Centre de recherche sur les transports (C.R.T.)
Centre for Research on Transportation

CRT-2005-19

THE-DAY-BEFORE PLANNING FOR ADVANCED FREIGHT TRANSPORTATION SYSTEMS IN CONGESTED URBAN AREAS

by

Teodor Gabriel Crainic
Nicoletta Ricciardi
Giovanni Storchi

June 2005

Université de Montréal
C.P. 6128, succursale Centre-ville, Montréal QC H3C 3J7 Canada
Téléphone: (514) 343-7575 / Télécopieur: (514) 343-7121

crt@crt.umontreal.ca
www.crt.umontreal.ca

HEC ÉCOLE POLYTECHNIQUE MONTRÉAL Université de Montréal

PUBLICATION
CRT-2005-19

THE-DAY-BEFORE PLANNING FOR ADVANCED FREIGHT TRANSPORTATION SYSTEMS IN CONGESTED URBAN AREAS

by

Teodor Gabriel Crainic [1]
Nicoletta Ricciardi [2]
Giovanni Storchi [2]

The research was supported in part by the Universitá degli Studi di Roma "La Sapienza", the Natural Sciences and Engineering Research Council of Canada (NSERC), and by MIUR, Ministero Istruzione Universitá Ricerca.

[1] Département de management et technologie, Université du Québec à Montréal, and Centre de recherche sur les transports, Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal, Canada H3C 3J7 (theo@crt.umontreal.ca)

[2] Dipartimento di Statistica, Probabilità E Statistiche Applicate, Univesità degli studi di Roma "La Sapienza", Piazzale Aldo More, 5 – 00185 Roma, ITALY (nicoletta.ricciardi@uniroma1.it, giovanni.storchi@uniroma1.it)

Dépôt légal – Bibliothèque nationale du Québec
Bibliothèque nationale du Canada, 2005

Abstract

City Logistics aims to reduce the nuisances associated to freight transportation in urban areas while supporting the economic and social development of the cities. The fundamental idea is to view individual stakeholders and decisions as components of an integrated logistics system. This implies the coordination of shippers, carriers, and movements as well as the consolidation of loads of several customers and carriers into the same environment-friendly vehicles. City Logistics explicitly aims to optimize such a advanced urban transportation systems. We focus on a challenging City Logistics planning issue, the integrated short-term scheduling of operations and management of resources, for the general two-tier case. We investigate the main issues related to the problem, propose a general approach, model its main components, and identify promising solution avenues. The simplification of this methodology for the single-tier case is also presented.

Keywords: City Logistics, advanced urban freight transportation, integrated short-term planning and management, service network design, vehicle routing.

Résumé

La logistique urbaine vise à réduire les impacts négatifs du transport des marchandises dans les zones urbaines, tout en supportant leur développement économique et social. L'idée fondamentale de cette approche est de concevoir l'ensemble des intervenants et des décisions comme les éléments d'un système logistique intégré. Cela implique la coordination des expéditions et des mouvements de transport, ainsi que la consolidation des charges d'expéditeurs et clients différents dans les mêmes véhicules. La logistique urbaine vise explicitement l'optimisation de tels systèmes avancés de transport de marchandises. Nous traitons plus particulièrement les problèmes de planification intégrée à court terme des opérations d'un système à deux niveaux. Nous décrivons le problème et les défis qui y sont associés. Nous proposons ensuite une méthodologie générale ainsi que des formulations pour les principales composantes du problème et nous identifions des approches de résolution prometteuses. L'adaptation de cette méthodologie au cas plus simple des systèmes à un seul niveau est également présentée.

Mots-clés : Logistique urbaine, systèmes avancés de transport de transport de marchandises en ville, planification et gestion intégrées, design de réseaux de service, tournées de véhicules.

1 Introduction

The transportation of goods constitutes a major enabling factor for most economic and social activities taking place in urban areas. For the city inhabitants, it directly ensures adequate supplies to stores and places of work and leisure, as well as the delivery of goods at home, the elimination of refuse, an so on. For firms established within city limits, it forms a vital link with suppliers and customers. Indeed, there are few activities going on in a city that do not require at least some commodities being moved. Yet, freight transportation is also a major disturbing factor to urban life. Freight vehicles compete with private and public vehicles transporting people for the capacity of the streets and arteries of the city, and contribute significantly to congestion and environmental nuisances, such as emissions and noise. Moreover, the amplitude of freight traffic also contributes to the belief that "cities are not safe" that pushes numerous citizens to move out of the city limits. And the problem is not going to disappear any time soon. In fact, the already important volume of freight vehicles moving within city limits is growing and is expected to continue to grow at a fast rate. The world-wide urbanization trend is emptying the countryside and small towns and making large cities even larger. Additional major contributing factors to this phenomenon are the current production and distribution practices based on low inventories and timely deliveries (the much talked about "just-in-time" paradigm), as well as the explosive growth of business-to-customer electronic commerce that generates significant volumes of personal deliveries.

One observes an increased awareness of the public, industry, and officials at all levels of government regarding these issues. The general consensus that seems to emerge is that one needs to analyze, understand, and control freight transportation within urban areas to reduce and control the number and dimensions of freight vehicles operating within the city limits, reduce congestion and pollution, increase mobility, improve living conditions, improve the efficiency of freight movements and reduce the number of empty vehicle-km, and, in general, contribute towards reaching the Kyoto targets for emission reductions (the spirit of the accord, at least), while not penalizing the city center activities. This has resulted in several initiatives, proposals, and projects, e.g., http://www.transports-marchandises-en-ville.org, http://www.bestufs.net, http://icl.kiban.kuciv.kyoto-u.ac.jp, Crainic and Gendreau (2004), Taniguchi *et al.* (2001), and references herein.

The fundamental idea that underlines most such initiatives is that one must stop considering each shipment, firm, and vehicle individually. Rather, one should consider that all stakeholders and movements are components of an integrated logistics system. This implies the *coordination* of shippers, carriers, and movements as well as the *consolidation* of loads of several customers and carriers into the **same** "green" vehicles. The term *City Logistics* encompasses these ideas and goals and explicitly refers to the *optimization* of such advanced urban freight transportation systems.

Most contemplated and initiated projects are implementing some form of single-tier system where transportation to and from the city is performed from facilities called *City Distribution Centers* (*CDC*; the terms *Intermodal Platforms* and *Logistics Platforms* are also used) located at the city limits. Single-tier systems do not appear interesting for large urban zones, however. More general two-tier systems, combining major CDCs and satellite platforms strategically located within the urban area, appear promising for such cases (Crainic, Ricciardi, and Storchi 2004, Gragnani, Valenti, and Valentini 2004).

For Operations Research and Transportation Science, City Logistics constitutes both a challenge and an opportunity in terms of methodological developments and actual social impact. Yet, currently, there are very few models that address City Logistics issues. Concepts are proposed and pilot studies are undertook, yet the corresponding Operations Research and Transportation Science literature related to the design, evaluation, planning, management, and control of such systems is very scarce. This paper aims to contribute towards closing this gap.

We focus on one of the most challenging issues in planning City Logistics systems, the integrated short-term scheduling of operations and management of resources. We present the developments for the general case of two-tier City Logistics systems, which also involve environment-friendly vehicles for most operations within the urban area and Intelligent Transportation Systems (ITS) capabilities for information exchanges and real-time control. We also examine the simplification of this methodology for the single-tier case.

Our objectives are to investigate the issues and challenges related to this problem and propose a general methodology to address them. This is fundamentally a *modelling* paper. We aim to present a comprehensive view of the subject, identify issues, and propose modelling approaches. We are identifying promising solution avenues, but detailed algorithmic developments are beyond the scope of the present work.

The contribution of this paper is three-fold. It identifies and analyzes a set of emerging issues that are both methodologically challenging and timely. It proposes a general approach to the problem and formulations for its main components. It identifies promising algorithmic avenues.

The paper is organized as follows. Section 2 briefly presents the single and two-tier City Logistics systems and describes the integrated short-term planning issues that we identify as the *day-before* problem. The general solution methodology is presented in Section 3. Section 4 is dedicated to the formulation of the first major sub-problem, which addresses the issue of the demand distribution to the satellite platforms and the design of the service network. Section 5 presents formulations for the second major sub-problem, the allocation of the city delivery vehicles and the management of their routes. Algorithmic perspectives are included in each of the last two sections. The relations between the methodology proposed and the single-tier City Logistics systems are discussed in Section 6. We conclude in Section 7.

2 Problem Description

The fundamental idea of City Logistics is that the volume and impact of freight vehicles travelling within urban areas may be reduced through a more efficient utilization of vehicles yielding higher average load factors and fewer empty movements. The *consolidation* of loads of different shippers and carriers associated to some form of *coordination* of operations within the city are among the most important means to achieve this rationalization of distribution activities. Intelligent Transportation Systems technologies and operations research-based methodologies enable the optimization of the design, planning, management, and operation of City Logistics systems (Crainic and Gendreau 2004, Taniguchi *et al.* 2001).

Consolidation activities take place at co-called City Distribution Centers. Long-haul transportation vehicles of various modes dock at a CDC to unload their cargo. Loads are then sorted and consolidated into smaller vehicles that will deliver them to their final destinations. Of course, a City Logistics system is also addressing the reverse movements, from origins within the city to destinations outside. To simplify the presentation, however, we focus on the in-bound, distribution activities only. This is the general approach of most City Logistic works and derives from the imbalance between entering and exiting flows that characterize most cities.

Most City Logistics projects address single-tier CDC systems where delivery circuits are performed directly from a single CDC. When more than one CDC is involved, the city is usually partitioned and each CDC serves a given partition (see the project descriptions on http://www.transports-marchandises-en-ville.org and http://www.bestufs.net, as well as in the proceedings of the City Logistics conferences on http://icl.kiban.kuciv.kyoto-u.ac.jp). Such approaches have not been successful for large cities, however. We are therefore addressing a more general, two-tier system that is appropriate for large urban zones (Crainic, Ricciardi, and Storchi 2004). We first present the system and its main components. We then introduce the short-term planning issues that are the scope of this paper.

2.1 A General Two-Tier City Logistics System

City Distribution Centers form the first level of the system and are usually located on the outskirts of the urban zone. The second tier of the system is constituted of satellite platforms, *satellites* for short, where the freight coming from the CDCs and, eventually, other external points may be transferred to and consolidated into environment-friendly vehicles adapted for utilization in dense city zones. In the advanced system we address in this paper, satellites do not perform any warehousing activities, transdock transshipment being the operational model (for a simpler proposal, see Gragnani, Valenti, and Valentini 2004). Existing facilities (e.g., underground parking lots or municipal bus garages) could thus be used Crainic, Ricciardi, and Storchi 2004, Gragnani, Valenti, and Valentini 2004).

Two types of vehicles are involved in a two-tier City Logistics system: urban-trucks and city-freighters. *Urban-trucks* move freight to satellites, possibly by using corridors (sets of streets) specially selected to facilitate access to satellites and reduce the impact on traffic and the environment. Moreover, since the goal is to minimize the truck movements within the city, rules may be imposed to have them travel as much as possible around the city, on a ring highway, and enter the city center as close to destination as possible. Urban-trucks may visit more than one satellite during a trip. Their routes have to be optimized and coordinated with satellite and city-freighter access and availability.

City-freighters are environment-friendly vehicles of relatively small capacity that can travel along any street in the downtown area (in European cities, these may be quite narrow) to perform the required distribution activities. City-freighters may be of several types in terms of functionality (e.g., refrigerated or not), box design, loading/unloading technology, capacity, and so on. Efficient operations require a certain standardization, however. The number of different city-freighter types within a given City Logistics system is thus assumed to be small.

Notice that not all demand for transportation processed by a City Logistics system passes through a stand-alone CDC. Freight may arrive on ships or trains and sorting and consolidation operations may be performed in CDC-type facilities located in the port or rail yard. Moreover, certain demand is generated at production facilities located close to the city and is already embarked in fully-loaded urban-trucks. Freight may also come from further away but also in fully-loaded vehicles that are allowed to enter the inter city and may thus be assimilated to urban-trucks. Such vehicles will have to stop, however, at designated points ("city gates") until the systems issues the dispatching decision that allows them to enter the city. To simplify the presentation, we refer to CDCs and all these facilities and sites as *external zones.*

From a physical point of view, the system operates according to the following sequence: Freight arrives at an external zone where it is consolidated into urban-trucks, unless it is already into a fully-loaded urban-truck; Each urban-truck receives a departure time and travels to one or several pre-assigned satellites; At a satellite, freight is transferred to city-freighters; Each city-freighter performs a route to serve the designated customers, and then travels to a satellite (or a depot) for its next cycle of operations.

From an information and decision point of view, it all starts with the demand for cargo volumes to be distributed within the urban zone. The corresponding freight will be consolidated at external zones yielding the actual demand for the urban-truck transportation and the satellite transdock transfer activities. These, in turn, generate the input to the city-freighter circulation which provides the last leg of the distribution chain as well as the timely availability of empty city-freighters at satellites. The objective is to have urban-trucks and city-freighters on the city streets and at satellites on a "needs-to-be-there" basis only, while providing timely delivery of loads to customers and efficient operations, based on sound economic principles.

The planning, deployment, management, and operation of such a system require a whole new set of Operations research models and methods. On the strategic side, one needs models to design the system: locate CDCs, satellites or both (Crainic, Ricciardi, and Storchi 2004), select the network open to urban-truck traffic, dimension the fleets of vehicles, and so on. On the operational side, there is the whole set of ITS-related models and methods to dynamically dispatch, control, and adjust satellite activities and urban-truck and city-freighter routes. In-between, there are the so-called tactical planning activities that concern the departure times, routes, and loads of urban-trucks and city-freighters, the routing of demand, the scheduling of personnel, the utilization of satellites and the distribution of work among those, and so on. The corresponding models and methods yield an operations plan used to guide the real-time operations of the system. Tactical planning models are also important components of models and procedures that may be used to evaluate City Logistics systems from initial proposals, to deployment scenarios and operation policies.

In this paper, we focus on part of the tactical planning process, namely the short-term planning of operations, that we identify as the *day-before* problem.

2.2 The Day-Before Planning Problem

We are here concerned with the short-term planning of activities. Thus, for example, the planning of the morning (e.g., from late at night or early morning until 7h00 or 8h00) distribution activities would take place on the day before, in time to inform all concerned parties of the planned schedule and operations. Hence the name.

The general goal of the process is to ensure an efficient and low-cost operation of the system, while demand is delivered on time and the impact on traffic within the city is minimized. This corresponds to the classical objective of tactical planning: Plan the allocation and utilization of the resources of the system for best performance in terms of customer satisfaction and system costs (and profits). Satellites, city-freighters, and urban-trucks are the resources of the system addressed in this paper.

One has thus to determine when each demand is served and how it is to be moved, on what urban-truck, through which satellite, and on what type of city-freighter. One must also determine when to dispatch each urban-truck, the loads carried and the satellites serviced. Finally, one must determine the circulation of the city-freighter fleet, which corresponds to planning the routing and scheduling of city-freighters during the contemplated period.

Given the issues considered and the associated time frame, a number of hypotheses may be made:

1. The logistics structure of the system is given. Satellites have been established, customer zones have been assigned to one or several satellites, corridors for urban-trucks have been determined. Each satellite has its own characteristics in terms of operating hours and capacity in terms of number of urban-trucks and city-freighters handled. We assume that all satellites are available (open), meaning that we do not have at this planning level to decide whether to use or not a given satellite, nor at what hour to start operations.

2. The types of vehicles, urban-trucks and city-freighters, and their characteristics are known.

3. Most demand is known and planning is performed accordingly. Eventual modifications to this demand as well as any additional demand are to be handled in "real-time" during actual operations. The characteristics of demand in terms of volume, product type, time window at the customer, etc., are also assumed known.

The methodology we propose to address these issues is introduced in the next section, while detailed models are the subject of subsequent sections.

3 Methodological Approach

The scope of this section is to, first, introduce the general methodology we propose to address the issues identified in the previous section and, then, to present global definitions and notation.

3.1 Proposed Methodology

The day-before planning process and the methodology proposed to assist aims to determine the most appropriate times and routes for demand distribution. "Most appropriate" is determined by concerns related to the impact of freight distribution on the traffic and congestion conditions in the city, the best possible utilization of the City Logistics system, and, of course, the customer requirements in terms of delivery period.

In a two-tier City Logistics system, demand is served by a combination of a "direct" route performed by an urban-truck from an external zone to a satellite, a transshipment operation at the satellite, and a delivery route performed by a city-freighter. Thus, as described in the previous section, the day-before planning problem encompasses two main components. The first concerns the starting time of each urban-truck and the satellites it visits, that is, the schedules and routes of the urban-truck fleet. The second addresses the issues of routing, and scheduling, city-freighters to provide the timely delivery of goods to customers and the supply of vehicles at satellites. The two problems are linked by the decisions regarding how demand is to be routed from an external zone, through a satellite, to the customer.

A model encompassing all these elements may be envisioned. This would yield a very complex formulation, however, and of a very large scale. The complexity and large dimension arise, in particular, from the interplay between the routing of demand and the routes and schedules of the city-freighters. Thus, to compute the total delivery time and cost for a given demand, one needs to know the order of the corresponding customer in the city-freighter route. On the other hand, in order to compute these routes, one needs the satellite demand is routed through and the particular city-freighter that will deliver it.

To achieve a workable model and planning tool that avoids this complexity, one may start with the observation that in a two-tier City Logistics system, most city-freighter delivery routes are rather short and compact. These routes start out of specific satellites to which known customers are associated. The capacity of city-freighters is relatively limited as well. City-freighter routes may thus be approximated quite well. Using these approximations to determine the demand itineraries simplifies the problem and separates the two main components mentioned earlier.

We therefore propose a hierarchical approach that decomposes the global problem according to the main decisions involved. Appropriate levels of data aggregation can then be introduced and the efficient resolution of the resulting models may be contemplated. The hierarchical modelling approach is made up of two formulations:

1. A *demand distribution - urban-truck service design* model that determines for each urban-trucks its route (satellites served) and departure time, as well as the distribution strategy for each demand: the urban-truck service, satellite, and city-freighter used (Section 4).

2. Given the results of the previous model, a *city-freighter fleet management* formulation determines to what satellite, or depot, to send city-freighters following a

distribution route and at what period they become available for the next assignment (Section 5).

One of the issues often encountered in planning freight transportation services is whether loads may be split or not during delivery. Splitting loads among vehicles allows a better utilization of vehicles. On the other hand, it implies more handling and more nuisance for customers due to multiple deliveries. In the system analyzed in this paper, loads may be split between urban-trucks. Given that freight is not stored at satellites, a load that has been divided among several urban-trucks will arrive in several deliveries to the final customer. One still has the choice, however, to allow further splitting when freight is transferred to city-freighters. In the following sections, we first present formulations for the unsplit case and then discuss the other possibilities.

3.2 Global Definitions and Notation

We group in this subsection the concepts and notation that is relevant for all the models presented in this paper. Table 1 summarizes this notation. The particular notation of each model is presented in the corresponding section.

Let $\mathcal{E} = \{e\}$ be the set of external zones where freight is sorted and consolidated into urban-trucks. On any given day, volumes of particular products $p \in \mathcal{P}$ are destined to a particular set $\mathcal{C} = \{c\}$ of customers. For planning purposes, the period of time available for the next-day operations is divided into $t = 1, ..., T$ periods.

Most customers are commercial entities with known opening hours and delivery periods determined both by known practice and municipal rules. Define the *customer-demand* d_i (or simply i) as the quantity of product p available starting in period t at the external zone e, to be delivered to customer c during the time interval $[a, b]$. Let $\mathcal{D} = \{d_i = d^{pec}_{t[a,b]}\}$. The time required to actually serve the customer is denoted δ_i.

The models used to assist the strategic decisions regarding the locations of the CDCs also yield the assignment of each zone of the city to one or several CDCs (Crainic, Ricciardi, and Storchi 2004). This zone definition must be further refined for use at the planning level addressed in this paper. Define a *customer zone* as a set of customers that may be served together, that it, they require the same product classes and may be served by the same satellites as determined during strategic planning.

We then define the demand d_k as the quantity of product p available starting in period t at the external zone e, to be delivered to customer zone z, during the time interval $[a, b]$; $\bar{\mathcal{D}} = \{d_k = d^{pez}_{t[a,b]}\}$. We also refer to *zone-demand* k. This demand results from aggregating along the time dimension individual demands of customers in the same customer zone, and will be considered as a unique entity for part of the distribution process. To ensure feasible deliveries, one then aggregates either individual customers that have the same delivery window, or then are clustered in time, that is, their delivery windows have significant intersections and the union is not too wide. The time window associated to the resulting customer zone demand is then taken as the union of the individual time restrictions.

Fleets of heterogeneous urban-trucks and city-freighters provide transportation services. Let $\mathcal{T} = \{\tau\}$ and $\mathcal{V} = \{\nu\}$ represent the sets of urban-trucks and city-freighters types, respectively. Each vehicle has a specific capacity, u_τ for an urban-truck of type τ, and u_ν for a city-freighter type ν.

Some products may use the same type of vehicle but cannot be loaded together (e.g., food and hardware products). This issue may be addressed by explicitly including exclusion constraints in the formulations. This approach is not very practical, however, because the potential number of exclusion constraints is huge. The approach we propose consists in defining vehicle types that include the identification of the products they may carry. One then includes as many "copies" of an actual vehicle as there are mutually exclusive products that may use it. Of course, all products which are not incompatible may use all the copies. In the present context, one then has $\mathcal{T}(p) \subseteq \mathcal{T}$ and $\mathcal{V}(p) \subseteq \mathcal{V}$ as the sets of urban-trucks and city-freighters, respectively, that may be used to transport product p.

Let $\mathcal{S} = \{s\}$ stand for the set of satellites. Each satellite has its own particular topology and access characteristics (available space, connections to the street network, forbidden access periods, etc.) that determine its capacity measured in the number of urban-trucks π_s and city-freighters λ_s that may be serviced simultaneously.

Urban-trucks are unloaded at satellites and their content is loaded into city-freighters. For simplicity of presentation, we assume that the corresponding times are the same in all satellites, and that they represent estimations based on historical operational data (or simulation, or both) thus including "safety" time slacks. Let δ_τ represent the time required to unload a urban-truck of type τ and δ_ν stand for the loading time (assuming a continuous operation) for a city-freighter of type ν.

Travel times are also assumed to be based on historical or simulation data (or both) which reflect the circulation rules proper to each particular application. It is clear, however, that travel times are intimately linked to congestion conditions and, thus, vary with time and the particular city zone where one travels (e.g., during morning rush hour, congestion propagates from the exterior toward the center of the city). The $\delta_{ij}^{h(t)}$ travel times are thus defined for given time intervals that correspond to somewhat homogeneous congestion periods.

$\mathcal{E} = \{e\}$	Set of external zones
$\mathcal{Z} = \{z\}$	Set of customer zones
$\mathcal{P} = \{p\}$	Set of products
$\mathcal{C} = \{c\}$	Set of customers
$\mathcal{D} = \{d_i = d_{t[a,b]}^{pec}\}$	Set of customer-demands: Quantity of product p available starting in period t at the external zone e to be delivered to customer c, during time window $[a, b]$
δ_i	Service time for customer-demand i
$\bar{\mathcal{D}} = \{d_k = d_{t[a,b]}^{pez}\}$	Set of zone-demands: Quantity of product p available starting in period t at the external zone e to be delivered to customer zone z, during time window $[a, b]$
$\mathcal{T} = \{\tau\}$	Set of urban-truck types
$\mathcal{V} = \{\nu\}$	Set of city-freighter types
u_τ	Capacity of urban-truck type τ
u_ν	Capacity of city-freighter type ν
$\mathcal{T}(p)$	Set of urban-truck types that may be used to transport product p
$\mathcal{V}(p)$	Set of city-freighter types that may be used to transport product p
$\mathcal{S} = \{s\}$	Set of satellites
π_s	Capacity of satellite s in terms of number of urban-trucks it may accommodate simultaneously
λ_s	Capacity of satellite s in terms of number of city-freighters it may accommodate simultaneously
δ_τ	Time required to unload a urban-truck of type τ
δ_ν	Loading time (continuous operation) for a city-freighter of type ν
$\delta_{ij}^{h(t)}$	Travel time between two points i, j in the city, where each point may be a customer, a customer zone, an external zone, a satellite, or a depot; Travel is initiated at period t and duration is adjusted for the corresponding congestion period $h = 1, \ldots, H$

Table 1: General Notation

We conclude this section by examining how to define the period length. Planning is performed for $t = 1, \ldots, T$ periods. The planning horizon is relatively small, a few hours to a half day in most cases. Consequently, each period should be relatively small, of the order of the quarter or half hour, for example. The precise definition of the planning horizon is application-specific, but a number of considerations may impact the modelling of the time discretization. In this paper, we consider two.

A first consideration is to select a sufficiently short period length such that each urban-truck that leaves an external zone in each period provides a different service (i.e., satellites serviced, type of vehicle, etc.). This simplifies the formulation of the service design model of Section 4. The second consideration comes from the need to account for urban-trucks and city-freighters that may take more than one period to unload and load, respectively, and thus, have to be counted against the satellite capacity in several periods. Consequently, the *period length* is defined as the time required to unload (and transfer) the contents of the smallest urban-truck. To simplify the presentation of the formulations, we assume that all urban-truck types are so configured that the corresponding unloading time is an integer multiple of the period length and that there is still at most one departure of each urban-truck service at each period and external zone.

4 Demand Distribution and Service Design Model

The first model addresses the issues of determining when urban-trucks leave the external zones and to which satellites they travel, as well as what itineraries are used to move the freight from the external zones toward their destinations. At this level, the type of city-freighter used is explicitly taken into account, while the duration and cost attributes of the final leg, the distribution route from the satellites to customers, are approximated. Demand is aggregated into zone-demands. The focus in on the selection, for each demand, of a set of urban-truck services and satellites that will ensure on-time delivery at minimum total system cost which, in this case, implies a minimum number of vehicle movements in the city. Table 2 summarizes the notation proper to this section.

Consider the set of urban-truck *services* $\mathcal{R} = \{R_i\}$. Service R_i originates at an external zone e and travels to one or several satellites. Define $\sigma(R_i)$, the set of satellites visited, in the order of visit. Together with the access and egress corridors, $\sigma(R_i)$ defines a route through the city. Associated to this route, there is a "fixed" cost $k_i^{h(t)}$ that accounts for the nuisance to get to satellites and to move from the last satellite in $\sigma(R_i)$ back to an external zone, given the level of congestion in the city. A "variable" cost, per urban-truck-km, could be considered. Since the service routes are pre-defined, however, this cost is assumed to be included in $k_i^{h(t)}$.

Let $\tau(R_i)$ be the vehicle type of service R_i and $t(R_i)$ its departure time from e. The service arrives at the first satellite s of $\sigma(R_i)$ at a time $t(R_i, s)$ determined by $\delta_{es}^{h(t)}$, the time required to travel the associated distance at the corresponding congestion period. The service arrives at s', the next satellite on its route, at time $t(R_i, s')$ determined by $\delta_{ss'}^{h(t)}$, the time required to travel between the two satellites. The set $\{t(R_i), t(R_i, s) \text{ for } s \in \sigma(R_i)\}$ gives the schedule for service R_i.

Let $\mathcal{M}_k$ stand for the set of *itineraries* that may be used for demand $d_k = d_{t[a,b]}^{pez} \in \bar{\mathcal{D}}$. An *itinerary* $M_j^k \in \mathcal{M}_k$ specifies how freight is to be distributed: From its external zone $e \in \mathcal{E}$, using an urban-truck service $R(M_j^k)$ of type $\tau(R(M_j^k)) \in \mathcal{T}(p)$, through a satellite (in most cases) $s(M_j^k) \in \sigma(R(M_j^k))$, delivered by a city-freighter of type $\nu(M_j^k) \in \mathcal{V}(p)$ to customer zone $z \in \mathcal{Z}$, within the specified time window $[a_k, b_k]$. Several conditions determine the feasibility of itineraries and limit their number:

- The itinerary must use a satellite to which the corresponding customer zone has been assigned; This condition is enforced by the urban-truck service definition;
- The types of the vehicles used must be compatible with the product as specified by $\mathcal{V}(p)$;
- The departure time of the service used, $t(R(M_j^k))$ must be later than the time of availability;
- The planned arrival time at the customer zone destination must occur during the specified time interval. This is determined by the arrival time at the satellite, $t(s(M_j^k)) = t(R(M_j^k), s(M_j^k))$, plus the handling time at the satellite that we approximate to the time to load the city-freighter, plus the routing time to destination, adjusted for congestion: $a_k \leq t(s(M_j^k)) + \delta_\nu + \delta_{s(M_j^k)z}^{h(t)} \leq b_k$.

Set $\mathcal{M}_k$ may then be partitioned into subsets of itineraries that obey these restrictions:

$$\begin{aligned}
\mathcal{M}_k^{st\nu} &= \{j \in \mathcal{M}_k | s(M_j^k) = s \text{ and } t(R(M_j^k)) \geq t \text{ and } \nu(M_j^k) = \nu \in \mathcal{V}(p) \\
&\quad \text{and the previous time restrictions are respected}\}; \\
\mathcal{M}_k^\nu &\subseteq \mathcal{M}_k^{st\nu} \text{ collects all itineraries with } \nu(M_j^k) = \nu.
\end{aligned}$$

As indicated in Section 3.1, city-freighter travel times to each customer (demand-zone, actually), $\delta_{sz}^{h(t)}$, are estimations that account for the congestion level in each period. The same approximation procedure also yields $k_\nu^{h(t)}$, the unit cost of a city-freighter of type ν, also adjusted for the congestion period.

When a satellite is located at an external zone, the sets of itineraries for the associated customer zones are somewhat limited, in the sense that itineraries do not include a urban-truck component. One still has to select the satellite and the departure time, however.

In order to allow for an uniform approach, we consider that all these itineraries include the R_0 service, from the external zone to itself, with 0 travel time.

Two sets of decision variables are defined. The first determines the urban-truck service network: to dispatch or not a given service at the planned departure time: $y_i = 1$ if service R_i is operated, 0 otherwise. It is possible to impose minimum load restrictions on departures, but these will not be included in this model not to overload the presentation.

$R_i \in \mathcal{R}$	Urban-truck service
$\sigma(R_i)$	Set of satellites visited, in the order of visit, by urban-truck service R_i
$k_i^{h(t)}$	Unit cost of urban-truck service R_i at period t, adjusted for the congestion period $h = 1, ..., H$
$\tau(R_i)$	Vehicle type of service R_i
$t(R_i)$	Departure time of service R_i from its origin $e \in \mathcal{E}$
$t(R_i, s)$	Arrival time of service R_i at satellite $s \in \sigma(R_i)$
$M_j^k \in \mathcal{M}_k$	Itinerary for demand $d_k \in \bar{\mathcal{D}}$
$R(M_j^k)$	Urban-truck service used by itinerary M_j^k
$\tau(R(M_j^k)$	Type of the urban-truck service used by itinerary M_j^k
$t(R(M_j^k))$	Departure time of the urban-truck service used by itinerary M_j^k
$s(M_j^k)$	Satellite used by itinerary M_j^k
$t(s(M_j^k))$	Arrival time at satellite $s(M_j^k)$ used by itinerary M_j^k
$\nu(M_j^k)$	Type of the city-freighter used by itinerary M_j^k
$\delta_{sz}^{h(t)}$	Estimated city-freighter travel time from customer zone z to satellite s, at period t, adjusted for the corresponding congestion period $h = 1, \ldots, H$
$k_\nu^{h(t)}$	Unit cost of a city-freighter of type ν at period t, adjusted for the congestion period $h = 1, \ldots, H$

Table 2: Service and Itinerary Notation

The second set relates to how demand is moved and when, e.g., what itinerary is used for each demand. Define $z_j^k = 1$, if itinerary j of demand d_k is used, 0 otherwise. When demand for a customer zone may be split between services, one also needs continuous variables x_j^k indicating the proportion of demand d_k moved by itinerary M_j^k.

The problem may be formulated as a scheduled service network design problem (Crainic 2000, 2003), where the specification of the time periods is included in the definition of demand and urban-truck services. The model to minimize the total cost of the system, and thus the number of urban-trucks in the city, with no splitting of demand, may then be written as follows:

$$\text{Minimize} \quad \sum_{i \in \mathcal{R}} k_i^{h(t)} y_i + \sum_{k \in \bar{\mathcal{D}}} \sum_{\nu \in \mathcal{V}} k_\nu^{h(t)} \left[\sum_{j \in \mathcal{M}_k^\nu} d_k z_j^k \right] / u_\nu \tag{1}$$

$$\text{Subject to} \quad \sum_{k \in \bar{\mathcal{D}}} \sum_{j \in \mathcal{M}_k | R(M_j^k) = R_i} d_k z_j^k \leq u_\tau y_i \quad \forall R_i \in \mathcal{R} \tag{2}$$

$$\sum_{j \in \mathcal{M}_k} z_j^k = 1 \quad \forall k \in \bar{\mathcal{D}} \tag{3}$$

$$\sum_{\tau \in \mathcal{T}} \sum_{t^- = t - \delta_\tau + 1}^{t} \sum_{i \in \mathcal{R} | t(R_i, s) = t^-} y_i \leq \pi_s \quad \forall s \in \mathcal{S}, \ t = 1, \ldots, T \tag{4}$$

$$\sum_{\tau \in \mathcal{T}} \sum_{t^- = t - \delta_\tau + 1}^{t} \sum_{i \in \mathcal{R} | t(R_i, s) = t^-} \alpha_\tau y_i \leq \lambda_s \quad \forall s \in \mathcal{S}, \ t = 1, \ldots, T \tag{5}$$

$$y_i \in \{0, 1\} \quad \forall R_i \in \mathcal{R} \tag{6}$$

$$z_j^k \in \{0, 1\} \quad \forall j \in \mathcal{M}_k, \ k \in \bar{\mathcal{D}} \tag{7}$$

The objective function (1) sums up the costs relative to the total number of urban-trucks and city-freighters used to satisfy demand. A linear approximation is used for the latter. Relations (2) enforce the urban-truck capacity restrictions, where the load of each service R_i equals the sum over all demands and all associated itineraries using that service. These are the classical linking constraints of network design formulations. Equations (3) indicate that each demand must be satisfied by a single itinerary. Constraints (4) and (5) enforce the satellite capacity restrictions in terms of urban-trucks and city-freighters, respectively, where the number of vehicles using a satellite at any given time equals those that arrive at time t and those that arrived before but are still at the satellite at time t. (In an actual implementation only the tightest constraints would be kept, of course.) The α_τ parameter represents the number of city-freighters of the smallest dimension required to load the freight brought by an urban-truck of type τ. This represents a worst-case approximation of the number of city-freighters required at a satellite (and thus provide some slack in the system for the actual operations).

Two cases must be considered when demand may be split. In the first case, demand may be split among urban-trucks, but not among city-freighters, while complete delivery splitting is allowed in the second case. Whatever the case, however, the actual routing of the cargo is addressed by the city-freighter circulation model of Section 5. The impact of the delivery-splitting policy is felt at the level of the service design model only through the estimation of the number of city-freighters required at satellites (constraints (5) of the previous model).

In both cases, the flow variables x_j^k are required and the z_j^k are dropped. When demand may be split among urban-trucks but not among city-freighter routes, the formulation becomes:

$$\text{Minimize} \quad \sum_{i \in \mathcal{R}} k_i^{h(t)} y_i + \sum_{k \in \bar{\mathcal{D}}} \sum_{\nu \in \mathcal{V}} \sum_{j \in \mathcal{M}_k^\nu} k_\nu^{h(t)} x_j^k / u_\nu \tag{8}$$

$$\sum_{k \in \bar{\mathcal{D}}} \sum_{j \in \mathcal{M}_k | R(M_j^k) = i} x_j^k \leq u_\tau y_i \quad \forall R_i \in \mathcal{R} \tag{9}$$

$$\sum_{j \in \mathcal{M}_k} x_j^k = d_k \quad \forall k \in \bar{\mathcal{D}} \tag{10}$$

$$x_j^k \geq 0 \quad \forall j \in \mathcal{M}_k, \ k \in \bar{\mathcal{D}} \tag{11}$$

and constraints (4), (5), and (6). When complete split delivery is allowed, constraints (5) are replaced by:

$$\sum_{\tau \in \mathcal{T}} \sum_{t^- = t - \delta_\tau + 1}^{t} \sum_{k \in \bar{\mathcal{D}}} \sum_{\nu \in \mathcal{V}} \left[\sum_{j \in \mathcal{M}_k^{st^- \nu}} x_j^k \right] / u_\nu \leq \lambda_s \quad \forall s \in \mathcal{S}, \ t = 1, \ldots, T. \tag{12}$$

The previous models are service network design formulations that belong to the class of fixed cost, capacitated, multicommodity network design problems. Magnanti and Wong (1984), Minoux (1989), Balakrishnan, Magnanti, and Mirchandani (1997), and Crainic (2000) survey the network design field. Recent surveys related to service network design models and applications were presented by Christiansen *et al.* (2005) for maritime transportation, Cordeau, Toth, and Vigo (1998) for rail transportation, Crainic (2003) for long-haul transportation, and Crainic and Kim (2005) for intermodal transportation.

Service network design problems are difficult. They usually exhibit weak relaxations and are of very large dimensions. As a result, the field is dominated by various heuristics (e.g., Barnhart, Jin, and Vance 2000; Crainic and Rousseau 1986; Crainic and Roy 1988; Equi *et al.* 1997; Farvolden and Powell 1991, 1994; Grünert and Sebastian 2000; Gorman 1998; Haghani 1989; Kim *et al.* 1999; Powell 1986; Powell and Sheffi 1989).

Very promising recent perspectives are provided by the work of Ghamlouche, Crainic, and Gendreau (2003, 2004) on meta-heuristics searching very large, cycle-based neighbourhoods, the model transformation proposed by Armacost, Barnhart, and Ware (2002) where combinations of services and demands reduce the dimensions of the problem and implicitly account for the flow distribution, and the application the adaptive dynamic programming methods proposed for resource management (Powell and Carvalho 1997, 1998; Powell and Topaloglu 2003; Powell 2003; Powell, Bouzaïene-Ayari, and Simaõ 2005) to service network design (Dall'Orto *et al.* 2005). Parallel computation, parallel cooperative search, in particular, which involves various exact and heuristic methods (e.g., Crainic and Gendreau 2002, Crainic 2005, and Crainic and Toulouse 2003) are the natural complement to these developments, especially given the complexity and dimensions of the urban-freight service design problem.

5 City-freighter Circulation Model

The service design formulation of the preceding section yields workloads for satellites, for each period and type of city-freighter. These workloads take the form of the customer zones, and the associated demands, that have to be served, starting at each time period, by city-freighters leaving the satellite. Once service is completed at all customers in the assigned zones, the city-freighters move either to a depot or to a satellite for further operations. The scope of the models developed in this section is to help plan the operations of the fleet of city-freighters, that is, to ensure that city-freighter routes deliver the goods on time and that vehicles arrive at satellites on time for their next assignments.

Recall that there are no waiting areas at satellites. Thus, city-freighters must arrive just-in-time for the designated freight to be transferred and depart according to the schedule planned by the service design formulation. The main difficulty in this problem is to evaluate the time required to finish serving the customers: time to travel from the satellite to the "first" customer and perform the service, plus the time to move from one customer to the next, and so on. The travel time from the "last" customer to any one of the satellites or depots in the system is known. One just has to know which one of the customers served by the current route is the "last" one and when service to that customer ends. This generally implies that the order of customers in the route is known. This type of information cannot be obtained from a service network model as presented in the previous section.

We present two formulations. First a general one, followed by a model that takes advantage of the particular setting of the problem and exploits the decomposition of the general formulation to obtain simpler problems and may form the basis for an efficient solution procedure. Notice that the split-load issue does not arise in this context because the demand for each city-freighter, at each satellite and time period, is determined by the service network design of the previous section.

5.1 The general fleet management model

Consider a given satellite s at time t, identified as $s(t)$. The service design formulation yields an assignment of one or several customer zones to $s(t)$, zones that must be served by city-freighters of type ν, leaving at time period t from s. Considering all customers of these zones together may conduct to a better utilization of the vehicles. Consequently, we work with customer demands $d_i \in \mathcal{D}$. We assume that each customer demand is less than the capacity of the designated city-freighter. When this is not the case, the customer demand is duplicated an appropriate number of time yielding some customers that require full city-freighters and one customer with demand less than the vehicle capacity. We assume customer demands to be delivered by a single vehicle. Denote by

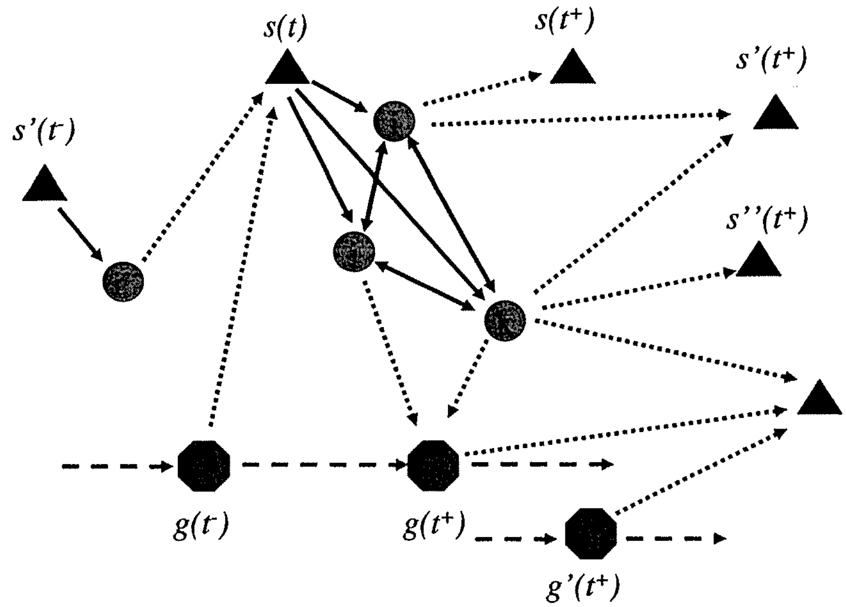

Figure 1: City Logistics Movements

$\mathcal{C}_{st\nu}$ the set of these customers. Also note $\mathcal{S}(t) = \{s(t)\}$ and $\mathcal{G}(t) = \{g(t)\}$ the sets of satellites and city-freighter depots, respectively, at time $t = 0, \ldots, T+1$, where the opening and closing hours for all depots are indicated as time 0 and $T+1$, respectively.

Figure 1 illustrates the dynamics of the system in a somewhat aggregated form, where full and dotted lines denote possible loaded and empty city-freighter movements, respectively. Operations are illustrated starting from a satellite s at time t (node $s(t)$) for one type of city-freighter (ν). Triangles and octagons denote satellites and city-freighter depots, respectively, at various time periods, while i, j, and k represent customers in $\mathcal{C}_{st\nu}$. A number of city-freighters leave the satellite at time t and each will first undertake a route to serve one or more customers in $\mathcal{C}_{st\nu}$. Once the last customer is served, the city-freighter goes either to a depot (e.g., the j to $g(t^+)$ movement) or to a satellite. This last may be the one it just left, $s(t^+)$, or a different one, e.g., $s'(t^+)$ or $s''(t^+)$, where t^+ indicates a later time period as determined by the total travel and customer service time. Recall that city-freighters cannot wait at satellites or customer locations and, thus, they must return to a depot to wait for later service. Consequently, city-freighters arriving at satellites for loading come either from depots (e.g., the $g(t^-)$ to $s(t)$ movement) or from the last customer on a previous service route, e.g., the i' to $s(t)$ movement in Figure 1. The restrictions on the time instances city-freighters must arrive at satellites and customers determine the actual feasible movements and the corresponding arcs in the space-time network representation:

- An arc $(s(t), i)$ goes from satellite $s(t)$ to each customer $i \in \mathcal{C}_{st\nu}$, such that the service time-window restriction, $a_i \leq t + \delta_{si}^{h(t)} \leq b_i$, is satisfied. Identify $\mathcal{A}_{st\nu}^{Z} = \{(s(t), i) \mid i \in \mathcal{C}_{st\nu}\}$, $s \in \mathcal{S}$, $\nu \in \mathcal{V}$, $t = 1, \ldots, T$. In Figure 1, $\mathcal{A}_{st\nu}^{Z} = \{(s(t), i), (s(t), j), (s(t), k)\}$.

  Set $\mathcal{A}_{st\nu}^{Z-} = \{(i', s(t) \mid i' \in \mathcal{C}_{s't^-\nu}, s' \in \mathcal{S}, \nu \in \mathcal{V}, t^- < t = 1, \ldots, T\}$, $s \in \mathcal{S}$, $\nu \in \mathcal{V}$, $t = 1, \ldots, T$, represents the backstar of node $s(t)$. Arc $(i', s(t))$ of Figure 1 belongs to $\mathcal{A}_{st\nu}^{Z-}$.

- An arc exists between each pair of customers (i, j), $i, j \in \mathcal{C}_{st\nu}$, for which the movement is feasible with respect to the time-window constraints. Given the time window $[a_i, b_i]$ and the service time δ_i of customer i, one adds only the arcs to customers j such that $a_j \leq a_i + \delta_i + \delta_{ij}^{h(t)}$ or $b_i + \delta_i + \delta_{ij}^{h(t)} \leq b_j$. Set $\mathcal{A}_{ist\nu}^{C}$ contains these arcs, while set $\mathcal{A}_{ist\nu}^{C-}$ holds the same type of arcs arriving at customer i at time t (the backstar of the node).

- Arcs link each customer $i \in \mathcal{C}_{st\nu}$ to depots in later periods. The set $\mathcal{A}_{ist\nu}^{G} = \{(i, g(t^+))\}$, $i \in \mathcal{C}_{st\nu}$, $s \in \mathcal{S}$, $\nu \in \mathcal{V}$, $t = 1, \ldots, T$, contains the arcs corresponding to feasible movements, that is, arcs that arrive at a depot g at time t^+, such that $a_i + \delta_i + \delta_{ig}^{h(t)} \leq t^+ \leq b_i + \delta_i + \delta_{ig}^{h(t)}$. For customer k of Figure 1 this set equals $\{(k, g(t^+)))\}$.

- Similarly, arcs link each customer $i \in \mathcal{C}_{st\nu}$ to satellites in later periods. The set $\mathcal{A}_{ist\nu}^{S} = \{(i, s'(t^+))\}$, $i \in \mathcal{C}_{st\nu}$, $s \in \mathcal{S}$, $\nu \in \mathcal{V}$, $t = 1, \ldots, T$, contains the arcs corresponding to such feasible movements, that is, arcs that arrive at a satellite $s' \in \mathcal{S}$ at time $t^+ - \delta_\nu \leq T$, such that city-freighters may be loaded and leave by time t^+: $a_i + \delta_i + \delta_{is'}^{h(t)} \leq t^+ - \delta_\nu \leq b_i + \delta_i + \delta_{is'}^{h(t)}$. In Figure 1, $\mathcal{A}_{ist\nu}^{S} = \{(i, s(t^+)), (i, s'(t^+))\}$.

- When needed, city-freighters may be dispatched out of depots to satellites. Arcs in $\mathcal{A}_{st\nu}^{GS} = \{(g(t^-), s(t)) \mid g \in \mathcal{G}, t^- = t - \delta_\nu - \delta_{gs}^{h(t)}\}$, $s \in \mathcal{S}$, $\nu \in \mathcal{V}$, $t = 1, \ldots, T$, represent these movements that must arrive on time at satellite s for the next assignment.

  From a depot point of view, the same arcs are grouped into the sets $\mathcal{A}_{gt\nu}^{D} = \{(g(t), s'(t^+)) \mid s' \in \mathcal{S}, t^+ > t\}$, $\forall g \in \mathcal{G}$, $t = 1, \ldots, T$.

- City-freighters may be held at depots, which yields the set $\mathcal{A}^{G} = \{(g(t), g(t + 1)), t = 0, \ldots, T, \forall g \in \mathcal{G}\}$.

- The starting and closing of the work horizon are indicated by two sets of arcs, $\mathcal{A}_0^G$ and $\mathcal{A}_T^G$, which include the initial movements out of depots and the final movements back to depots, respectively.

The resulting network is made up of the sets of nodes $\mathcal{N}$ and arcs $\mathcal{A}$:

$$\begin{aligned} \mathcal{N} &= \cup_t \{ \ \mathcal{S}(t) \cup \mathcal{G}(t) \cup_{s\nu} \{\mathcal{C}_{st\nu}\} \ \} \\ \mathcal{A} &= \cup_{st\nu} \mathcal{A}_{st\nu}^Z \cup_{ist\nu} \{\mathcal{A}_{ist\nu}^C \cup \mathcal{A}_{ist\nu}^G \cup \mathcal{A}_{ist\nu}^S\} \cup_{gst\nu} \mathcal{A}_{st\nu}^{GS} \cup \mathcal{A}^G \cup \mathcal{A}_0^G \cup \mathcal{A}_T^G. \end{aligned}$$

Two types of decision variables are defined

- Flow variables $\theta_{ij\gamma}^{\nu}$, $(i,j) \in \mathcal{A}$, $\gamma = 1, \ldots, n_\nu$, $\nu \in \mathcal{V}$, that equal 1 if arc (i,j) is used by the city-freighter γ of type ν, and 0 otherwise;
- Time variables $w_{i\gamma}^{\nu}$, $i \in \mathcal{N}$, $\gamma = 1, \ldots, n_\nu$, $\nu \in \mathcal{V}$, that indicate when the city-freighter γ, of type ν, starts service (arrives) at node i.

Let n_ν represent the number of available city-freighters of type ν, while $k_{ij\nu}^{h(t)}$ stands for the unit transportation cost for a city-freighter of type ν, between two points i, j in the city, where each point may be a customer, a customer zone, a satellite, or a depot. Travel is initiated at period t and its duration is adjusted for the congestion period $h = 1, \ldots, H$. A mathematical programming formulation of this problem may then be written as follows:

$$\text{Minimize} \quad \sum_{t=0}^{T} \sum_{\nu \in \mathcal{V}} \sum_{\gamma=1}^{n_\nu} \left[\sum_{(i,j)\in\mathcal{A}} k_{ij\nu}^{h(t)} \theta_{ij\gamma}^{\nu} + k_{\nu}^{h(t)} \sum_{s\in\mathcal{S}} \sum_{i\in\mathcal{C}_{st\nu}} \theta_{si\gamma}^{\nu} \right] \tag{13}$$

$$\text{Subject to} \quad \sum_{(s,i)\in\mathcal{A}_{st\nu}^Z} \theta_{si\gamma}^{\nu} = 1 \quad \forall s \in \mathcal{S}, \ \gamma = 1, \ldots, n_\nu, \ \forall \nu \in \mathcal{V}, \ t = 1, \ldots, T \tag{14}$$

$$\sum_{(g,s)\in\mathcal{A}_{st\nu}^{GS}} \theta_{gs\gamma}^{\nu} + \sum_{(i,s)\in\mathcal{A}_{st\nu}^{Z-}} \theta_{is\gamma}^{\nu} = \sum_{(s,i)\in\mathcal{A}_{st\nu}^Z} \theta_{si\gamma}^{\nu} \qquad \forall s \in \mathcal{S}, \ \forall g \in \mathcal{G}, \ \forall \nu \in \mathcal{V}, \ t = 1, \ldots, T \tag{15}$$

$$\sum_{(i,j)\in\mathcal{A}_{ist\nu}^C} \theta_{ij\gamma}^{\nu} + \sum_{(i,s')\in\mathcal{A}_{ist\nu}^S} \theta_{is'\gamma}^{\nu} + \sum_{(i,g)\in\mathcal{A}_{ist\nu}^G} \theta_{ig\gamma}^{\nu} = 1 \qquad \forall i \in \mathcal{C}_{st\nu}, \ \forall s \in \mathcal{S}, \ \forall \nu \in \mathcal{V}, \ t = 1, \ldots, T \tag{16}$$

$$\theta_{si\gamma}^{\nu} + \sum_{(j,i)\in\mathcal{A}_{ist\nu}^{C-}} \theta_{ji\gamma}^{\nu} = 1 \qquad \forall i \in \mathcal{A}_{st\nu}^Z, \ \forall s \in \mathcal{S}, \ \forall \nu \in \mathcal{V}, \ t = 1, \ldots, T \tag{17}$$

$$\theta^{\nu}_{g(t-1)g(t)\gamma} + \sum_{(i,g)\in\mathcal{A}^{G}_{ist\nu}} \theta^{\nu}_{ig\gamma} = \theta^{\nu}_{g(t)g(t+1)\gamma} + \sum_{(g,s)\in\mathcal{A}^{D}_{gt\nu}} \theta^{\nu}_{gs\gamma}$$
$$\forall g \in \mathcal{G},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (18)$$

$$w^{\nu}_{i\gamma} + \delta_i + \delta^{h(t)}_{ij} - w^{\nu}_{j\gamma} \leq (1 - \theta^{\nu}_{ij\gamma})(b_i + \delta_i + \delta^{h(t)}_{ij} - a_j)$$
$$\gamma = 1,\ldots,n_{\nu},\ \forall (i,j) \in \mathcal{A}^{C}_{ist\nu},\ \forall s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (19)$$

$$a_i \left[\theta^{\nu}_{si\gamma} + \sum_{(j,i)\in\mathcal{A}^{C-}_{ist\nu}} \theta^{\nu}_{ji\gamma}\right] \leq w^{\nu}_{i\gamma} \leq b_i \left[\sum_{(i,j)\in\mathcal{A}^{C}_{ist\nu}} \theta^{\nu}_{ij\gamma} + \sum_{(i,s)\in\mathcal{A}^{S}_{ist\nu}} \theta^{\nu}_{is\gamma} + \sum_{(i,g)\in\mathcal{A}^{G}_{ist\nu}} \theta^{\nu}_{ig\gamma}\right]$$
$$\forall i \in \mathcal{C}_{st\nu},\ \gamma = 1,\ldots,n_{\nu},\ \forall s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (20)$$

$$(w^{\nu}_{i\gamma} + \delta_i + \delta^{h(t)}_{is} - w^{\nu}_{s\gamma}) \leq (1 - \theta^{\nu}_{is\gamma})(b_i + \delta_i + \delta^{h(t)}_{is} - (t - \delta_{\nu} - \delta))$$
$$\gamma = 1,\ldots,n_{\nu},\ \forall (i,s) \in \mathcal{A}^{Z-}_{st\nu},\ \forall s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (21)$$

$$(w^{\nu}_{s\gamma} + \delta_{\nu} + \delta^{h(t)}_{is} - w^{\nu}_{i\gamma}) \leq (1 - \theta^{\nu}_{si\gamma})(t + \delta^{h(t)}_{is} - a_i)$$
$$\gamma = 1,\ldots,n_{\nu},\ \forall (i,s) \in \mathcal{A}^{Z-}_{st\nu},\ \forall s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (22)$$

$$t - \delta_{\nu} - \delta \leq w^{\nu}_{s\gamma} \leq t - \delta_{\nu} \quad \forall s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,..,.T \quad (23)$$

$$\sum_{i\in\mathcal{A}^{Z}_{st\nu}} d_i \left[\theta^{\nu}_{si\gamma} + \sum_{(j,i)\in\mathcal{A}^{C-}_{ist\nu}} \theta^{\nu}_{ji\gamma}\right] \leq u_{\nu} \quad \gamma = 1,\ldots,n_{\nu},\ s \in \mathcal{S},\ \forall \nu \in \mathcal{V},\ t = 1,\ldots,T \quad (24)$$

$$\theta^{\nu}_{ij\gamma} \in \{0,1\} \quad \forall (i,j) \in \mathcal{A},\ \gamma = 1,\ldots,n_{\nu},\ \forall \nu \in \mathcal{V} \quad (25)$$

Equations (14) ensure that each vehicle leaving a satellite goes to one customer only and equations (15) represent the conservation of flow at satellites for each service route. Constraints (16) force the single assignment of customers to routes, ensure that the city-freighter leaving a customer goes either to another customer of the same route, a satellite, or a depot and, combined to constraints (17), provide the flow conservation relations at customer nodes. Equations (18) represent the conservation of flow at depots.

Constraints (19) and (20), enforce schedule feasibility with respect to the service time consideration for movements between customers. Expressions (21), (22), and (23) represent the same constraints for the movements from customers to satellites and from satellites to customers. The δ factor that appears in these constraints stands for the relatively small variation in arrival time at satellites allowed to vehicles. The corresponding constraints for the depot-to-satellite movements are enforced through the definition of sets $\mathcal{A}^{GS}_{st\nu}$. Relations (24) enforce the restrictions on the city-freighter capacities, each time a vehicle leaves a satellite to deliver customer demands. Finally conditions (25) impose binary values on the flow variables.

The service network design model of Section 4 assigns customer zones, and thus, customer demands to each satellite, time period, and city-freighter type. Lower (l^{ν}_{st}) and upper (u^{ν}_{st}) bounds on the number of city-freighters of each type that leave a satellite at any given period may be derived from this demand and constraints (26) may be added to make the formulation tighter.

$$l^{\nu}_{st} \leq \sum_{(s,i)\in\mathcal{A}^{Z}_{st\nu}} \theta^{\nu}_{si\gamma} \leq u^{\nu}_{st} \quad \forall s \in \mathcal{S},\ \gamma = 1,\dots,n_{\nu},\ \forall \nu \in \mathcal{V},\ t = 1,\dots,T \qquad (26)$$

The (13)-(25) formulation may be viewed as a time-dependent, multi-depot, heterogeneous fleet vehicle routing problem with time windows, and additional constraints that capture the synchronization aspect of the problem. This "coordination" of activity starting times at satellites over the entire time horizon adds to what already is a hard combinatorial problem.

Meta-heuristics have proved most adequate for the class of problems considered here. Toth and Vigo (2002) present a collection of surveys of vehicles routing problems, properties, and solution approaches, including the contributions by Cordeau *et al.* (2002) Gendreau, Laporte, and Potvin (2002) dedicated to problems with time window restrictions and to meta-heuristics, respectively. Bräysy and Gendreau (2005a,b) present an in-depth and up-to-date survey of the same field.

These surveys provide the ground to be confident in our capabilities to develop appropriate meta-heuristics for the problem at hand. They also point out that progress in recent times has been achieved quite often by combining ("hybridising" is the trendy term) several methods, leading to complex algorithmic designs. A different approach has also emerged, however, where the goal is to build simpler but more robust methods that consistently achieve very high solution qualities. The Unified Tabu Search proposed by Cordeau, Laporte, and Mercier (2001) and the cooperative search of Le Bouthillier, Crainic, and Kropf (2005; see also Le Bouthillier and Crainic 2005) illustrate this trend that we intend to follow for this problem.

One must recall, however, that the actual routing is to be decided during operations, when the exact demand will be known. Thus, in the following, we propose a decomposition approach that takes advantage of the context and characteristics of the problem.

5.2 A decomposition approach

The formulation (13)-(25) introduced earlier on is a "complete" model that integrates both issues related to the routing of each vehicle and the coordination of the fleet and the synchronization of activities at satellites. It a sense, the model is general but does not attempts to take advantage of the structure of the problem. We propose a decomposition approach which does just that and may thus become the basis for an efficient solution methodology. The two phases of this approach are:

Routing. Solve *independently* each vehicle routing problem with time windows (VRPTW) associated with customers in $\mathcal{C}_{st\nu}$, that is with city-freighters of type $\nu \in \mathcal{V}$, leaving satellites $s \in \mathcal{S}$, at times $t = 1, \ldots, T$.

Circulation. Solve the problem of moving city-freighters among activities at satellites (loading), customers (end of service route), and depots (to wait, eventually), so that the timing and synchronization of all activities is provided at minimum total cost.

The output of the service design model of Section 4 yields the sets $\mathcal{C}_{st\nu}$, that is the input to the Routing phase, which thus consists in solving many small VRPTW problems. The number of VRPTW subproblems corresponds to all combinations (s, t, ν) defined by the service design problem, which is bounded by $|\mathcal{S}| \times |\mathcal{V}| \times T$. The size of each problem is relatively small, however, the cardinality of sets $\mathcal{C}_{st\nu}$ being in the low teens. Individual VRPTW problems (return arcs from each customer to the satellite with 0 travel time and cost are included) may thus be addressed very efficiently either exactly (see; Toth and Vigo 1998 for a survey) or by one of the fast meta-heuristics presented in the surveys introduced previously (e.g., the cooperative search of Le Bouthillier, Crainic, and Kropf 2005). The global of efficiency of this phase may be increased by solving these individual problems in parallel.

The output of the routing phase specifies for each satellite, time period, and vehicle type, when city-freighters become available for re-positioning after their service routes as well as their number. Let $\Delta_{st\nu}$ stand for the time required to serve customers in $\mathcal{C}_{st\nu}$, and $n_{st\nu}$ represent the (integer) number of city-freighters of type ν, available for repositioning (following their circuits) "at" satellite s at time $t + \Delta_{st\nu}$. A multiflow formulation may then be built to plan the circulation of the city-freighters during the planing period.

The network is a much simplified version of the one described in the previous section, as illustrated in Figure 2. Two types of nodes are included in set $\mathcal{N}$, *operation* nodes and depots. An operation node $(s(t), \nu)$ is defined for each combination of satellite s, time period t, and city-freighter type ν for which a non-negative demand $n_{st\nu}$ was defined by the service design problem. Depot nodes $g(t)$ represent the vehicle depots $g \in \mathcal{G}$ at all

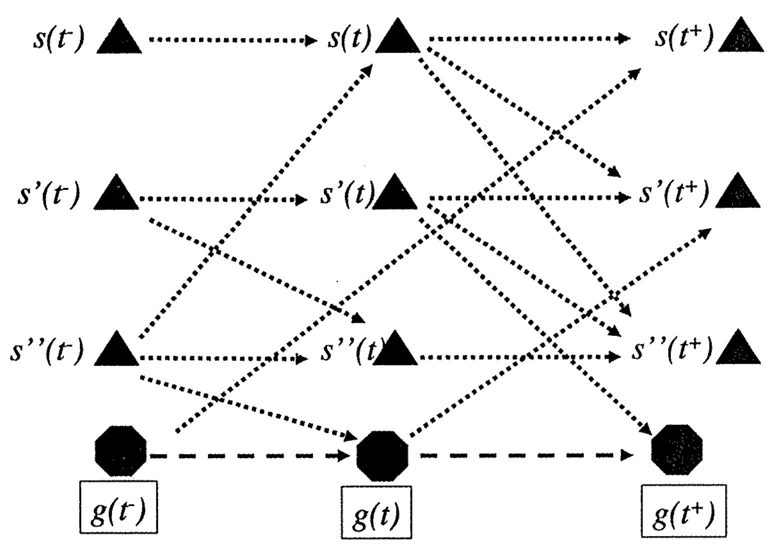

Figure 2: Multicommodity City-freighter Network

time periods $t = 0, \ldots, T+1$. The set $\mathcal{A}$ may then be defined as the union of following sets of arcs:

- $\{(s(t),\ s(t^+)) \mid s \in \mathcal{S},\ \nu \in \mathcal{V},\ t^+ = t + \Delta_{st\nu} + \delta_\nu \leq T,\ t = 1, \ldots, T\}$ representing the feasible re-positioning movements of city-freighters at the same satellite;

- $\mathcal{A}^S_{st\nu} = \{(s(t),\ s'(t^+)) \mid t^+ = t + \Delta_{st\nu} + \delta^{h(t)}_{s(t),s'(t^+)\nu} + \delta_\nu \leq T\}$, $\forall s \in \mathcal{S},\ \nu \in \mathcal{V},\ t = 1, \ldots, T$, representing feasible re-positioning of city-freighters leaving s at time t at different satellites in later periods;

  The corresponding backward star set, $\mathcal{A}^{S-}_{st\nu}$, corresponds to feasible movements from nodes $s'(t^-)$ to node $s(t)$ such that $t^- = t - \delta_\nu - \Delta_{s't^-\nu} - \delta^{h(t^-)}_{s'(t^-)s(t)\nu} \geq 1$, $\forall s' \in \mathcal{S},\ \nu \in \mathcal{V},\ t = 1, \ldots, T$;

- $\mathcal{A}^{GS}_{st\nu} = \{(g(t^-), s(t)) \mid g \in \mathcal{G},\ t^- = t - \delta_\nu - \delta^{h(t)}_{gs} \geq 0\}$, $s \in \mathcal{S},\ \nu \in \mathcal{V},\ t = 1, \ldots, T$, i.e., arcs standing for feasible movements of city-freighters from depots to satellite s arriving in period t;

  From a depot point of view, the same arcs are grouped into the sets $\mathcal{A}^D_{gt\nu} = \{(g(t), s'(t^+)) \mid s' \in \mathcal{S},\ t^+ > t\}$, $\forall g \in \mathcal{G},\ t = 0, 1, \ldots, T$;

- $\mathcal{A}^{SG}_{st\nu} = \{(s(t), g(t)) \mid g \in \mathcal{G}\}$ includes arcs corresponding to feasible movements of city-freighters of type $\nu \in \mathcal{V}$ from satellite $s \in \mathcal{S}$, at time $t = 1, \ldots, T$, to depots; City-freighters arrive at a depot g at time $t^+ = t + \Delta_{st\nu} + \delta^{h(t)}_{sgt\nu}$;

  From a depot point of view, the same arcs are grouped into the sets $\mathcal{A}^{D-}_{gt\nu}$ representing movements arriving at depot $g \in \mathcal{G}$ at time $t = 1, \ldots, T+1$, i.e., starting from $s(t^-)$ at time $t^- = t - \Delta_{s^-t^-\nu} - \delta_{s(t^-)g\nu}$;

- $\mathcal{A}^G$ stands for the holding decisions at city-freighter depots, for $t = 0, \ldots, T+1$.

Define the decision variables $f_{ij\nu}$ to stand for the number of city-freighters of type ν that move between nodes $i, j \in \mathcal{N}$. The associated cost is $k^{h(t)}_{ij\nu}$. Recalling that the first phase yields $n_{st\nu}$, the number of city-freighters of type ν serving customers of satellite s at period t, the multicommodity minimum cost flow formulation becomes:

$$\text{Minimize} \quad \sum_{t=0}^{T+1} \sum_{\nu \in \mathcal{V}} \sum_{(i,j) \in \mathcal{A}} k^{h(t)}_{ij\nu} f_{ij\nu} \tag{27}$$

Subject to

$$f_{s(t)s(t^+)\nu} + \sum_{(i,j)\in\mathcal{A}^{S}_{st\nu}\cup\mathcal{A}^{SG}_{st\nu}} f_{ij\nu} = n_{st\nu} \quad \forall\, s\in\mathcal{S},\ g\in\mathcal{G},\ \nu\in\mathcal{V},\ t=1,\ldots,T \quad (28)$$

$$f_{s(t^-)s(t)\nu} + \sum_{(i,j)\in\mathcal{A}^{S-}_{st\nu}\cup\mathcal{A}^{GS}_{st\nu}} f_{ij\nu} = n_{st\nu} \quad \forall\, s\in\mathcal{S},\ g\in\mathcal{G},\ \nu\in\mathcal{V},\ t=1,\ldots,T \quad (29)$$

$$f_{g(t-1)g(t)\nu} + \sum_{(i,j)\in\mathcal{A}^{D-}_{gt\nu}} f_{ij\nu} = f_{g(t)g(t+1)\nu} + \sum_{(i,j)\in\mathcal{A}^{D}_{gst\nu}} f_{ij\nu}$$
$$\forall\, g\in\mathcal{G},\ \nu\in\mathcal{V},\ t=0,\ldots,T+1 \quad (30)$$

$$f_{ij\nu}\geq 0 \quad \forall\,(i,j)\in\mathcal{A},\ \nu\in\mathcal{V} \quad (31)$$

Constraints (28) and (29) represent the conservation of flow at operation nodes $(s(t),\nu)$. Conservation of flow at depot nodes $g(t)$ are enforced by constraints (30).

6 The Single-tier Case

Most City Logistics projects already initiated or contemplated belong to the single-tier distribution center class and involve either a single or multiple distribution centers. It is therefore appropriate to examine how the methodology proposed in this paper applies to this class. Note that, when multiple distribution centers exist each serving exclusively a particular territory of the city, the problem reduces to solving several single-distribution-center applications.

A number of general considerations apply to both cases. It is clear that satellites do not belong to this problem class. Consequently, the issues related to the city-truck movements between platforms and satellites are not part of the problem either and only city-freighters need to be considered. The problem thus reduces to planning the distribution of demand from external zones, distribution centers and other similar facilities, to customers. The goal is to deliver the goods to customers in time, i.e., within the specified time windows, through an optimal utilization of the fleet of city-freighters in terms of cost and vehicle load.

As in the previous models, the demand $d_i = d^{pec}_{t[a,b]}$ specifies the quantity of product p available starting in period t at the external zone e, to be delivered to customer c within the time window $[a,b]$. Different from the Section 5 models, however, the demand which must be delivered at each time period is not pre-determined (in the general two-tier case, it is an output of the demand distribution and service design model). Consequently, the *design* dimension of the problem has to be explicitly integrated to the formulation to decide when to ship each particular demand and when to start particular vehicle circuits.

When several distribution centers exist, the city-freighter circulation aspect must also be considered to decide where (i.e., to what distribution center) each vehicle must go after the last customer of the route has been serviced.

The time-related design dimension differentiates this problem from a "classical" multiple-depot, time-dependent vehicle routing problem with time windows, even when a single distribution center is considered or when a strategically-determined policy assigns customers to particular CDCs. It also appears to prevent a solution approach based on the simple decomposition scheme presented in Section 5.2. We propose therefore an integrated formulation following the approach presented in Section 5.1.

The time-dependent network of Section 5.1 is modified to account for the differences identified at the beginning of the section.. The set of nodes becomes $\mathcal{N} = \cup_t\{\mathcal{E}(t) \cup \mathcal{G}(t) \cup \mathcal{C}(t)\}$, where the sets of external zones, depots, and customers, respectively, are repeated at each time period t. Obviously, the sets $\mathcal{C}(t)$ may be reduced by deleting all customers with $b < t$. Recall that the service time of customer i is δ_i, while δ_ν represents the time required to load a vehicle of type ν. There are no service times at the other nodes.

A travel time $\delta_{ij}^{h(t)}$, adjusted for congestion conditions, is associated to each arc $(i, j) \in \mathcal{A}$. It is convenient to partition the set of arcs according to the type of nodes linked by the arcs and the period to which the initial node of the arc belongs: $\mathcal{A} = \cup_t\{\mathcal{A}_t^Z,\ \mathcal{A}_t^S,\ \mathcal{A}_t^C,\ \mathcal{A}_t^G,\ \mathcal{A}_t^D,\ \mathcal{A}_t^H\}$, where

$\mathcal{A}_t^Z$: Set of arcs from distribution centers at time t to customers;

$\mathcal{A}_t^S$: Set of arcs from customers at time t to distribution centers;

$\mathcal{A}_t^C$: Set of arcs from customers at time t to customers;

$\mathcal{A}_t^G$: Set of arcs from customers at time t to depots;

$\mathcal{A}_t^D$: Set of arcs from depots at time t to customers;

$\mathcal{A}_t^H$: Set of vehicle-holding arcs at depots at time t (the explicit inclusion of demand-holding arcs at distribution centers is not necessary); For set $\mathcal{A}_t^H$, the travel time is equal to the duration of a period.

Each city-freighter will then perform a route through this graph: starting from its depot at a to-be-determined period, going to an external zone for loading, visiting customers, then returning to a distribution center, and so on. According to the operating policies of the operator, the route may return to the depot of the vehicle and stay there for a number of periods. Several such returns could eventually take place. The route terminates at the depot of the vehicle. To simplify the writing of the model, we make all routes start at period 0 and terminate at period $T+1$. The appropriate number of vehicle-holding arcs are then included to account for late departures and early returns. The arrival time at node j from its predecessor node i on the route performed by vehicle γ of type ν (the time decision variables of the model of Section 5.1) may then simply be computed as

$$w_{j\gamma}^{\nu t} = w_{i\gamma}^{\nu t} + \delta_{ij}^{h(t)} + \begin{cases} \delta_i & i \in \mathcal{C} \\ \delta_\nu & i \in \mathcal{E} \\ 0 & \text{otherwise} \end{cases} \tag{32}$$

A route is *feasible* if it respects all the time restrictions of the customers it includes and if the vehicle-capacity restrictions are enforced at all times. Let $\mathcal{R}_\gamma^\nu = \{R_{\gamma i}^\nu\}$, $\gamma = 1, \ldots, n_\nu$, $\nu \in \mathcal{V}$, represent the set of feasible routes for vehicle γ of type ν. The customers included in route $R_{\gamma i}^\nu$ form the set $\mathcal{C}_{\gamma i}^\nu$ that may be partitioned into $K_{\gamma i}^\nu$ sets $\mathcal{C}_{\gamma i}^{\nu k}$ corresponding to the customers served following each passage at a distribution center. The first feasibility condition is equivalent to $w_{c\gamma}^{\nu t} \leq b_c$ for every customer $i \in \mathcal{C}_{\gamma i}^\nu$. The second condition reduces to $\sum_{i \in \mathcal{C}_{\gamma i}^{\nu k}} d_i \leq u_\nu$, $k = 1, \ldots, K_{\gamma i}^\nu$. Let sets $\mathcal{E}_{\gamma i}^\nu$ and $\mathcal{A}_{\gamma i}^\nu$ stand for the series of distribution centers and arcs, respectively, visited by vehicle γ of type ν, ordered according to the sequence of activities (the same distribution center or arc may appear several times, but not the same customer-demand). The cost of the route may then be computed as

$$k_{\gamma i}^\nu = k_\nu^{h(t)} + \sum_{(i,j) \in \mathcal{A}_{\gamma i}^\nu} k_{ij\nu}^{h(t)} \tag{33}$$

Define the following route-selection decision variables:

$y_{\gamma i}^\nu = 1$ if route $R_{\gamma i}^\nu$ of vehicle γ of type ν is operated, and 0 otherwise.

A path-based formulation for the multiple distribution center case with unsplit delivery problem may then be formulated as follows:

$$\text{Minimize} \quad \sum_{\nu \in \mathcal{V}} \sum_{\gamma=1}^{n_\nu} k_{\gamma i}^\nu y_{\gamma i}^\nu \tag{34}$$

Subject to

$$\sum_{\nu \in \mathcal{V}} \sum_{\gamma=1}^{n_\nu} \sum_{R_{\gamma i}^\nu \in \mathcal{R}_\gamma^\nu \,:\, i \in \mathcal{C}_{\gamma i}^\nu} y_{\gamma i}^\nu = 1 \;\forall d_i \in \mathcal{D} \tag{35}$$

$$\sum_{R_{\gamma i}^\nu \in \mathcal{R}_\gamma^\nu} y_{\gamma i}^\nu \leq 1, \;\forall \nu \in \mathcal{V}, \;\gamma = 1, \ldots, n_\nu \tag{36}$$

$$\sum_{\gamma=1}^{n_\nu} \sum_{R^\nu_{\gamma i} \in \mathcal{R}^\nu_\gamma} y^\nu_{\gamma i} \leq n_\nu, \ \forall \nu \in \mathcal{V} \tag{37}$$

$$y^\nu_{\gamma i} \in \{0, 1\}, \ \forall R^\nu_{\gamma i} \in \mathcal{R}^\nu_\gamma, \ \gamma = 1, \ldots, n_\nu, \ \forall \nu \in \mathcal{V} \tag{38}$$

Equations (35) make sure that all customer demand is satisfied and that exactly one route is selected to serve each demand. Constraints (36) indicate that each city-freighter may perform at most one route (it may be idle), while relations (37) enforce the fleet-dimension restrictions.

Model (34) - (38) belongs to the well-known class of the set covering formulations, for which a significant literature and methodology exists (e.g., Barnhart *et al.* 1998; Desrosiers *et al.* 1995; Desaulniers *et al.* 1998; Gentili 2003).

7 Conclusions

City Logistics ideas, projects, and initiatives appear to hold one of the keys to achieving a more balanced distribution of the benefits of moving freight in and out of the city and the environmental, social, and economical nuisance and cost associated to freight transportation, particularly in large and congested urban zones. The core operation is the coordinated delivery of freight of many different shipper-carrier-consignee commercial relations, through consolidation facilities such as Urban Distribution Centers, satellites, and so on. City Logistics explicitly refers to the *optimization* of such advanced urban freight transportation systems.

In this paper, we focused on "the-day-before" problem an important and challenging component of this optimization process, which addresses the integrated short-term scheduling of operations and management of resources. We proposed models for the general case of two-tier City Logistics systems, which also involve environment-friendly vehicles for most operations within the urban area and Intelligent Transportation Systems (ITS) capabilities for information exchanges and real-time control. We also examined the simplification of this methodology for the single-tier case. In all cases, promising algorithmic directions have been provided as well.

Acknowledgments

Partial funding for this project has been provided by the Universitá degli Studi di Roma "La Sapienza", the Natural Sciences and Engineering Council of Canada, through its Discovery Grants program, and by MIUR, Ministero Istruzione Universitá Ricerca, through project PRIN 2003 *Infomobility and design of integrated system for urban transport* prot. 2003095533.

References

Armacost, A.P., Barnhart, C., and Ware, K.A. (2002). Composite Variable Formulations for Express Shipment Service Network Design. *Transportation Science*, 36(1):1–20.

Balakrishnan, A., Magnanti, T.L., and Mirchandani, P. (1997). Network Design. In Dell'Amico, M., Maffioli, F., and Martello, S., editors, *Annotated Bibliographies in Combinatorial Optimization*, pages 311–334. John Wiley & Sons, New York, NY.

Barnhart, C., Jin, H., and Vance, P.H. (2000). Railroad Blocking: A Network Design Application. *Operations Research*, 48(4):603–614.

Barnhart, C., Johnson, E.L., Nemhauser, G.L., Savelsbergh, M.W.F., and Vance, P.H. (1998). Branch-and-Price: Column Generation for Solving Huge Integer Programs. *Operations Research*, 46(3):316–329.

Bräysy O. and Gendreau M. (2005a). Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms. *Transportation Science*, 39(1):104–118.

Bräysy O. and Gendreau M. (2005b). Vehicle Routing Problem with Time Windows, Part II: Metaheuristics. *Transportation Science*, 39(1):119–139.

Campo Dall'Orto, L., Crainic, T.G., Léal, J.E., and Powell, W.B. (2005). The Single-node Dynamic Service Scheduling and Dispatching Problem. *European Journal of Operational Research.* to appear.

Christiansen, M., Fagerholt, K., Nygreen, B., and Ronen, D. (2005). Maritime Transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, Handbooks in Operations Research and Management Science. North-Holland, Amsterdam.

Cordeau, J.-F., Desaulniers, G., Desrosiers, J., Solomon, M.M., and Soumis, F. (2002). The VRP with Time Windows. In Toth, P. and Vigo, D., editors, *The Vehicle Routing Problem*, SIAM, Monographs on Discrete Mathematics and Applications, chapter 7, pages 157–193. SIAM, Philadelphia, PA.

Cordeau, J.-F., Laporte, G., and Mercier, A. (2001). A Unified Tabu Search Heuristic for Vehicle Routing Problems with Time Windows. *Journal of the Operational Research Society*, 52:928–936.

Kim, D., Barnhart, C., Ware, K., and Reinhardt, G. (1999). Multimodal Express Package Delivery: A Service Network Design Application. *Transportation Science*, 33(4):391–407.

Le Bouthillier, A. and Crainic, T.G. (2005). A Cooperative Parallel Meta-Heuristic for the Vehicle Routing Problem with Time Windows. *Computers & Operations Research*, 32(7):1685–1708.

Le Bouthillier, A., Crainic, T.G., and Kropf, P. (2005a). A Guided Cooperative Search for the Vehicle Routing Problem with Time Windows. *IEEE Intelligent Systems*. forthcoming.

Le Bouthillier, A., Crainic, T.G., and Kropf, P. (2005b). Towards a Guided Cooperative Search. Publication CRT-05-09, Centre de recherche sur les transports, Université de Montréal, Montréal, QC, Canada.

Magnanti, T.L. and Wong, R.T. (1984). Network Design and Transportation Planning: Models and Algorithms. *Transportation Science*, 18(1):1–55.

Minoux, M. (1989). Network Synthesis and Optimum Network Design Problems: Models, Solution Methods and Applications. *Networks*, 19:313–360.

Powell, W.B. (1986). A Local Improvement Heuristic for the Design of Less-than-Truckload Motor Carrier Networks. *Transportation Science*, 20(4):246–357.

Powell, W.B. (2003). Dynamic Models of Transportation Operations. In Graves, S. and Tok, T.A.G., editors, *Supply Chain Management*, volume 11 of *Handbooks in Operations Research and Management Science*, pages 677–756. North-Holland, Amsterdam.

Powell, W.B., Bouzaïene-Ayari, B., and Simaõ, H.P. (2005). Dynamic Models for Freight Transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, Handbooks in Operations Research and Management Science. North-Holland, Amsterdam. to appear.

Powell, W.B. and Carvalho, T.A. (1997). Dynamic Control of Multicommodity Fleet Management Problems. *European Journal of Operations Research*, 98:522–541.

Powell, W.B. and Carvalho, T.A. (1998). Dynamic Control of Logistics Queueing Networks for Large-Scale Fleet Management. *Transportation Science*, 32(2):90–109.

Powell, W.B. and Sheffi, Y. (1989). Design and Implementation of an Interactive Optimization System for the Network Design in the Motor Carrier Industry. *Operations Research*, 37(1):12–29.

Powell, W.B. and Topaloglu, H. (2003). Stochastic Programming in Transportation and Logistics. In Ruszczynski, A. and Shapiro, A., editors, *Stochastic Programming*, volume 10 of *Handbooks in Operations Research and Management Science*, pages 555–635. North-Holland, Amsterdam.

Taniguchi, E., Thompson, R.G., Yamada, T., and Duin, J.H.R. van (2001). *City Logistics: Network Modelling and Intelligent Transport Systems.* Pergamon, Amsterdam.

Toth, P. and Vigo, D. (1998). Exact Solution of the Vehicle Routing Problem. In T.G. Crainic and G. Laporte, editors, *Fleet Management and Logistics*, pages 1–31. Kluwer Academic Publishers, Norwell, MA.

Toth, P. and Vigo, D., editors (2002). *The Vehicle Routing Problem*, volume 9 of *SIAM Monographs on Discrete Mathematics and Applications.* SIAM.