	0,23	112579.0	5	0,23	112579.0	5	0,23
network094_1_e	140276.5	32264.5	5	5	0,54				108012.0	5	0,23	115194.0	5	0,23
	142188.9	32275.9	5	5	0,54				112579.0	5	0,23	109913.0	5	0,23
	142313.3	32400.3	5	5	0,54	109931.0	5	0,23	112579.0	5	0,23	109913.0	5	0,23
	144259.0	32087.0	5	5	0,54				113666.0	5	0,23	112172.0	5	0,23
	144436.5	32264.5	5	5	0,54				112579.0	5	0,23	112172.0	5	0,23
network094_2_b	146986.1	35784.1	8	9	0,89	111202.0	4	0,28						
	147468.3	35730.3	7	9	0,89	113192.0	5	0,23	112295.0	4	0,28	111738.0	4	0,28
	147723.4	35730.4	8	9	0,89	112290.0	4	0,28	111993.0	4	0,28	112295.0	4	0,28
	148026.9	35731.9	8	9	0,89	114370.0	4	0,28	112354.0	4	0,28	112295.0	4	0,28
network094_2_e	142059.1	34074.1	3	3	0,89	107985.0	5	0,23	110650.0	5	0,23	110650.0	5	0,23
	142110.0	34125.0	3	3	0,89	107985.0	5	0,23	110650.0	5	0,23	111993.0	5	0,23
	142170.0	34185.0	3	3	0,89	107985.0	5	0,23	110650.0	5	0,23	111993.0	5	0,23
	142184.6	34199.6	3	3	0,89	107985.0	5	0,23	110650.0	5	0,23	111993.0	5	0,23
	142256.1	34271.1	3	3	0,89	107985.0	5	0,23	110650.0	5	0,23	111993.0	5	0,23
network094_3_b	159269.0	66148.1	8	9	0,89	93120.9	3	0,37	93733.5	3	0,37	93733.5	3	0,37
	159284.2	66148.1	8	9	0,89	93136.1	4	0,28	93733.5	3	0,37	93136.1	4	0,28
	160497.8	66148.1	7	9	0,89	94349.7	3	0,37						
	160781.8	66148.1	8	9	0,89	96626.4	3	0,37				94633.7	3	0,37
	161650.5	66148.1	7	9	0,89	95502.4	3	0,37						
network094_3_e	139914.5	46793.6	4	4	0,67				93733.5	3	0,37	93120.9	3	0,37
	140069.3	46948.4	4	4	0,67	118801.0	4	0,28	93120.9	3	0,37	93120.9	3	0,37
	140080.0	46943.9	4	4	0,67	96973.1	3	0,37	93136.1	4	0,28	93136.1	4	0,28
	140531.6	46798.1	4	4	0,67	96400.5	4	0,28	96503.0	3	0,37	93733.5	3	0,37
network095_1_b	132123.5	24141.5	7	8	0,9	107982.0	5	0,22	110382.0	5	0,22	110382.0	5	0,22
	133229.6	24141.6	6	8	0,9	110779.0	5	0,22	109088.0	5	0,22	113526.0	4	0,28
	135913.5	24141.5	6	8	0,9	113603.0	5	0,22	111772.0	5	0,22	113420.0	4	0,28
	137561.5	24141.5	6	8	0,9				148640.0	6	0,19	113420.0	4	0,28
network095_1_e	138599.6	30131.6	4	5	0,48	114810.0	5	0,22	148640.0	6	0,19	108468.0	5	0,22
	139779.6	29397.6	4	4	0,6	111772.0	5	0,22	110382.0	5	0,22	110382.0	5	0,22
	139779.7	29397.7	4	4	0,6	111772.0	5	0,22	110382.0	5	0,22	110382.0	5	0,22
	139804.9	29422.9	5	5	0,48	111772.0	5	0,22	110382.0	5	0,22	110382.0	5	0,22
	139910.4	30052.4	5	5	0,48	109858.0	5	0,22	110382.0	5	0,22	110382.0	5	0,22
network095_2_b	144094.1	35878.1	4	8	0,9	145352.0	5	0,22	144884.0	6	0,19	108216.0	4	0,28
	144094.2	35878.2	4	8	0,9	145352.0	5	0,22	144884.0	6	0,19	108216.0	4	0,28
network095_2_e	142643.0	34427.0	3	3	0,8	108216.0	4	0,28	108216.0	4	0,28	108216.0	4	0,28
	142791.8	34575.8	3	3	0,8	108216.0	4	0,28	108216.0	4	0,28	108216.0	4	0,28
network095_3_b	153151.9	59607.4	6	8	0,9	93544.5	3	0,37	93603.3	4	0,28	121486.0	5	0,22
	153152.0	59607.5	6	8	0,9	93544.5	3	0,37	93544.5	3	0,37	93603.3	4	0,28
	153210.7	59607.4	7	8	0,9	93603.3	4	0,28	95829.5	3	0,37	93603.3	4	0,28
network095_3_e	140108.3	46505.0	4	4	0,6	93603.3	4	0,28	93733.0	3	0,37	93603.3	4	0,28
	140158.7	46614.2	4	4	0,6	93603.3	4	0,28	93544.5	3	0,37	93544.5	3	0,37
	140158.8	46614.3	4	4	0,6	93544.5	3	0,37	93544.5	3	0,37	93603.3	4	0,28
	140217.6	46614.3	4	4	0,6	93603.3	4	0,28	93603.3	4	0,28	93603.3	4	0,28
	144978.6	51434.1	5	5	0,48	96407.1	4	0,28	93544.5	3	0,37	93603.3	4	0,28
network096_1_b	150098.3	30891.3	10	10	0,92				119207.0	5	0,17	119208.0	5	0,17
	150098.4	30891.4	10	10	0,92				119208.0	5	0,17	119207.0	5	0,17
	150125.3	30918.3	10	10	0,92				119207.0	5	0,17	119207.0	5	0,17
	X	30848.8	8	10	0,92									
network096_1_e	157647.6	39929.6	6	6	0,51				117718.0	5	0,17	119207.0	5	0,17
	158520.6	39929.6	6	6	0,51				118591.0	5	0,17	119208.0	5	0,17
	158773.1	39566.1	6	6	0,51				152991.0	6	0,14	119207.0	5	0,17
	192307.3	39316.3	6	6	0,51				152991.0	6	0,14	152991.0	6	0,14
network096_2_b	159544.9	46182.9	8	10	0,92				113362.0	5	0,17	113362.0	4	0,21
	159570.8	46208.8	8	10	0,92	116103.0	4	0,21	113362.0	5	0,17	113362.0	4	0,21

(continued on next page)

Table 13 (continued)

Instance	cost	2L			1L - M1			1L - M2			1L - M3			
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	159578.1	46216.1	8	10	0,92	116103.0	4	0,21	113362.0	5	0,17	113362.0	4	0,21
	159608.6	46246.6	8	10	0,92	116103.0	4	0,21	113748.0	5	0,17	113362.0	4	0,21
network096_2_e	161586.6	48224.6	5	5	0,62	113362.0	5	0,17	113362.0	4	0,21	113362.0	4	0,21
	161752.9	48390.9	5	5	0,62	116416.0	4	0,21	113362.0	4	0,21	113362.0	4	0,21
	161799.6	48437.6	5	5	0,62	113362.0	5	0,17	113362.0	4	0,21	113362.0	4	0,21
	161823.9	48461.9	5	5	0,62	113362.0	4	0,21	113362.0	4	0,21	113362.0	4	0,21
network096_3_b	163824.3	75364.8	8	10	0,92	88459.5	3	0,28	88459.5	3	0,28	88459.5	3	0,28
	163853.8	75394.3	8	10	0,92	88459.5	3	0,28	88459.5	3	0,28	88459.5	3	0,28
	163941.9	75482.4	8	10	0,92	90419.2	4	0,21	88459.5	3	0,28	90419.2	4	0,21
	163955.9	75496.4	8	10	0,92	90419.2	4	0,21	88459.5	3	0,28	88459.5	3	0,28
	163956.0	75496.5	8	10	0,92	88459.5	3	0,28	88459.5	3	0,28	90419.2	4	0,21
network096_3_e	145731.3	57271.8	4	4	0,77	88459.5	3	0,28	88459.5	3	0,28	88459.5	3	0,28
	146153.2	57693.7	4	4	0,77	90419.2	4	0,21	88459.5	3	0,28	88459.5	3	0,28
	146458.8	57999.3	4	4	0,77	88459.5	3	0,28	88459.5	3	0,28	88459.5	3	0,28
	149466.3	61006.8	5	5	0,62	88459.5	3	0,28	88459.5	3	0,28	88459.5	3	0,28
network097_1_b	139703.1	26042.1	9	10	0,86				118082.0	5	0,16	113661.0	5	0,16
	139898.0	26099.0	8	10	0,86				119059.0	5	0,16	113799.0	5	0,16
	140284.1	26099.1	8	10	0,86				118854.0	5	0,16	114185.0	5	0,16
	143167.1	26068.1	8	10	0,86				118083.0	5	0,16	117099.0	5	0,16
	143818.2	26042.2	8	10	0,86				118854.0	5	0,16	117776.0	5	0,16
network097_1_e	149970.6	35720.6	6	7	0,41	119759.0	5	0,16	115695.0	5	0,16	114250.0	5	0,16
	150475.5	35032.5	6	6	0,48	115443.0	5	0,16	119059.0	5	0,16	118672.0	5	0,16
	150512.3	35356.3	6	6	0,48	115156.0	5	0,16	119059.0	5	0,16	118672.0	5	0,16
	150942.9	35567.9	6	6	0,48	115375.0	5	0,16	119059.0	5	0,16	118672.0	5	0,16
	153504.7	35421.7	6	6	0,48	118083.0	5	0,16	119059.0	5	0,16	118672.0	5	0,16
network097_2_b	159240.6	44527.6	8	10	0,86	116259.0	4	0,2	114713.0	5	0,16	114713.0	4	0,2
	159572.3	44859.3	7	10	0,86	116316.0	4	0,2	151849.0	5	0,16	114713.0	4	0,2
	159698.2	44985.2	7	10	0,86	115054.0	4	0,2	148709.0	5	0,16	114713.0	4	0,2
	159720.0	45007.0	9	10	0,86	115054.0	4	0,2	114713.0	4	0,2	115655.0	5	0,16
	159720.1	45007.1	8	10	0,86	152688.0	5	0,16	114713.0	5	0,16	114713.0	4	0,2
network097_2_e	154479.6	42906.6	5	5	0,57	111573.0	4	0,2	114713.0	4	0,2	114713.0	4	0,2
	154479.7	42906.7	5	5	0,57	111573.0	4	0,2	112173.0	4	0,2	114713.0	4	0,2
	155469.7	43896.7	5	5	0,57	111573.0	4	0,2	114951.0	4	0,2	114713.0	4	0,2
	155828.7	44255.7	6	6	0,48	112597.0	4	0,2	111573.0	4	0,2	114713.0	4	0,2
network097_3_b	159918.7	70821.9	8	9	0,95	97688.5	3	0,27	89096.8	3	0,27	89096.8	3	0,27
	160025.5	70928.7	8	9	0,95	97725.4	3	0,27	89096.8	3	0,27	89096.8	3	0,27
	160125.5	71028.7	8	9	0,95	97688.5	3	0,27	89096.8	3	0,27	91770.9	4	0,2
	160434.5	71337.7	8	9	0,95	97688.5	3	0,27	91770.9	4	0,2	89096.8	3	0,27
	163033.2	71262.3	8	9	0,95	97725.4	3	0,27	91770.9	4	0,2	93765.6	3	0,27
network097_3_e	152614.3	63517.5	6	6	0,48	91770.9	4	0,2	89096.8	3	0,27	91770.9	4	0,2
	152614.4	63517.6	6	6	0,48	89096.8	3	0,27	91770.9	4	0,2	89096.8	3	0,27
	152964.0	63867.2	6	6	0,48	89096.8	3	0,27	89096.8	3	0,27	91770.9	4	0,2
	158211.6	69114.8	6	6	0,48	91770.9	4	0,2	91770.9	4	0,2	89096.8	3	0,27
network098_1_b	98227.5	23285.9	7	8	0,9	108049.0	5	0,16	74941.6	4	0,2	80275.8	4	0,2
	98248.5	23306.9	8	8	0,9	109018.0	5	0,16	81034.2	3	0,26	74941.6	4	0,2
	99509.0	23273.1	7	8	0,9	108049.0	5	0,16	114352.0	5	0,16	76235.9	4	0,2
	99524.1	23288.2	7	8	0,9	113192.0	5	0,16	111897.0	5	0,16	76235.9	4	0,2
network098_1_e	112403.3	31369.1	5	5	0,48	81034.2	3	0,26				111897.0	5	0,16
	143339.4	31442.4	5	5	0,48				111897.0	5	0,16	112089.0	5	0,16
network098_2_b	112745.0	36387.0	8	8	0,9	76358.0	3	0,26	108171.0	4	0,2	111491.0	4	0,2
	144558.0	36387.0	7	8	0,9	108171.0	4	0,2	111491.0	4	0,2	111491.0	4	0,2
	144593.3	36422.3	7	8	0,9	108171.0	4	0,2	112826.0	4	0,2	111491.0	4	0,2
	144799.6	36427.6	7	8	0,9	108372.0	4	0,2	110434.0	4	0,2	111491.0	4	0,2
	146852.2	36418.2	7	8	0,9	110434.0	4	0,2	111491.0	4	0,2	111491.0	4	0,2
network098_2_e	113499.6	37141.6	4	4	0,6	108171.0	4	0,2	76358.0	3	0,26	108171.0	4	0,2
	144768.5	36597.5	4	4	0,6	108171.0	4	0,2	108969.0	4	0,2	111491.0	4	0,2
	144768.6	36597.6	4	4	0,6	108171.0	4	0,2	111491.0	4	0,2	111491.0	4	0,2
	144899.8	36728.8	4	4	0,6	108171.0	4	0,2	108171.0	4	0,2	111491.0	4	0,2
	145176.2	37005.2	4	4	0,6	108171.0	4	0,2	111491.0	4	0,2	111491.0	4	0,2
network098_3_b	122614.1	59504.1	6	8	0,9	92536.4	4	0,2	88548.7	4	0,2	63110.0	3	0,26
	148052.8	59504.1	7	8	0,9	95000.7	3	0,26	88548.7	4	0,2	88548.7	4	0,2
network098_3_e	111463.7	48353.7	4	4	0,6	88548.7	4	0,2	67097.7	3	0,26	63110.0	3	0,26
	111463.8	48353.8	4	4	0,6	88548.7	4	0,2	88548.7	4	0,2	63110.0	3	0,26
	114870.1	47772.4	4	4	0,6	88548.7	4	0,2	67097.7	3	0,26	67097.7	3	0,26
	115166.7	48069.0	4	4	0,6	88548.7	4	0,2	67097.7	3	0,26	67097.7	3	0,26

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Table 13 (continued)

Instance	cost	2L				1L - M1			1L - M2			1L - M3		
		cost	nb.v	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap	cost	nb.t	cap
	115423.5	48325.8	4	4	0,6	67097.7	3	0,26	67097.7	3	0,26	67097.7	3	0,26
network099_1_b	143417.7	26789.7	8	10	0,86				117719.0	5	0,23	116628.0	5	0,23
	144027.7	26789.7	9	10	0,86				117971.0	5	0,23	117238.0	5	0,23
	144508.8	26789.8	8	10	0,86				117719.0	5	0,23			
network099_1_e	151498.3	33552.3	5	5	0,58				117946.0	5	0,23	117946.0	5	0,23
	151541.9	33595.9	5	5	0,58				117971.0	5	0,23	117946.0	5	0,23
network099_2_b	158962.8	42176.8	9	10	0,86	116786.0	5	0,23	117435.0	4	0,28	117435.0	4	0,28
	159098.0	42312.0	9	10	0,86	117232.0	4	0,28				116786.0	4	0,28
	159466.8	42234.8	9	10	0,86	117435.0	4	0,28	117232.0	4	0,28	117232.0	4	0,28
	159532.8	42300.8	9	10	0,86	117232.0	4	0,28	117687.0	4	0,28	117232.0	4	0,28
	197496.9	42367.9	7	10	0,86	155129.0	5	0,23						
network099_2_e	159165.2	42379.2	6	6	0,48	117206.0	4	0,28	117232.0	4	0,28	116786.0	4	0,28
	159165.3	42379.3	6	6	0,48	116786.0	4	0,28	117232.0	4	0,28	116786.0	4	0,28
	160126.2	43340.2	6	6	0,48	116786.0	4	0,28	117232.0	4	0,28	116786.0	4	0,28
	160533.8	43747.8	6	6	0,48	116786.0	4	0,28	117232.0	4	0,28	116786.0	4	0,28
	161528.6	44742.6	6	6	0,48	117232.0	4	0,28	117206.0	4	0,28	116786.0	4	0,28
network099_3_b	166953.5	68665.2	8	9	0,96	98288.3	3	0,38						
	167055.2	68525.8	7	9	0,96	98529.4	3	0,38						
	167274.3	68986.0	8	9	0,96	98288.3	3	0,38						
	167374.5	68631.0	8	9	0,96	98743.5	3	0,38						
network099_3_e	159418.2	61309.7	6	6	0,48	98529.4	3	0,38	98288.3	3	0,38	98108.5	3	0,38
	159470.8	61182.5	6	6	0,48	98288.3	3	0,38	98288.3	3	0,38	98288.3	3	0,38
	159762.3	61653.8	6	6	0,48	98108.5	3	0,38	98529.4	3	0,38	98108.5	3	0,38
	159762.4	61653.9	6	6	0,48	98108.5	3	0,38	98288.3	3	0,38	98288.3	3	0,38
network09_1_b	141052.2	25629.2	9	9	0,95	115423.0	5	0,22	117061.0	5	0,22	117061.0	5	0,22
	141210.1	25629.1	8	9	0,95				117586.0	5	0,22	115581.0	5	0,22
	142580.1	25629.1	7	9	0,95				117586.0	5	0,22	116951.0	5	0,22
	142690.1	25629.1	8	9	0,95				117313.0	5	0,22	117061.0	5	0,22
	X	25629.2	8	9	0,95									
network09_1_e	148068.4	32487.4	5	5	0,57	117803.0	5	0,22	115581.0	5	0,22	117061.0	5	0,22
	148068.5	32487.5	5	5	0,57	117400.0	5	0,22	115581.0	5	0,22	117061.0	5	0,22
	148349.4	32487.4	5	5	0,57	115862.0	5	0,22	117061.0	5	0,22	117586.0	5	0,22
	149548.4	32487.4	5	5	0,57	117400.0	5	0,22	117061.0	5	0,22	117586.0	5	0,22
	150073.4	32487.4	5	5	0,57				117586.0	5	0,22	117586.0	5	0,22
network09_2_b	153982.6	39825.6	8	9	0,95	114157.0	4	0,27	114157.0	4	0,27	114991.0	4	0,27
	153983.2	39826.2	8	9	0,95	114157.0	4	0,27	115567.0	4	0,27	114991.0	4	0,27
	155392.6	39825.6	7	9	0,95	115567.0	5	0,22						
network09_2_e	151789.2	37632.2	4	4	0,71	114157.0	4	0,27	114991.0	4	0,27	114991.0	4	0,27
	151789.4	37632.4	4	4	0,71	114157.0	4	0,27	115567.0	4	0,27	114991.0	4	0,27
	152019.2	37632.2	4	4	0,71	114387.0	4	0,27	115567.0	4	0,27	114991.0	4	0,27
	152019.3	37632.3	4	4	0,71	114387.0	4	0,27	115270.0	4	0,27	114991.0	4	0,27
	153283.2	39126.2	4	5	0,57	114157.0	4	0,27	116947.0	4	0,27	114991.0	4	0,27
network09_3_b	164206.0	66982.6	7	9	0,95	97358.6	3	0,36	97358.6	3	0,36	97223.4	3	0,36
	164321.2	66962.6	7	9	0,95	97358.6	3	0,36	97358.6	3	0,36	97962.8	3	0,36
	165222.4	66982.6	7	9	0,95	99962.1	3	0,36	98239.8	3	0,36	98239.8	3	0,36
network09_3_e	146183.9	48960.5	4	4	0,71	97358.6	3	0,36	97223.4	3	0,36	97223.4	3	0,36
	146644.0	49420.6	4	4	0,71	125478.0	4	0,27	97962.8	3	0,36	97223.4	3	0,36
	146833.1	49609.7	4	4	0,71	97358.6	3	0,36	98239.8	3	0,36	97223.4	3	0,36
	146833.2	49609.8	4	4	0,71	97358.6	3	0,36	97358.6	3	0,36	97223.4	3	0,36
	151347.6	54124.2	5	5	0,57				97358.6	3	0,36	97223.4	3	0,36

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