CIRRELT
Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport
Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

Models for Evaluating and Planning City Logistics Systems

Teodor Gabriel Crainic
Nicoletta Ricciardi
Giovanni Storchi

March 2009

CIRRELT-2009-11

Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

Université Laval · UQÀM · HEC Montréal · École Polytechnique Montréal · Université de Montréal

Models for Evaluating and Planning City Logistics Systems[†]

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

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT), and Department of Management and Technology, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, Canada H3C 3P8

[2] Dipartimento di Statistica, Probabilità e Statistiche Applicate, Università di Roma "La Sapienza", Piazzale Aldo More, 5 – 00185 Roma, Italy

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 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 case involving a two-tier distribution structure. We investigate the main issues related to the problem, introduce a new problem class, propose both a general model and formulations for the main system components, and identify promising solution avenues.

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

Acknowledgements. Partial funding for this project has been provided by the Universitá degli Studi di Roma "La Sapienza", the Natural Sciences and Engineering Research Council of Canada (NSERC), through its Industrial Research Chair and Discovery Grants programs, by the partners of the Chair, CN, Rona, Alimentation Couche-Tard and the Ministry of Transportaton of Québec, by the Fonds de recherche sur la nature et les technologies (FQRNT) through its Team Research Grants program, and by MIUR, Ministero Istruzione Universitá Ricerca, through project PRIN 2003 Infomobility and design of integrated system for urban transport prot. 2003095533. We want to take this opportunity to thank our colleagues and friends, Professors Lucca Bertazzi, Michel Gendreau, Guido Perboli, and Maria Grazia Speranza, as well as our students Abderrahim Benjelloun, Jesus Gonzales Feliu, Lorraine Cauquil, and Simona Mancini, for enlighting exchanges, help with the literature search, and starting the exploration of algorithmic developments for the problems introduced in this paper. We also want to thank the Editor of the Journal and the anonymous Associate Editor and referees for their comments, critics, and suggestions, which all helped us write a better paper.

[†] This publication updates CIRRELT-2007-65 and CRT-2005-19

---

* Corresponding author: Teodor-Gabriel.Crainic@cirrelt.ca

Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2009

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 supplies stores and places of work and leisure, delivers goods at home, provides the means to get rid 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 (OECD, 2003).

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. In major French cities, for example, it has been found that freight vehicles consume, on average, 30% of the city street capacity, two-thirds representing parking for delivery and pick-up operations (Patier, 2002). On average, for thirteen American cities, freight transportation represents some 10% of the total vehicle-kilometers travelled (Figliozzi, 2007); the same measure for the three largest French cities varies from 13% to 20% (Patier, 2002). Figures are equally telling regarding emissions. An OECD report (OECD, 2003) assigns, for example, 43% of sulphur oxides and 61% of particulate matter emissions in London to freight transportation, whereas for nitrogen oxides emissions, the figures are 28% for London, 50% for Prague, and 77% for Tokyo. These nuisances impact the life of people living or working in cities, as well as the productivity of the firms located in urban zones and of supply chains involving these firms. And the problem is not going to disappear any time soon. In fact, the number of freight vehicles moving within city limits, which is already important, is growing and is expected to continue to grow at a fast rate. Major contributing factors are the current production and distribution practices based on low inventories and timely deliveries, and the explosive growth of business-to-customer electronic commerce that generates significant volumes of personal deliveries. Probably even more important, a worldwide urbanization trend is emptying the countryside and small towns and making large cities even larger. Within the countries that are members of OECD, the urban population was 50% of the total population in 1950, 77% in 2000, and should reach the 85% mark by 2020 (OECD, 2003). It is estimated that 2007 has seen for the first time in recorded history, the worldwide urban population being larger than the rural population.

Several projects have been undertaken in recent years to address these issues, to better understand and "control" freight transportation within urban areas. The general goal is to reduce the impact of freight-vehicle movements on the city-living conditions and, in particular, improve the congestion/mobility, emissions, and pollution conditions, while not penalizing the city social and economic activities. More precisely, one aims to reduce and control the number and dimensions of freight vehicles operating within the city, improve the efficiency of freight movements, and reduce the number of empty vehicle-kilometers. The fundamental idea that underlies most initiatives is to stop considering each shipment, firm, and vehicle individually. Rather, one should consider them as components of an *integrated logistics system.* Recall that, in its contemporaneous scope, "Logistics" targets the analysis, planning, and management of the integrated and coordinated physical (e.g., materials, products, and money) and electronic (e.g., information and decisions) flows within a potentially multi-partner value network. It is from this view that the term *City Logistics* has been coined to emphasize the need for an optimized *consolidation* of loads of different shippers and carriers within the same delivery vehicles and for the *coordination* of the resulting freight transportation activities within the city.

City Logistics challenges the city authorities, businesses, carriers, and citizens in their relation to freight transportation, introduces new business and operating models, and requires public-private understanding, collaboration, and innovative partnerships. For Operations Research and Transportation Science, City Logistics constitutes both a challenge and an opportunity in terms of methodological developments and actual social impact. A review of existing literature reveals, however, that the "optimization" component of the City Logistics concept is not very developed yet. Concepts are proposed and pilot studies are undertaken, but very few formal models and methods are dedicated to their design, evaluation, planning, management, and control. This paper aims to contribute to fill this gap.

We focus our study on City Logistics systems where consolidation and coordination activities are performed at facilities organized into a hierarchical, two-tiered structure with major terminals sited at the city limits and satellite facilities strategically located close to or within the city-center area. Particular vehicle fleets are dedicated to each system tier, load transshipment being performed at satellites. Such systems are increasingly proposed for large cities with serious transportation-related problems, but no methodology has been proposed yet to assist the associated planning processes. A particularly challenging issue in planning two-tier City Logistics systems concerns the integrated short-term (next "day") scheduling of operations and management of resources. The problem addresses the selection of routes and the scheduling of departures for vehicles, as well as the selection of the delivery routes for customer demands from the major terminals, through satellites, to the final customer. Coordination and time-synchronization of vehicle operations are central elements of the problem and the formulations proposed, and contribute to both their originality and their difficulty. Two new problem classes are thus introduced, the single and the *two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows.*

Our objectives are to investigate the issues and challenges related to this problem and propose a general methodology to address them. The methodology targets two important utilization modes: 1) the actual planning of resource utilization and operations for the next activity period, and 2) the evaluation of proposed system designs. In the latter mode, the results of the model applied to various scenarios of system design, layout, and operation policies would yield information needed to compute performance measures for the contemplated City Logistics system and forecast its impact on the city considered. This is fundamentally a *modeling* paper. We aim to present a comprehensive view of the topic, identify issues and challenges, and propose and analyze modeling approaches. We are also identifying promising solution avenues, but detailed algorithmic developments are beyond the scope of the present work. The contribution of this paper is thus three-fold. 1) It presents a comprehensive view of City Logistics, an emerging field in Transportation Science, and identifies and analyzes a set of issues that are both methodologically challenging and timely. 2) It defines a new problem class to represent these issues and proposes a general model and formulations for its main components. 3) It analyzes these models both with respect to possible utilization modes and by contrasting them to other major problem classes encountered in service network design and vehicle routing settings, and identifies promising algorithmic avenues.

The paper is organized as follows. Section 1 reviews the City Logistics concepts, challenges, and trends, presents associated planning issues, and reviews the literature. Section 2 describes the general two-tier City Logistics systems and introduces the *day-before* tactical planning problem we address. Section 3 introduces the main formulation and a number of important variants, as well as an adaptation to the case of single-tier City Logistics systems, which emphasizes the general interest of our work. The problem and models are analyzed and contrasted to other well-known settings in Section 4, and a general methodology is proposed. Sections 5 and 6 address the two major components of this methodology, the design of the first-tier service network and the determination of the vehicle circulation at the second tier of the system, respectively. We conclude in Section 7.

1 City Logistics

In this section, we describe the setting and fix the vocabulary for the work presented in this paper. We start by recalling the fundamental concepts, issues, trends, and challenges of City Logistics, together with a brief history of previous studies and projects. More detailed information may be found in, e.g., Benjelloun and Crainic (2008), Russo and Comi (2004), Taniguchi et al. (2001a), and the proceeding books of the City Logistics conferences available through the Institute of City Logistics (http://ww.citylogistics.org), as well as the websites of the projects Trendsetter, CITY PORTS, BESTUFS, the CIVITAS Initiative, and Transports de Marchandises en Ville, etc. The section concludes with an overview of the main planning issues associated to these systems.

1.1 General concepts and a brief history of City Logistics

Historically, one finds a brief period of intense activity at the beginning of the 1970s dedicated to urban freight transportation issues. This period yielded traffic regulation to avoid the presence of heavy vehicles in cities and thus limit the impact of freight transport on automobile movements. Very little activity took place from 1975 to the end of the 1980s. The increased traffic-related problems and the associated public pressure have revived the interest from 1990 on and have resulted in traffic surveys and data collection activities, research projects, and experimental deployments, some of which continue to operate. The initial developments took place mainly in the countries of the European Union and Japan.

The surveys (e.g., Dufour, 2001; Dietrich, 2001; Patier-Marque, 2001; Morris et al., 1999; STA, 2000; Ricci and Fagiani, 2001; Ambrosini and Routhier, 2004) helped quantify the issues related to urban freight transportation, in particular, the low average vehicle loads and the high number of empty trips. They also documented the fact that traffic and parking regulations do not seem to be able to cope with the problem. The construction of automated underground systems dedicated to freight transportation was proposed as means to reduce the number of vehicles traveling in urban areas, but the huge investments required make this concept unrealistic in most cases (van Duin, 1998; Ooishi and Taniguchi, 1999). As indicated in most of the City Logistics literature, significant gains can only be achieved through a streamlining of distribution activities resulting in less freight vehicles traveling within the city and a better utilization of these vehicles. The *consolidation* of loads of different shippers and carriers within the same vehicles associated to some form of *coordination* of operations within the city are among the most important means to achieve these goals. The utilization of so-called green vehicles and the integration of public-transport infrastructures (e.g., light rail and barges on rivers and water canals) may enhance these systems and further reduce truck movements and related emissions in the city. But consolidation and coordination are the fundamental concepts of City Logistics.

Consolidation activities take place at so-called *City Distribution Centers* (*CDC*s; the term Urban Freight Consolidation Center is also used). Long-haul transportation vehicles of various modes dock at a CDC to unload their cargo. Loads are then sorted and consolidated into smaller vehicles for distribution. The CDC concept is close to that of intermodal logistic platforms and freight villages, which offer the means for load transfer between vehicles of different characteristics and modes, as well as for storage, sorting, and consolidation/deconsolidation of freight (related services, such as accounting, legal counsel, and brokerage, are also generally offered). They may be stand-alone facilities situated close to the city access or ring highways, or may be part of air, rail, or navigation terminals. CDCs may then be viewed as intermodal platforms or freight villages with enhanced functionality to provide coordinated and efficient freight movements within the urban zone. They are thus an important step toward a better organization of urban freight transportation and are instrumental in most City Logistics proposals and projects so far (Browne et al., 2006). Of course, a City Logistics system would also address the reverse movements, from origins within the city to destinations outside, as well as movements among origins and destinations within the city. Currently, however, only inbound distribution activities are generally addressed, following the imbalance between entering and exiting flows that characterizes most cities. To simplify the presentation, we adopt the same perspective.

Single-tier City Logistics systems operate only one level of consolidation-distribution activities, distribution routes starting at a CDC and delivering the loads directly to the customers. The City Logistics projects initially undertaken in Europe and Japan were based on the single-tier concept, mostly involving a single CDC and a limited number of shippers and carriers. Different business models and strategies were tested (see previous references and also van Duin, 1997; Janssen and Oldenburger, 1991; Kohler, 1997, 2001; Ruske, 1994; Taniguchi et al., 2000, 2001a; Thompson and Taniguchi, 2001; Visser et al., 1999). The "City Logistik" concept developed in Germany, and also applied by a number of Swiss cities, corresponds to "spontaneous" groupings of carriers for coordination and consolidation activities with very light government involvement. There were no, or very few, privileges granted to participating enterprises (in terms of access and parking regulations, for example) but, projects being private initiatives, the systems were supposed to become profitable over a short period. The approach was different in The Netherlands, where central and local governments played an active role. They introduced permits restricting vehicle loads and the total number of vehicles entering the city on any given day, but also modified traffic regulations to allow longer delivery hours (policies promoting the use of electric vehicles were also introduced). This resulted in carriers initiating collaboration activities to consolidate shipments and reduce the number of trips. A third major approach was first introduced in Monaco, where urban freight delivery was identified as a public service. Large trucks were (and still are) banned from the city and had to deliver to a CDC, with a unique carrier taking charge of the final distribution with special vehicles. The move from a public carrier to a private one did not modify the system structure and general operating policy.

The significant involvement of local and central governments may explain the success and continuation of permit-based projects within The Netherlands, although they did not gained much acceptance elsewhere. The private City Logistik projects have yielded mixed results, as most did not continue once the initial funds secured through European Union programs were over (only 15 out of some 200 planned or carried out projects were still in existence by the end of 2002). Indeed, consolidation in CDCs results in extra costs and delays, which are rather difficult to account for in the context of a combination of hands-off policy practiced by authorities and short-term profitability requirements. The "public-utility" system in Monaco performed and continues to do so as planned. Yet, for some time, it was the only one of its kind.

The field is continuously evolving, however, and the new generation of projects are found over a broader geographical range, studies being reported in Australia, Asia, Eastern Europe, and North America. The CDC is still at the core of the system, but a broader range of options is considered, usually combining elements from the different initial business models reviewed above. The involvement of public institutions, municipal authorities principally, and the private-public partnerships are thus significantly stronger and wide-spread than previously. The number of private initiatives that are part of City Logistics systems is, in fact, rising. From the year 2000 on, the need for advanced information and decision technologies is also increasingly acknowledged. While the latter is for the most part still to be developed, integration of Intelligent Transportation Systems (ITS) principles and technologies into City Logistics is increasingly observed.

One notices a higher rate of "success", defined as systems still in existence after a certain number of years, for small to medium-size cities than for large ones (Dablanc, 2007). In the former case, a single zone is generally under City Logistics conditions. Moreover, the controlled zone is relatively small and close to the outskirts of the city where the CDC is located. This facilitates the deployment and operations of enhanced Monaco-type systems, where a single operator is designated for operations within the city. Such approaches have not been successful for large cities, however. A number of factors combine to explain this observation. First, the areas one aims to control in a large city, e.g., the city center, are also large and generally far from the CDCs, usually located well beyond the outskirts of the city (most such facilities were neither initially located nor designed specifically for City Logistics). Second, in many large cities, the city center displays high-density levels of population and buildings for commercial, administrative, and cultural activities, served by a dense network of mostly narrow and generally congested streets. Parking space is at a premium and strict regulations limit the size of vehicles in the city center. A direct CDC-to-customer distribution mode than makes for long distances yielding two equally unsatisfactory transportation choices. The first option is to use large vehicles, which offer low per unit transportation costs but, when fully loaded, operate long distribution tours once in the city center. This makes it more difficult to respect customer delivery time windows, many deliveries being requested within a rather limited time period. It also generally implies an inefficient utilization of the vehicle capacity, the most part of a vehicle tour being traveled with a low load. Moreover, even when the street configuration and the city-access regulations make this option feasible, the sustained presence of large vehicles in the city center does not contribute to the actual and perceived well-being of the population. The second option is to use small vehicles more appropriate for city-center traffic. This would require a very large fleet, however, resulting in high vehicle acquisition and operation cost, high personnel (driver) costs, and a non-negligible contribution to traffic congestion.

More complex systems are thus emerging for large cities, encompassing a number of not necessarily integrated sub-systems. Most of these display a two-tier structure of consolidation and distribution. In such systems, loads are first consolidated at a CDC into rather large vehicles, which bring them to a smaller CDC-like facility “close” to the city center. This makes up the first tier of the system. Loads are then transfered to smaller vehicles, appropriate for city-center activities, which then deliver them to the final customers, thus making up the second tier of the system. (More complex, multi-tier systems may be contemplated, but we are not aware of any such proposal.) Most proposed and implemented systems have access to some of the city infrastructure, e.g., the light rail system or municipal parkings, even when they result from private initiatives.

This is the case for the CityCargo system, which combines truck and tram (light rail) modes into a two-tier system for Amsterdam (http://www.citycargo.nl/): loads are consolidated at warehouses located on the outskirts of the city and transferred to specially configured trams, which bring them to locations inside the city where they are met by smaller electric vehicles providing the final distribution of freight to customers. The pilot project proved successful and a ten-year concession has been awarded to the CityCargo company, regular operations being scheduled to start in the first half of 2009 with 1 CDC, 5 trams, and 47 electric trucks (the final system is planned with 2 CDCs, 42 trams, and 611 trucks). Chronopost International (2007) deployed in many French cities a simple two-tier system for express courier delivery: a truck transports the mail to a location in the center of the city (e.g., a parking lot), where it is transferred to various types of electric vehicles (adapted for their assigned neighborhoods) for delivery. More complex proposals for two-tier systems may be also found in Crainic et al. (2004) and Gragnani et al. (2004), the city of Rome providing the motivation and the modeling framework.

Operations research-based methodologies, which enable the optimization of the design, planning, management, and operation of City Logistics systems, are still generally missing, however, with the few exceptions described in the next section. In particular, to the authors knowledge, no models or procedures have been proposed for the evaluation and planning of two-tier systems. This makes it very difficult, for example, to design a formal procedure to determine whether, according to the city characteristics, a single or a multi-tier structure is most appropriate. This paper is a contribution to addressing these issues. The models we propose may be used both for short-range planning of activities and for strategic studies of possible City Logistics system designs. To better position the issues we address, the next subsection describes the main planning issues associated to City Logistics systems.

1.2 Planning Issues

Similarly to any complex transportation system, City Logistics systems require planning at strategic, tactic, and operational levels (Benjelloun and Crainic, 2008). The strategic level is concerned with the design of the system and its evaluation. The latter activity refers to the evaluation of the probable behavior and performance of proposed systems and operating policies under a broad range of scenarios. It also addresses the continuous analysis of deployed systems and the planning of their evolution, both as stand-alone systems and in relation to the general transportation system of the city and the larger region that encompasses it. In particular, the choice of a particular City Logistics structure, e.g., single or two-tiered, should be based on cost-benefit analyzes performed using such strategic planning models.

Although very few formal models have been proposed specifically for City Logistics (Taniguchi and van der Heijden, 2000; Taniguchi et al., 2001a; Taniguchi and Thompson, 2002), these issues are generally part of transportation-system planning methodologies, which are well known, particularly for passenger transportation within urban areas, but also for passenger and freight regional/national planning (e.g., Cascetta, 2001; Crainic and Florian, 2008; Florian, 2008). The main components of such methodologies are: *Supply* modeling to represent the transportation infrastructure and services with their operation characteristics and economic, service, and performance measures and criteria; *Demand* modeling to capture the product definition, identify producers, shippers, and intermediaries, represent production, consumption, and point-to-point distribution volumes, and determine the mode choice for particular products or origin-destination markets; *Assignment* of multicommodity flows (from the demand model) to the multimode network (the supply representation). This procedure simulates the behavior of the transportation system and its output forms the basis for strategic analyzes and planning activities. Benjelloun and Crainic (2008) discuss the adaptation of this methodology to City Logistics, but the individual models and methods that would make it up are still to be developed for the most part.

A few models have been proposed for evaluating the demand for freight movements within urban areas (see Gentile and Vigo, 2007, for a recent review). Most are descriptive models based on extensive surveys in large cities and economic principles (e.g., Patier, 2002; Ambrosini and Routhier, 2004; Friedrich et al., 2003; Boerkamps and van Binsbergen, 1999). A gravity-based methodology is presented in Gentile and Vigo (2007). The models integrate elements representing the city topology, traffic regulation, and some representation of the logistics chains and vehicle tours used to move products within major product classes. Significant work is still required in this area, however, to integrate City Logistics considerations to demand modeling.

The supply and assignment aspects are even less developed. The former requires decisions on the number, location, and characteristics of CDCs in single and multi-tier settings. The models should also select the City Logistics network, e.g., the access corridors and the streets open to each vehicle type, and determine the vehicle fleets composition and size. We are aware of only two contributions, Taniguchi et al. (1999) and Crainic et al. (2004) for two-tier systems, targeting some of these important and challenging issues.

The assignment step requires to simulate the behavior of the system under various scenarios relative to the system organization and the social, economic, and regulatory environment. Dynamic traffic simulation, where passenger and other freight vehicles may be considered as well, appears the methodology of choice for such evaluations. City Logistics simulators require methods to represent how vehicles and flows would circulate through the city and how the proposed infrastructures and services would be used under the conditions of a given scenario. These are the same tactical and, eventually, dynamic-routing models as those required to plan and control operations for an actual system. We are aware of only one fully-developed contribution, where a traffic micro-simulator is coupled to a dynamic-routing model to evaluate projects for small European cities (Barceló et al., 2007). Micro-simulation appears difficult to scale for larger urban areas, however. Mezo-simulators (e.g., Mahut et al., 2004) addressing larger urban areas, coupled to tactical planning models as those proposed in this paper, offer more interesting perspectives, but no contribution to this area has yet been made.

On the operational side, issues related to the work schedules of vehicle drivers and terminal personnel must be addressed, as well as the control and dynamic adjustment of vehicle and terminal operations within an ITS environment. Although we are not aware of any specific contribution to the first topic, a few papers deal with the second, focusing generally on the operations of a single fleet within a limited part of the city (e.g., Taniguchi et al., 2001b; Thompson, 2004).

City Logistics transportation systems rely on consolidation. Tactical planning for consolidation-based transportation systems aims to build a transportation plan to provide for efficient operations and resource utilization, while satisfying the demand for transportation within the quality criteria (e.g., delivery time) publicized or agreed upon with the respective customers (Crainic, 2000, 2003; Crainic and Kim, 2007). The same issues must be addressed in a City Logistics context, but for a shorter planning horizon due to the day-to-day demand variability. Tactical planning models for City Logistics concern the departure times, routes, and loads of vehicles, the routing of demand and, when appropriate, the utilization of the second-tier consolidation facilities and the distribution of work among them. Tactical planning models assist the deployment of resources and the planning of operations and guide the real-time activities of the system. They are also important components of models and procedures to evaluate City Logistics systems, from initial proposals to deployment scenarios and operation policies. According to the best knowledge of these authors, there are no published contributions targeting these issues. Our work thus focuses on the tactical planning process for City Logistics, that we identify as the *day-before* problem, in the general case of two-tier systems.

2 Problem Description and General Notation

We initiate the section by recalling the general two-tier City Logistics system description introduced by Crainic et al. (2004) (the systems mentioned in the previous section may be described as special cases). We simultaneously introduce the definitions and notation that apply to all cases and formulations considered in this paper. Table 1 in the Annex summarizes this notation. We then proceed to describe the day-before planning problem for two-tier City Logistics.

2.1 Two-Tier City Logistics Systems

CDCs form the first level of the system and are assumed to be located on the outskirts of the city. In general, however, not all demand for transportation processed by a City Logistics system passes through a CDC. Freight may also arrive on ships or trains, and sorting and consolidation operations may be performed in CDC-like facilities located in the port, rail yard, or a rail station situated close to or within the city. Moreover, certain demand is generated at production facilities located close to the city and is already embarked in fully-loaded vehicles. Freight may also come from further away in fully-loaded vehicles that are allowed to enter the city under the supervision of the City Logistics system. To simplify the presentation, we refer to CDCs and all these facilities and sites as *external zones*, denoted in the following by the set $\mathcal{E} = \{e\}$.

On any given day, loads of particular products $p \in \mathcal{P}$ are destined to a particular set $\mathcal{C} = \{c\}$ of customers. For planning purposes, the period available for operations is divided into $t = 1, ..., T$ periods. Most customers of the system are commercial entities with known opening hours and delivery periods determined both by known practice and municipal rules. Let $\mathcal{D} = \{d\}$ represent the set of *customer demands* the system has to serve during the contemplated time horizon. Each customer demand d is characterized by a number of attributes: a volume $vol(d)$ of product $p(d) \in \mathcal{P}$ available starting in period $t(d)$ at the external zone $e(d)$, to be delivered to customer $c(d)$ during the time interval $[a(d), b(d)]$. The time required to actually serve (i.e., unload the freight) the customer is denoted $\delta(d)$.

The second tier of the system is constituted of satellite platforms, *satellites* for short, where the freight coming from external zones are transferred to and consolidated into vehicles adapted for utilization in dense city zones and which perform the actual delivery routes. In the advanced system we address in this paper, satellites operate according to a vehicle synchronization and cross-dock transshipment operational model. In other words, the *urban vehicles* and *city freighters* moving loads in the first and second tier, respectively, must meet at satellites at an appointed time, with very short waiting times permitted, loads being directly moved from an urban vehicle to the appropriate city freighters, without intermediate storage. Determining these meeting times and the corresponding vehicle routes and schedules is one of the principal goals of the models introduced later in the paper. No permanent facility thus needs to be constructed for satellites, existing urban spaces, e.g., city squares and parkings, being used instead. The Amsterdam CityCargo illustrates this notion. Transfers from trams (our urban vehicles) to the electric delivery vehicles (city freighters) take place at selected locations (satellites) where there is sufficient space close to the tram line, but where transfer activities do not interfere with passengers waiting for their trams or with other city traffic. Let $\mathcal{S} = \{s\}$ stand for the set of satellites. The nature of each satellite location determines when it can be used, its topology, available space, and connections to the street network yielding its capacity measured in the number of urban vehicles π_s and city freighters λ_s it can accommodate simultaneously. The (small) time vehicles are allowed to wait at satellites is assumed, for simplicity of presentation, the same for all satellites and is denoted δ.

The two types of vehicles involved in a two-tier City Logistics system are supposed to be environmentally friendly. *Urban vehicles* 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 vehicle movements within the city, rules may be imposed to have them travel as much as possible around the city, on the "ring highway" system surrounding the city, and enter the city center as close to destination as possible. Urban vehicles may visit more than one satellite during a trip. Their routes and departures have to be optimized and coordinated with satellite access and city-freighter availability. This optimization is performed independently of the urban-vehicle circulation when the City Logistics system does not manage the fleet. This is the most general case, as vehicles from outside of town may deliver directly to satellites, leaving the system once finished, and is addressed in Section 3.1. The alternate case, where the urban-vehicle fleet is managed as part of the City Logistics system, is addressed in Section 3.2. Let $\mathcal{T} = \{\tau\}$ represent the set of urban-vehicle types, with corresponding fleet sizes n_τ and capacities u_τ.

City freighters are vehicles of relatively small capacity that can travel along any street in the city center to perform the distribution of freight from satellites to customers. 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 (a single type is included in the CityCargo system, for example). Let $\mathcal{V} = \{\nu\}$ represent the set of city-freighter types, with corresponding fleet sizes n_ν and capacities u_ν.

From a physical point of view, the system then operates according to the following sequence: freight arrives at an external zone where it is consolidated into urban vehicles, unless it is already into a fully-loaded urban vehicle; each urban vehicle receives a departure time and route, travels to one or several satellites, unloads, and either leaves the system or travels to an external zone where it waits for the next departure; at satellites, freight is transferred to city freighters; each city freighter performs a route serving the designated customers, and then travels to a satellite, or a depot, for its next cycle of operations.

Because city freighters cannot wait at satellites, they travel to a so-called *depot* when the last customer on the route is served and no immediate operation is planned at a satellite. Depots, represented by set $\mathcal{G}$, may be the actual city-freighter garages or other existing facilities, e.g., parking lots or municipal bus garages. Notice that such facilities may also be used for satellite activities, longer waiting times being possible at these specific locations. The number of such locations is limited, however, and their presence does not modify the basic structure of the models of the following sections. To avoid ambiguities, however, we include such facilities both in the satellite set, where no waiting is permitted, and in the depot set where it can take place. Zero travel time is assumed between the two representations of such locations.

From an information and decision point of view, the process starts with the demand for loads to be distributed within the urban zone. The consolidation of the corresponding freight yields the actual demand for the urban-vehicle transportation and the satellite cross-dock transfer activities that, in turn, generate the input to the city-freighter circulation. The objective is to have urban vehicles 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 economically and environmentally efficient operations. The following subsection defines the particular two-tier City Logistics planning issues we address.

2.2 The Day-Before Planning Problem

The general goal of planning the operations of a City Logistics system is the efficient and low-cost operation of the system, while delivering demand on time with as-low-as-possible impact on the city traffic conditions. As indicated in Section 1.2, this corresponds to the classical objective of tactical planning for freight transportation systems with consolidation, where satellites, city freighters, and urban vehicles are the resources to efficiently allocate and use. Different from the systems mentioned in Section 1.2, the length of time targeted by the planning process is very short, however. Indeed, while a number of requests for transportation may appear on a regular basis, most will not. We are here therefore 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 *day-before planning* that we coined for this set of planning issues.

The planning process aims to determine when each demand is served and how it is to be moved, on what urban vehicle, through which satellite, and on what type of city freighter. One must also determine when to dispatch each urban vehicle, the loads carried, and the satellites serviced, as well as the circulation of the city-freighter fleet, which corresponds to planning the routing and scheduling of city freighters during the contemplated period. The output of the process determines the fleet and personnel deployment for the next-day period of activities and provides users with the freight-delivery schedules. While real-time control and adjustment of operations will be required, similarly to most actual distribution systems, the gains of a City Logistics system cannot be achieved without the integrated planning and coordination of operations and activities of the system's resources.

The models presented in the remaining part of the paper address the planning problem just described. We present the models specifying each time how they may be adapted and used either in *project-evaluation* mode or in *planning* actual operations. With respect to the latter, we present models in their general form, that is, as if all services and operations are planned the day before. It is clear, however, that this might not always be the case. Thus, for example, following some intensive simulation of operations, one could design and implement a more regular urban-vehicle service. Then, most urban-vehicle departures and routes would be fixed and the next-day planning process would adjust this service, if needed, and focus on the last-leg delivery aspect of the problem. To achieve this state one still needs the complete model framework presented in this paper and the algorithmic developments that will follow.

3 A General Modeling Framework

The modeling framework we introduce reflects the two-tier City Logistics system description, where demand is served by the integrated activities of two transportation systems operating urban vehicles and city freighters, respectively, the two systems connecting and synchronizing operations at transfer facilities, the satellites. The day-before planning problem and proposed models thus encompass two main components. The first concerns the departure time of each urban-vehicle service and the satellites it visits, that is, the schedules and routes of the urban-vehicle fleet. The second addresses the issues of routing and scheduling city freighters to provide the timely delivery of goods to customers and the adequate supply of vehicles at satellites. The two problems are linked by decisions regarding how demand is to be routed.

The modeling framework is introduced in the first subsection. We examine a number of variants in the second subsection, variants aimed principally at the utilization of the model in either system-evaluation or planning mode. The generality of the modeling framework is emphasized in the third subsection where it is used to address the day-before planning problem for single-tier City Logistics systems.

3.1 The Model

Given the issues and time-frame considered a number of hypotheses are made. First, the logistics structure of the system is given. Satellites and their characteristics have been established, customers have been assigned to one or several satellites, and corridors for urban vehicles have been determined. The types and number of vehicles available and their characteristics are known for both urban vehicles and city freighters. Second, most demand is known, and eventual modifications 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. Finally, ITS and e-business infrastructures and procedures are implemented providing the means for traffic-related data collection, efficient exchange of information among participants, and the control of operations (Crainic et al., 2008).

Planning is performed for $t = 1, \dots, T$ periods. The planning horizon is relatively small, a few hours to a half day in most cases, and thus, each period should also be relatively small, of the order of the quarter or half hour, for example. The precise definition of the planning horizon is application-specific. To simplify the presentation, we adopt a definition of the *period length* such that 1) at most one departure of a service from its external zone may take place during a period (thus avoiding the need to define non-negative integer-valued frequency-design variables), and 2) the unloading times for urban vehicles are integer multiples of the period length. Let $\delta(\tau)$ represent the time required to unload an urban vehicle of type τ and $\delta(\nu)$ stand for the loading time (assuming a continuous operation) of a city freighter of type ν. Without loss of generality, we assume these durations to be independent of particular satellites.

In is well known that travel times are intimately linked to traffic and congestion conditions and, thus, vary with time and the particular city zone where one travels (e.g., congestion propagates from the exterior toward the center of the city during morning rush hour). Moreover, according to the particular time of the day, possible paths between two points in the city might be different, due either to traffic regulation or to a policy of avoiding heavily congested areas. We assume, therefore, that travel times $\delta_{ij}(t)$, between all couples i, j of (origin, destination) points in the system, are based on historical or simulation data (or both) reflecting the settings of each particular application, in particular the estimated congestion conditions at departure time t. Travel times are not necessarily symmetric and the triangle inequality conditions cannot be assumed.

Several products make up demand, some of which may use the same type of vehicle but cannot be loaded together (e.g., food and hardware products). To address this issue explicitly in the formulation is unpractical due to the potentially very large number of exclusion constraints required. The approach we propose consists in defining vehicle types that encompass the identification of the products they may carry, and including as many "copies" of an actual vehicle as there are mutually exclusive products that may use it. Of course, products which are not incompatible may use all the copies. One then has $\mathcal{T}(p) \subseteq \mathcal{T}$ and $\mathcal{V}(p) \subseteq \mathcal{V}$ as the sets of urban vehicles and city freighters, respectively, that may be used to transport product p. We can now proceed with the formulation for the general case of Section 2.1: urban-vehicle service schedules to be optimized independently of the vehicle circulation, while the fleet of city freighters is centrally managed for the duration of the planning horizon.

Consider the set of urban-vehicle *services* $\mathcal{R} = \{r\}$. Service r operates a vehicle of type $\tau(r) \in \mathcal{T}$, originates at external zone $e(r) \in \mathcal{E}$, travels to one or several satellites, and returns to an external zone $\bar{e}(r)$, possibly different from $e(r)$. The ordered set of visited satellites is denoted $\sigma(r) = \{s_i \in \mathcal{S},\ i = 1, \ldots, |\sigma(r)|$, such that if r visits satellite i before satellite j then $i < j\}$. The cost associated to operating service $r \in \mathcal{R}$ is denoted $k(r)$. The cost captures not only the monetary expenses of operating the route, but also any "nuisance" factors related to the presence of the urban vehicle in the city at the particular time of the service.

Together with the access and egress corridors, $\sigma(r)$ defines a route through the city. Let $t(r)$ be the period the service leaves its origin $e(r)$ to perform this route. The urban vehicle then arrives at the first satellite on its route, $s_1 \in \sigma(r)$, at period $t_1(r) = t(r) + \delta_{e(r)s_1(r)}(t(r))$, accounting for the time required to travel the associated distance given the congestion conditions at period $t(r)$. The service leaves the satellite at period $t_1(r)+\delta(\tau)$, once all freight is transferred. In all generality, the schedule of service r is given by the set $\{t_i(r),\ i = 0, 1, \ldots, |\sigma(r)|+1\}$, where $t_0(r) = t(r)$, $t_i(r) = t_{i-1}(r)+\delta(\tau)+\delta_{s_{i-1}(r)s_i(r)}(t(r))$, for $i > 0$, represents the period the service visits satellite $s_i \in \sigma(r)$, and the service finishes its route at the external zone $\bar{e}(r)$ at period $t_{|\sigma(r)|+1}$.

Let $\mathcal{W} = \{w\}$ be the set of feasible work segments for city freighters. A feasible *work segment* $w \in \mathcal{W}(\nu)$ for a city freighter of type $\nu(w) \in \mathcal{V}$, $\mathcal{W} = \bigcup_{\nu} \mathcal{W}(\nu)$, starts at period $t(w)$ at the first satellite on its route, and visits a sequence of satellites and associated customers. (The city-freighter arrives empty out of a depot, but this movement is not included in the work segment.) The ordered set of visited satellites is denoted $\sigma(w) = \{s_l \in \mathcal{S},\ l = 1, \ldots, |\sigma(w)|$, such that if w visits satellite l before satellite j then $l < j\}$. At each satellite s_l on its route, the city freighter takes loads to deliver to a set of customers $\mathcal{C}_l(w)$. We denote as the route *leg* l, the work-segment component that starts at satellite s_l, serves the customers in $\mathcal{C}_l(w)$, and then proceeds to satellite s_{l+1} (or a depot $g(w)$ when satellite s_l is last in $\sigma(w)$). The set $\mathcal{L}(w)$ contains all route legs of work segment w sorted in the same order as $\sigma(w)$.

Figure 1 illustrates a two-leg work segment, where st and (gt) represent the pairs of (satellite, period) (s, t) and (depot, period) (g, t), respectively, $s_1 = s$ and $s_2 = s'$, $s_1,\ s_2, \in \sigma(w)$, and $\mathcal{C}_1(w) = \{i, k, j, \ldots, f\}$ and $\mathcal{C}_2(w) = \{a, b, c, \ldots, d\}$. The dashed lines stand for undisplayed customers, whereas the dotted lines indicate the empty arrival from a depot (not included in segment), the empty movement from the last customer-demand

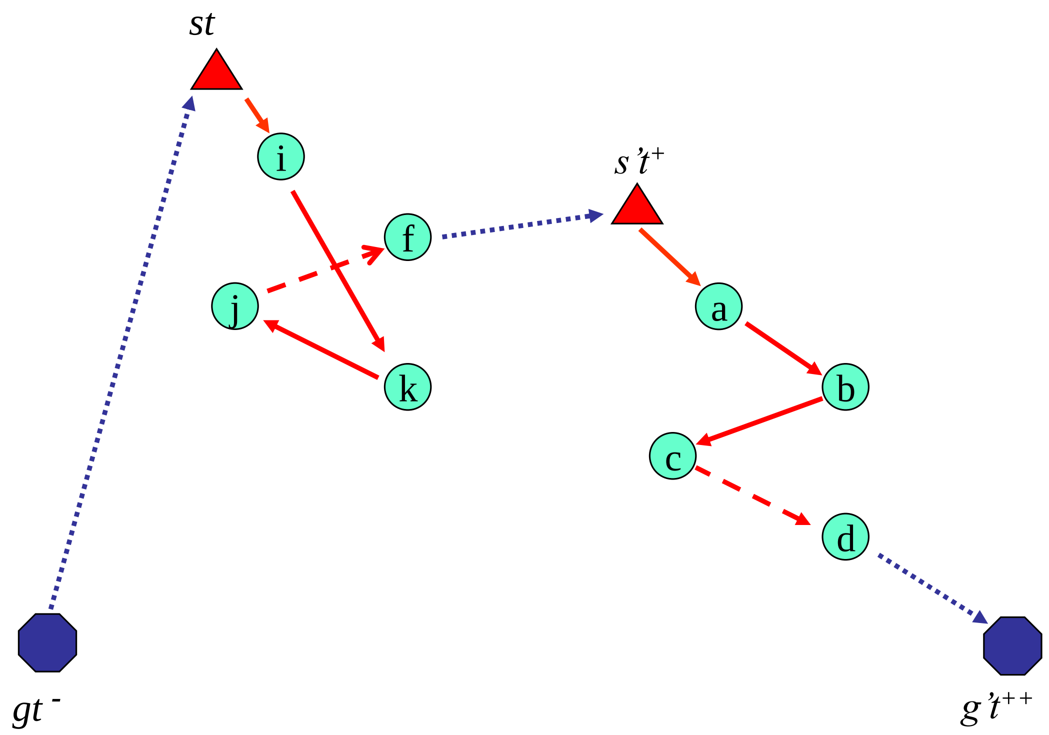

Figure 1: A City-Freighter two-Leg Work Segment Illustration

in the first leg to the satellite of the second leg, and the empty movement to a, possibly different, depot once the segment is finished.

Let $t_l(w)$ represent the period the city freighter operating the work segment w arrives at satellite $s_l \in \sigma(w)$ (e.g., $t_1(w) = t$ in Figure 1). Let $\delta_l(w)$, $l \in \mathcal{L}(w)$, stand for the total duration of leg l, that is, the total time required to visit and service the customers in $\mathcal{C}_l(w)$, as well as travel from the last customer to the next satellite in the work-segment sequence (or the depot, when $l = |\sigma(w)|$), given the congestion conditions generally prevailing at that period. The schedule of the work segment $w \in \mathcal{W}(\nu)$ is then given by the set $\{t_l(w),\ l = 0, 1, \ldots, |\sigma(w)| + 1\}$, where the *starting time* of the work segment equals the arrival time at the first satellite in the sequence, $t(w) = t_1(w))$, and $t_l(w) = t_{l-1}(w) + \delta(\nu) + \delta_l(w)$, $l = 2, \ldots, |\sigma(w)| + 1$, with $t_{|\sigma(w)|+1}(w) = t(g(w))$ the time period the vehicle arrives at the depot; $t_0(w)$ indicates when the city freighter leaves the depot in time to reach the first satellite given the congestion condition prevailing at that period. The total duration (without the first movement out of the depot) of work segment w is denoted $\delta(w)$.

A complete city-freighter *work assignment* $h \in \mathcal{H}(\nu)$ ($\mathcal{H} = \bigcup_\nu \mathcal{H}(\nu)$) is made up of a sequence of work segments $\sigma(h) = \{w_i \in \mathcal{W}(\nu),\ i = 1, \ldots, |\sigma(h)|\}$, where the time between two consecutive work segments is sufficiently long to accommodate the movements into and out of the depot. The set of all legs making up a work assignment is denoted $\mathcal{C}_l(h) = \bigcup_{w \in \sigma(h)} \mathcal{C}_l(w)$. The costs of operating city-freighter legs, work segments, and work assignments are denoted $k_l(w)$, $k(w)$, and $k(h)$, respectively, where $k(h) = sum_{w \in \sigma(h)} k(w)$ and $k(w) = \sum_{l \in \mathcal{L}(w)} k_l(w)$. A "fixed" cost is also included in $k(w)$ to represent the cost of travel from and to the depot and capture the economies of scale related to long (but legal) work segments. A similar cost in included in $k(h)$ to penalize unproductive waiting times at depots between two consecutive work segments.

Freight is moved from external zones to customers via *itineraries*, each made up of an urban-vehicle movement, a transshipment operation at a satellite, and the final distribution by a city-freighter route. Let $\mathcal{M}(d) = \{m\}$ stand for the set of itineraries that may be used to satisfy customer demand $d \in \mathcal{D}$. The itinerary $m \in \mathcal{M}(d)$ then proceeds according to the following route and schedule: Departure from its external zone $e(d) \in \mathcal{E}$ on urban-vehicle service $r(m) \in \mathcal{R}$ at $t_e(m) = t(r(m)) > t(d)$; arrival at satellite $s(m) \in \sigma(r(m))$ in period $t_s^{\text{in}}(m) = t_{s(m)}(r(m))$; transfer, together with the loads of the other customers in $\mathcal{C}_{l(w(h(m)))}(w(h(m)))$, to a city-freighter operating leg $l(h(m))$ of segment $w(h(m))$ of its work assignment $h(m) \in \mathcal{H}(\nu)$; departure from $s(m)$ in period $t_s^{\text{out}}(m) = t_{l(w(h(m)))}(w(h(m))) + \delta(\nu)$; and arrival at the final customer $c(d)$ according to its time window. The vehicle types $\tau(r(m)) \in \mathcal{T}(p(d))$ and $\nu \in \mathcal{V}(p(d))$ are appropriate for the demand product $p(d) \in \mathcal{P}$.

When customers are "close" to an external zone, they may be served directly from it. The service of such customers is then similar to the case of single-tier City Logistics systems and itineraries do not include an urban-vehicle component (see Section 3.3). One still has to select how (the itinerary) and when (vehicle departure time) each customer is served, however. Then, to allow for an uniform presentation, we consider that all these itineraries include the service r_0 from the external zone to itself, with 0 travel time. This is equivalent to assuming that each external zone includes a virtual satellite served by a service route r_0.

Three sets of decision variables are defined to select urban-vehicle services, city-freighter work assignments, and demand itineraries, respectively:

$\rho(r) =$ 1, if the urban-vehicle service $r \in \mathcal{R}$ is selected (dispatched), 0, otherwise; it is possible to impose minimum load restrictions on departures, but these will not be included in this formulation as not to overload the presentation;

$\varphi(h) =$ 1, if the work assignment $h \in \mathcal{H}(\nu)$ is selected (operated), 0, otherwise;

$\zeta(m) =$ 1, if itinerary $m \in \mathcal{M}(d)$ of demand $d \in \mathcal{D}$ is used, 0, otherwise.

The goal of the formulation is to minimize the number of vehicles in the city, urban vehicles, in particular, while satisfying demand requirements (demand cannot be split between itineraries):

$$\text{Minimize} \quad \sum_{r\in\mathcal{R}} k(r)\rho(r) + \sum_{h\in\mathcal{H}} k(h)\varphi(h) \tag{1}$$

$$\text{Subject to} \quad \sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d,r)} vol(d)\zeta(m) \le u_\tau \rho(r) \quad r\in\mathcal{R}, \tag{2}$$

$$\sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d,l,h)} vol(d)\zeta(m) \le u_\nu \varphi(h) \quad l\in\mathcal{C}_l(w), h\in\mathcal{H}, \tag{3}$$

$$\sum_{m\in\mathcal{M}(d)} \zeta(m) = 1 \quad d\in\mathcal{D}, \tag{4}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{r\in\mathcal{R}(s,t^-)} \rho(r) \le \pi_s \quad s\in\mathcal{S},\ t=1,\ldots,T, \tag{5}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{h\in\mathcal{H}(s,t^-)} \varphi(h) \le \lambda_s \quad s\in\mathcal{S},\ t=1,\ldots,T, \tag{6}$$

$$\sum_{h\in\mathcal{H}(\nu)} \varphi(h) \le n_\nu \quad \nu\in\mathcal{V}, \tag{7}$$

$$\rho(r)\in\{0,1\} \quad r\in\mathcal{R}, \tag{8}$$

$$\varphi(h)\in\{0,1\} \quad h\in\mathcal{H}, \tag{9}$$

$$\zeta(m)\in\{0,1\} \quad m\in\mathcal{M}(d),\ d\in\mathcal{D}. \tag{10}$$

The objective function (1) computes the total cost of operating the system as the sum of the costs of the selected urban-vehicle services and city-freighter work assignments. Relations (2) enforce the urban-vehicle capacity restrictions, where the load of each service $r\in\mathcal{R}$ equals the sum of the freight volumes of all itinerary demands using that service: $\mathcal{M}(d,r) = \{m\in\mathcal{M}(d) \mid r(m)=r,\ r\in\mathcal{R}\},\ d\in\mathcal{D}$. Similarly, constraints (3) enforce the city-freighter capacity restrictions on each leg of an operated work assignment: $\mathcal{M}(d,l,h) = \{m\in\mathcal{M}(d) \mid l(h(m))=l,\ l\in\mathcal{C}_l(h)\},\ h\in\mathcal{H}$. These last two groups of relations are the linking (or forcing) constraints of network design formulations. Equations (4) indicate that each demand must be satisfied by a single itinerary.

Define, for each satellite s and period t, $\mathcal{R}(s,t) = \{r\in\mathcal{R} \mid s\in\sigma(r) \text{ and } t_s(r)=t\}$, the set of urban-vehicle services that stop at satellite s at period t, and $\mathcal{H}(s,t) = \{h\in\mathcal{H} \mid s\in\sigma(w) \text{ for one } w\in\sigma(h) \text{ and } t_s(w)=t\}$, the set of city-freighter work assignments that load at satellite s at period t. Then, constraints (5) and (6) enforce the satellite capacity restrictions in terms of urban vehicles and city freighters, respectively, where the number of vehicles using a satellite at any given period t equals those that arrive at t plus those that arrived before but are still at the satellite at time t. (In an actual implementation only the tightest constraints are kept, of course.) The coherence of the respective numbers of urban vehicles and city freighters present simultaneously at satellites is provided by the flow of freight imposed by the demand itineraries. Constraints (7) limit the number of city-freighter work assignments simultaneously operated to the available numbers of vehicles of each type.

3.2 Model Variants

This subsection is dedicated to the discussion of a number of assumptions of the previous formulation and their impact on its utilization in system *evaluation* and *planning* modes.

The first set of assumptions concerns the degree of management of the urban-vehicle fleet. The model introduced in Section 3.1 is built on the assumption that the urban-vehicle movements are not controlled once service is completed. A path-based modeling approach similar to that for the city-freighter fleets may be used in the alternate case, where urban vehicles return to external zones to be reloaded and dispatched on a new service. To simplify the presentation, we consider that the entire fleet is controlled, the extension to the mix-fleet case being rather straightforward.

Define a work assignment $\gamma \in \Gamma(\tau) \subseteq \Gamma$ for an urban vehicle of type τ, as an ordered sequence of services $r \in \mathcal{R}(\gamma) \subseteq \mathcal{R}$, plus an external zone (or depot) $\bar{e}(r)$ where the service terminates at the end of the day. An urban-vehicle work assignment is feasible if its schedule is feasible, that is, if there is sufficient time to travel from the last satellite of one service to the external zone of the next service, load, and leave according to the schedule of the service. Different from city-freighter working rules, urban vehicles may arrive to their next designated external zone at any time prior to departure and wait for the scheduled loading and departure activities. Similar to the definition of work assignments for city freighters, the initial and last movements, out of and into the depot, respectively, are not explicitly represented but their cost is included in the cost of the work assignment. (The associated adjustment of the rest of the notation is straightforward and is not included.) A new set of decision variables must be defined:

$\xi(\gamma) = 1$, if the urban-vehicle work assignment $\gamma \in \Gamma(\tau),\ \tau = 1, \ldots, \mathcal{T}$, is selected (operated), 0, otherwise,

and urban-vehicle fleet capacity

$$\sum_{\gamma \in \Gamma(\tau)} \xi(\gamma) \leq n_\tau \qquad \tau \in \mathcal{T}, \tag{11}$$

and work-assignment linking constraints

$$\rho(r) \leq \xi(\gamma) \qquad r \in \mathcal{R}(\gamma),\ \gamma \in \Gamma(\tau),\ \tau = 1, \ldots, \mathcal{T}, \tag{12}$$

are added to the model, which would yield complete schedules for a number of vehicles compatible with existing resources. A similar approach may be used to model, for example, depot capacities, as well as initial and final conditions on the distribution of the vehicle fleets among depots.

A second assumption concerns the size of the controlled fleets. Once the system is established, this information is known and, on any given day, operators have good estimates of the vehicles and crews ready for service on the next day. The previous models address such system-planning settings. A simpler formulation may be used for system design and evaluation, when the system is not implemented yet and its main operating characteristics are still to be defined. The focus is then on the number of vehicles present in the city and not on their detailed work assignments. The space-time synchronization of operations is still essential, however, to capture the core characteristics of the two-tier City Logistics system.

The simplified formulation with unconstrained vehicle fleets eliminates the work assignments, considers the initial urban-vehicle service definition, and defines the city-freighter operations and the customer-demand itineraries directly in terms of work segments. Thus, the definition of an itinerary m is the same as previously, except for the movement out of the satellite, where the load is transferred to a city-freighter leaving the satellite in period $t_s^{\text{out}}(m) = t_{l(w(m))}(w(m)) + \delta(\nu)$ to perform leg $l(w(m))$ of work segment $w \in \mathcal{W}(\nu)$. The sets of decision variables selecting city-freighter routes are now written

$$\varphi(w) = 1, \text{ if the work segment } w \in \mathcal{W}(\nu) \text{ is selected (operated), 0, otherwise,}$$

and the formulation becomes

$$\text{Minimize} \quad \sum_{r \in \mathcal{R}} k(r)\rho(r) + \sum_{w \in \mathcal{W}} k(w)\varphi(w) \tag{13}$$

$$\text{Subject to} \quad \sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,l,w)} vol(d)\zeta(m) \le u_\nu \varphi(w) \qquad l \in \mathcal{C}_l(w),\ w \in \mathcal{W}, \tag{14}$$

$$\sum_{t^- = t - \delta(\tau)+1}^{t} \sum_{w \in \mathcal{W}(s,t^-)} \varphi(w) \le \lambda_s \qquad s \in \mathcal{S},\ t = 1, \ldots, T, \tag{15}$$

$$\varphi(w) \in \{0,1\} \qquad w \in \mathcal{W}(\nu), \tag{16}$$

plus constraints (2), (4), (5), (8), and (10), where $\mathcal{W}(s,t) = \{w \in \mathcal{W} \mid s \in \sigma(w) \text{ and } t_s(w) = t\}$, the set of city-freighter work segments that load at satellite s at time t.

The previous formulation yields a "best" combination of urban-vehicle and city-freighter services for a given demand scenario and, thus, an evaluation of the intensity of the vehicle flows in the controlled urban area and the required dimensions for the respective fleets and crews. Notice that this simplified formulation could be applied in system-planning mode as well, when the fleet dimensions are relatively larger than the contemplated demand. This would yield the numbers of vehicles of each type to be used next day, the service routes operated, the corresponding schedules at each terminal, external zone or satellite, and the demand distribution strategy. The complete vehicle and crew schedules may then be obtained by solving rather standard crew-scheduling-type problems (see surveys by, e.g., Barnhart et al., 2003; Desrosiers et al., 1995; Desaulniers et al., 1998a,b) for each vehicle fleet, where the tasks to be covered are the urban-vehicle service routes from one external zone to another and the city-freighter routes between two consecutive visits at the depot, respectively.

An issue often encountered in planning freight transportation services is whether loads may be split or not during delivery. Splitting loads among vehicle routes allows for a better utilization of vehicles. On the other hand, it also implies additional handling and a certain level of nuisance for customers due to multiple deliveries. A number of firms thus impose no-split-delivery conditions to their suppliers of transportation services. The previous models enforce the no-split requirement, that is, each customer-demand travels along one itinerary and is delivered by one vehicle only. This assumes, of course, that the volume of each demand is lower than the capacity of the city-freighter making the final delivery, or that a suitable division has been performed at the external zone. This case also requires the largest number of vehicles compared to that of any split-delivery scenario and is thus appropriate for a system-evaluation case.

When split deliveries are allowed, a straightforward operation policy is to divide loads among itineraries, that is among urban-vehicle routes and city-freighter work assignments and, thus, satellites. One then defines continuous variables $\chi(m) \geq 0$, indicating the proportion of demand d moved by itinerary m, and the model (1) - (10) may be written as (1), subject to

$$\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,r)} \chi(m) \leq u_\tau \rho(r) \qquad r \in \mathcal{R}, \tag{17}$$

$$\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,l,h)} vol(d)\zeta(m) \leq u_\nu \varphi(h) \qquad l \in \mathcal{C}_l(w),\ h \in \mathcal{H}(\nu), \tag{18}$$

$$\sum_{m \in \mathcal{M}(d)} \chi(m) = vol(d) \qquad d \in \mathcal{D}, \tag{19}$$

as well as (5) - (9), plus

$$\chi(m) \geq 0 \qquad m \in \mathcal{M}(d),\ d \in \mathcal{D}. \tag{20}$$

A different policy would require loads to travel on a single urban-vehicle route and be handled at an unique satellite, taking advantage of the large capacity of urban vehicles, but would allow the final delivery to be performed by several vehicles, thus addressing the issue of loads larger, in weight, volume or both, than the limited capacity of city freighters. To represent such a case, we define decision variables that reflect the selection of urban-vehicle routes for specific demands: $\zeta(d,r) = 1$, if the freight of demand $d \in \mathcal{D}$ moves using urban-vehicle route $r \in \mathcal{R}$, and 0, otherwise. The model then becomes (1), subject to (5) - (9), (17) - (20), and

$$\sum_{m \in \mathcal{M}(d,r)} \zeta(d,r) \qquad d \in \mathcal{D}, \tag{21}$$

$$\chi(m) \leq vol(d)\zeta(d,r) \qquad m \in \mathcal{M}(d),\ d \in \mathcal{D}, \tag{22}$$

$$\zeta(d,r) \in \{0,1\} \qquad d \in \mathcal{D},\ r = r(m) \in \mathcal{R},\ m \in \mathcal{M}(d), \tag{23}$$

where constraints (21) enforce the selection of an unique urban-vehicle service (and, thus, satellite), while relations (22) limits the selection of itineraries to those using the selected urban-vehicle route. In the rest of the paper, we focus on the unsplit demand case.

3.3 The Single-tier Case

Many City Logistics projects already initiated or contemplated belong to the single-tier distribution-center class involving one or several CDCs. Note that, when multiple distribution centers exist, each serving exclusively a particular territory of the city, the problem reduces to solving several single-CDC applications. Single-tier City Logistics planning issues are beyond the scope of this paper and we will not examine them in any significant depth. Our goal is to emphasize the generality of the modeling framework we propose by deriving a single-tier model as a particular case.

Satellites and movements between CDCs and satellites do not belong to the single-tier problem class. The problem then reduces to planning the distribution of demand from external zones to customers, i.e., deliver the goods to customers in time, through an optimal utilization of the fleet of vehicles in terms of cost and vehicle load. Reflecting the practice of single-tier City Logistics systems and without loss of generality, we assume city freighters are used.

The problem structure still combines service network design and vehicle routing aspects, but without the service-coordination and time-synchronization characteristics of the two-tier setting. The service network design aspect comes from the requirement to select the best set of city-freighter work assignments and their departure times, and decide when to ship each particular demand. The vehicle routing aspect corresponds to the requirement to serve customers within their specified time windows by city-freighter tours starting at an external zone and returning for eventual reloading to the same or a different external zone. When several CDCs exist, the city-freighter circulation aspect must also be considered to decide where, i.e., to what distribution center, each vehicle must go once the last customer on the route has been serviced.

With respect to the notation of Section 3.1, all work segments are single legged and, thus, a city-freighter work segment w starts at period $t(w)$ at an external zone, visits a sequence of customers identified by the set $\mathcal{C}(w)$, and proceeds to the next external zone on its work assignment or to the depot if the work assignment is finished. The work segment is feasible if all customer time restrictions are respected and the vehicle-capacity restrictions are enforced at all times. The work assignment h is feasible if its segments are feasible and if the time between two consecutive work segments is sufficiently long to accommodate the travel time from the last customer of a work segment to the external zone of the next work segment plus the time required for the vehicle loading operation. The definition of a demand itinerary m then reduces to the indicator functions

> $m(d, w, h) = 1$ if the work segment $w \in \sigma(h)$ of work assignment $h \in \mathcal{H}(\nu)$ includes serving the customer-demand $d \in \mathcal{D}$ within its time window, and 0, otherwise.
>
> $m(d, h) = 1$ if the work assignment $h \in \mathcal{H}(\nu)$ includes serving the customer-demand $d \in \mathcal{D}$ within its time window, and 0 otherwise.

and the only decision variables required select city-freighter work assignments:

> $\varphi(h) = 1$, if the work assignment $h \in \mathcal{H}(\nu)$ is selected, and 0, otherwise.

A path-based formulation for the multiple CDC case with unsplit deliveries may then be formulated as follows:

$$\text{Minimize} \quad \sum_{h \in \mathcal{H}} k(h)\varphi(h) \tag{24}$$

$$\text{Subject to} \quad \sum_{d \in \mathcal{D}} m(d, w, h) vol(d) \varphi(h) \leq u_\nu \quad w \in \sigma(h),\ h \in \mathcal{H}(\nu),\ \nu \in \mathcal{V}, \tag{25}$$

$$\sum_{\nu \in \mathcal{V}} \sum_{h \in \mathcal{H}(\nu)} m(d, h)\varphi(h) = 1 \quad d \in \mathcal{D}, \tag{26}$$

$$\sum_{h \in \mathcal{H}(\nu)} \varphi(h) \leq n_\nu, \quad \nu \in \mathcal{V}, \tag{27}$$

$$\varphi(h) \in \{0, 1\}, \quad h \in \mathcal{H}(\nu),\ \nu \in \mathcal{V}. \tag{28}$$

Relations (25) enforce the city-freighter capacity restrictions on each work segment. Equations (26) make sure each customer-demand is delivered by exactly one vehicle (work assignment). Constraints (27) enforce the fleet-dimension restrictions for each type of vehicle. Model (24) - (28) belongs to the well-known class of set partitioning formulations, for which a significant literature and methodology exists (e.g., Barnhart et al., 1998; Desrosiers et al., 1995; Desaulniers et al., 1998b; Gentili, 2003).

4 Solution Methodology Issues

We initiate this discussion with an analysis of the type of problem considered, the formulation we propose, and relations to the literature. We then present a decomposition approach that allows a more detailed study of the main building blocks of the formulation and paves the way to algorithmic developments.

4.1 Problem and formulation analysis

The formulations introduced in the previous section combine network design, service network design, actually, and vehicle routing with time windows elements and characteristics within a time-dependent framework where coordination and synchronization of multi-echelon transportation and transshipment operations are of essence.

Service network design formulations are generally associated with medium-term, so-called tactical planning of operations for consolidation carriers, that is, carriers letting the loads of more than one customer share the capacity of their vehicles. Railroads, less-than-truckload motor carriers, long-course maritime liners are examples of consolidation carriers. The goal of the planning process is to determine the transportation plan, i.e., select the services that will be offered, their frequencies and schedules. In building the plan, one aims for customer satisfaction and cost-efficient utilization of given resources leading to profits. Service network design models take the form of capacitated, fixed-cost, multicommodity network design formulations (Magnanti and Wong, 1984; Minoux, 1989; Balakrishnan et al., 1997; Crainic, 2000). Time-space network representations of service departures and movements are used when schedules must be determined. There is quite a significant body of literature on the topic surveyed by, e.g., Christiansen et al. (2004) and Christiansen et al. (2007) for maritime transportation, Cordeau et al. (1998) for rail transportation, Crainic (2003) for long-haul transportation, and Crainic and Kim (2007) for intermodal transportation.

Vehicle routing problems, on the other hand, are generally associated with the short-term, so-called operational level of planning. Given depots from where distribution activities take place, customers requiring known quantities of these same goods, and vehicles of known capacities, the goal is to determine the best set of vehicle routes to provide the required delivery services at customers. "Best" is usually meant in terms of total cost of delivery measured in total distance covered and total number of vehicles used. The first formal formulation of the vehicle routing problem (VRP) goes back to Dantzig and Ramser (1959). Similarly to this pioneer contribution, practical applications have prompted many research efforts and significant progress has been achieved in terms of problem statements, formulations, solution methods, and commercial software packages. In particular, a number of problem characteristics have been captured through "generic" problem classes defined in the scientific literature. Of particular interest here is the so-called Vehicle Routing Problem with Time Windows (VRPTW) specifying restrictions on when customers may be serviced and, eventually, depots may be visited. Surveys of routing problems may be found in, e.g., Bodin et al. (2003), Bräysy and Gendreau (2005a,b), Cordeau et al. (2007), Desaulniers et al. (1998a), Laporte and Semet (2002), and the collection of papers in Toth and Vigo (2002).

The underlying routing element of the proposed formulations is the series of VRPTW associated to each satellite, potentially for all city-freighter types and time periods. Referring to the main model of Section 3, the service network design component relates to the selection and scheduling of urban-vehicle services. When urban vehicles may call at more than two or three satellites during a single route or when the urban-vehicle fleet is limited in size and controlled (Section 3.2), the urban-vehicle service design problem may also be cast as a scheduled multi-depot multiple-tour VRPTW. These problems are not independent, however, as the routes and schedules of the urban vehicles and city freighters must be synchronized at satellites. This class of problems and models is, according to our best knowledge, new and we denote it the *two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* problem (*2SS-MDMT-VRPTW*).

We are not aware of problem settings similar to the ones we introduce, neither in the literature already indicated, nor in possibly related fields, such as multi-echelon system design and planning (e.g., Ambrosino and Scutellà, 2005; Pirkul and Jayaraman, 1996; Verrijdt and de Kok, 1995) and cross-dock distribution systems (e.g., Croxton et al., 2003; Donaldson et al., 1998; Ratliff et al., 1999; Wen et al., 2008). Inventories and inventory policies play an important role in most such settings, where they link the activities occurring at different levels. The issue is not relevant for the problems we address, the scheduling and synchronization of transportation (and satellite cross-dock) activities linking the two levels of the system. An equally important difference concerns the integration of the fleet-management aspect into the tactical planning of multi-echelon systems. This aspect is a central piece of the problem we address and the models we propose. It is not a relevant issue in most problems and models mentioned, the focus being on production and supply-chain management issues (e.g., the relations between facilities at different levels and the flows of goods through the system). At most, the selection of transportation modes is part of the decision process, but determining the actual routes and schedules of vehicles is not. Mail and express courier services display multi-echelon structures and decision processes, which may appear to share a number of characteristics with the problems we consider (see, e.g., Armacost et al., 2002, 2004; Grünert and Sebastian, 2000; Buedenbender et al., 2000). The differences are significant, however. Service design and fleet management issues are generally restricted to the expensive air (sometimes, rail) layer only, focusing on selecting service routes to perform the inter-hub movements within the allocated period (the night, usually). The routing and scheduling of the second-level vehicles is decided separately, the important sorting operations at hubs and other terminals linking activities at different layers (rather then the inter-layer synchronization characteristic of the 2SS-MDMT-VRPTW). As for the more recent systems based on City Logistics ideas for courier delivery within cities (e.g., Chronopost International, 2007), they are special cases of the 2SS-MDMT-VRPTW and no description of planning processes and models is available. The issue of jointly designing the service network and scheduling and synchronizing fleets and activities in a multi-level context is thus not present in the surveyed literature and marks the 2SS-MDMT-VRPTW as an original and yet unexplored problem setting.

Network design and routing problems are difficult. They are NP-Hard in all but the simplest cases. Given the structure of the 2SS-MDMT-VRPTW, one can safely assume it is NP-Hard as well. The normal path of algorithm development will therefore lead to exact and meta-heuristic solution methods, parallel computing playing an important role in addressing large-size instances. Given the state-of-the-art in vehicle routing and network design, we expect the development of column-generation-based branch-and-price (and cut) algorithms for the former case. The field of meta-heuristics is too broad for safe predictions, but combining neighborhood and population-based methods into co-operative search strategies, which could also include exact solution methods for partial solutions, (Crainic and Toulouse, 2009) is the path that we intend to follow. Addressing directly the full formulation of the 2SS-MDMT-VRPTW is beyond the scope of this paper, however. In the following, we propose a decomposition approach, which offers a solution-methodology perspective, and provides a better understanding of the building blocks of the formulation for more elaborate algorithmic developments.

4.2 A hierarchical decomposition approach

Two main issues make up the day-before planning problem, the scheduling of the urban-vehicle services and the distribution of loads from satellites to customers via tours performed by city freighters. We therefore propose a hierarchical approach that decomposes the global problem according to these two main issues and yields two formulations:

1. An *urban-vehicle service network design* model that determines schedules (departure times) and routes (satellites serviced) for urban vehicles, as well as the first-level demand distribution strategy: the urban-vehicle service, the satellite, and the type of city freighter to use for each demand considered. Section 5 details this formulation.
2. A *city-freighter fleet management* formulation that, given the results of the previous model, determines the city-freighter routes and schedules to 1) deliver loads to customers within their time windows, and 2) re-position city freighters at satellites, or depots, for their next assignment within the time restrictions imposed by the synchronization with urban-vehicle schedules. Section 6 is dedicated to this issue.

The decomposition approach and the urban-vehicle service network design model receive as input the possible allocations of customer-demands to satellites together with an estimation of the costs of servicing each demand from its associated satellites. Such information is relatively easy to obtain. In evaluation mode, system-design models that select satellite locations and attributes also determine customer-to-satellite allocation policies (Crainic et al., 2004). A number of methods may then be used to approximate satellite-to-customer delivery costs: continuous approximations, simple VRPTW heuristics (e.g., distance and time-based clustering), Monte-Carlo simulations embedding routing heuristics, and so on. Once the City Logistics system is operational, these methods are of course still available, but a probably more efficient approach would use the data on operations performed on previous days to refine the prediction.

The proposed approach could be used in a single or a multiple-pass setting. The former appears appropriate for a general evaluation of the system. The second should improve the results by iteratively solving the two problems using the results of the city-freighter fleet management model to adjust the customer-to-satellite assignments and costs. More importantly, the two problems defined by this decomposition should appear as subproblems in most exact or meta-heuristic solution methods for the 2SS-MDMT-VRPT. The next two sessions are dedicated to the presentation of these problems and formulations for the main model of Section 3.

5 The Urban-Vehicle Service Network Design Model

The models described in this section aim to determine when urban vehicles leave the external zones and the satellites they serve, as well as the itineraries used to move the freight from the external zones until the satellite from where the final distribution is to be performed. The type of city freighter used by each itinerary is explicitly taken into account, while the duration and cost associated to the distribution from satellites to customers are approximated. The goal is on-time delivery of freight at minimum total system cost which, in this case, implies a minimum number of vehicle movements in the city.

Most notation and definitions of the general case (Section 3.1) apply without modification, except when the routing of city freighters was involved. Define $\tilde{\delta}(d, s, t)$, the approximation of the delivery time of customer-demand $d \in \mathcal{D}$ by a city-freighter tour leaving satellite s at period t, given the congestion conditions at that time, and $\tilde{c}(d, s, t)$, the corresponding approximate delivery cost. The definition of demand itineraries $m \in \mathcal{M}(d)$ is modified to reflect these approximations, by stopping them at satellite $s(m)$ and by setting the departure time from satellite at $t_s^{\text{out}}(m) = t_s^{\text{in}}(m) + \delta(\nu)$, and the arrival time at the customer at $t_c(m) = t_s^{\text{out}}(m) + \tilde{\delta}(d, s, t) \in [a(d), b(d)]$.

Two sets of binary decision variables are kept from the initial formulation, $\rho(r)$ selecting urban-vehicle services, and $\zeta(m)$ selecting the itinerary for each customer-demand. The problem may then be formulated as a path-based scheduled service network design problem, where the specification of the schedules associated to each demand itinerary and urban-vehicle service are included in their respective definitions:

$$\text{Minimize} \quad \sum_{r \in \mathcal{R}} k(r)\rho(r) + \sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d)} \tilde{c}(d,s,t) vol(d)\zeta(m) \tag{29}$$

subject to (2), (4), (5), (8), (10), and

$$\sum_{\nu \in \mathcal{V}} \left[\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,s,t)} vol(d)\zeta(m) \right] / u_\nu \leq \lambda_s \qquad s \in \mathcal{S}, \quad t = 1, \ldots, T, \tag{30}$$

The model minimizes the total cost of the system, and thus the number of urban vehicles in the city, as captured by the objective function (29) that sums up the costs relative to the total number of urban vehicles and delivery of demand to customers. Constraints (30) enforce the satellite capacity restrictions in terms of city freighters, their respective numbers by vehicle type being approximated from the total volume to be delivered to customers from each satellite s at each period t (set $\mathcal{M}(d,s,t)$ includes all itineraries of demand d that use satellite s at period $t_s^{\text{in}}(m) \leq t \leq t_s^{\text{out}}(m)$). The results of the formulation in terms of distribution strategy, i.e., the satellite, period, and city-freighter type selected for each demand, are passed on to the city-freighter fleet management model (Section 6) as the sets $\mathcal{C}_{st}^\nu \subseteq \mathcal{D}$ of customer-demands $d \in \mathcal{D}$ that must be served by city freighters of type ν, leaving at period t from satellite s. The total demand associated to each $\mathcal{C}_{st}^\nu$ is given by

$$vol(\mathcal{C}_{st}^\nu) = \sum_{d \in \mathcal{C}_{st}^\nu} \sum_{m \in \mathcal{M}(d,s,t)} vol(d). \tag{31}$$

Service network design problems are difficult. They usually exhibit weak relaxations and are of large dimensions. As a result, the field is dominated by various heuristics as reviewed by the references indicated in Section 4. The particular developments for the present problem are still to come. In the remaining part of this section, we only indicate a few ideas that appear promising, together with the previous work that may be of interest in this context.

To reduce the possibly large problem size, we notice that the customer time windows and the impossibility to wait at satellites imply that the feasible itineraries for any customer-demand leave the associated external zone within a time interval easy to determine and of roughly the same width as the customer time window. To further reduce the size, one may try to re-formulate the problem by defining new variables that account for more than one activity. Time-related aggregations appear appropriate as in the work of Joborn et al. (2004), where so-called kernel paths represented sets of paths with the same physical route and similar temporal characteristics. In our case, this idea could be translated in the definition of "kernel" paths for combinations of departure time intervals and satellites. An alternate idea comes from the service network design model transformation proposed by Armacost et al. (2002), where combinations of services and demands reduced the dimensions of the problem and implicitly accounted for the flow distribution. The last two ideas may be combined, of course.

With respect to solution methods, heuristics will be required for actual applications even if problem dimensions may be reduced. The cycle-based meta-heuristics proposed by Ghamlouche et al. (2003, 2004), which are among the current-best heuristics for the fixed-cost, capacitated, multicommodity network design problem, offer interesting perspectives. Indeed, urban-vehicle routes are relatively short, most services visiting one or two satellites only (this follows from the capacity of the vehicles and the objective of reducing the distance traveled though the city). This, combined to the time-space problem structure, implies that cycles of urban-vehicle design variables will also be short and display particular structures (e.g., involving the "same" service at different time periods) that could be exploited in meta-heuristic moves and parallel computing strategies.

We close this section with two remarks. First, in evaluation mode, detailed, customer-level demand is often not available, estimations for pre-defined customer zones being available instead (see the discussion in Crainic et al., 2004, for example). These zones or a refinement thereof (e.g., at the level of a street or small neighborhood) may then also be used in formulation (29) - (30), which would be smaller and, thus, easier to address. The aggregation along the time dimension of demands of individual customers in the same customer zone would then be considered as a unique customer-demand entity. To ensure feasible deliveries, one should aggregate customers that 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. Of course, such an aggregation could also be used in planning mode for a faster but, potentially, less-precise result.

The second remark concerns the case when urban-vehicle fleets are limited and controlled (Section 3.2). The specialization of urban-vehicle service network design to this context requires the introduction of repositioning arcs from satellites to external zones, as well as of holding arcs at external zones. Moreover, one must also add urban-vehicle flow conservation constraints at external zones and fleet size constraints at each period. The resulting formulation belongs then to the class of design-balanced service network design models (Pedersen et al., 2008). The developments for this class of models are recent and few (e.g., Andersen et al., 2009, 2008; Smilowitz et al., 2003) and none addresses the problem at hand. The meeting of design-balanced service network design models and City Logistics evaluation and planning issues constitutes an open research field.

6 City-freighter Circulation Models

The service design formulation of the preceding section yields workloads for city freighters at satellites, at particular time periods, which take the form of customer-demands that have to be serviced by particular vehicle types. Once all customer-demands are serviced, the city freighters move either to a satellite for further operations or to a depot to complete the work assignment or wait for the next work segment. The scope of the models developed in this section is the planning of the city-freighter fleet operations to ensure that city freighters deliver the goods on time and that they arrive at satellites on time for their assignments. Recall that there are no waiting areas at satellites and that city freighters must arrive at satellites just-in-time to load the designated freight and depart according to the schedule planned by the service design formulation. Feasible city-freighter work assignments must therefore contend not only with the soft time windows of customer-demands, but also with the hard *rendez-vous* points at particular satellites and time periods. We denote this operating mode, apparently seen for the first time in the context of planning City Logistics operations, the *synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* (*SS-MDMT-VRPTW*).

We present two formulations in Sections 6.2 and 6.3, respectively. The first addresses the full time-synchronization issue of the city-freighter SS-MDMT-VRPTW. It can therefore be used both within a City Logistics system-evaluation procedure and as a decision-support tool for a functioning system. The second model takes advantage of the particular role of the (satellite, period) rendez-vous points to decompose the general SS-MDMT-VRPTW formulation into significantly simpler problems. The crude approximation of the synchronization requirements is compensated by the efficiency of the procedure that estimates the number of required city-freighters and the associated circulation, particularly in the context of a City Logistics system-evaluation procedure. We start by presenting the general notation used for these models and the dynamics of the city-freighter circulation problem.

6.1 Notation and System Dynamics

As introduced in Section 5, the city freighter workloads are given by the sets of customer-demands $d \in \mathcal{C}^{\nu}_{st} \subseteq \mathcal{D}$ that must be serviced by city freighters of type ν, leaving at period t from satellite s. Let $\mathcal{ST}(\nu) \subseteq \mathcal{S}\text{x}\mathcal{T}$ be the set of (satellite, period) combinations where sets $\mathcal{C}^{\nu}_{st}$ are non empty. We assume that each demand is less or equal to the capacity of the designated city freighter.

Figure 2 illustrates the dynamics of the system in a somewhat aggregated form (the network is fully described in Section 6.2), where full and dotted lines denote possible loaded and empty city-freighter movements, respectively. Operations are illustrated

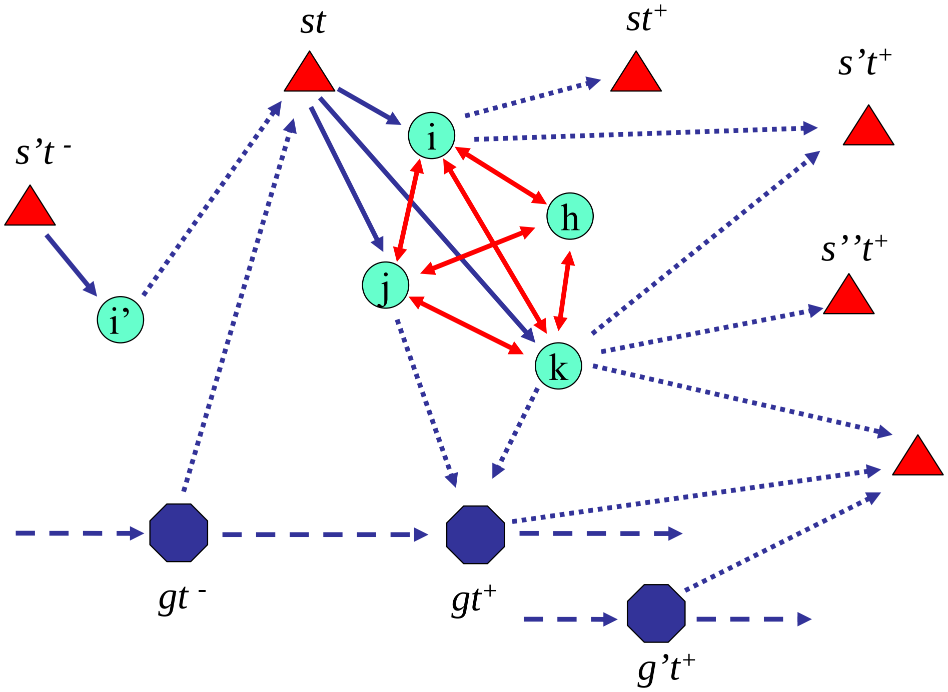

Figure 2: City-freighter Possible Movements

starting from a satellite s at time t (node st) for one type of city freighter. Triangles and octagons denote satellites and city-freighter depots, respectively, at various periods, while disks identified with letters i, j, h, and k represent customers in $\mathcal{C}^{\nu}_{st}$ (while $i' \in \mathcal{C}^{\nu}_{s't^-}$, $t^- < t$). A number of city freighters leave the satellite s at time t and each will first undertake a route to service the customers in $\mathcal{C}^{\nu}_{st}$. Once the last customer is serviced, the city freighter goes either to a depot, e.g., the (j, gt^+) movement, or to a satellite. This last may be the one it just left, e.g., arc (i, st^+), or a different one, e.g., arcs $(k, s't^+)$ and $(k, s''t^+)$, where t^+ indicates a later period as determined by the total travel and customer service time. Given the (satellite, period) rendez-vous points, city freighters arriving at satellites for loading come either directly from a depot, e.g., the (gt^-, st) movement, or from the last customer serviced on a previous service route, e.g., the (i', st) movement. The restrictions on the time instances city freighters must arrive at satellites and customers determine the actual feasible movements.

6.2 The SS-MDMT-VRPTW formulations

The city freighter SS-MDMT-VRPTW formulation is defined on a space-time network $(\mathcal{N}, \mathcal{A})$, where the set of nodes $\mathcal{N}$ represents physical locations at various periods, arcs in $\mathcal{A}$ standing for the feasible movements between these nodes with respect to time and demand-itinerary definitions. Set $\mathcal{N}$ is made up of three subsets:

- $\{st\}$ representing the (satellite, period) rendez-vous points $(s,t) \in \mathcal{ST}(\nu)$ for all city-freighter types ν;
- $\{d\}$ for the customer-demands associated to the nodes in $\{st\}$, i.e., $d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$; We also use $i,j,k \in \mathcal{C}^{\nu}_{st}$;
- $gt \in \mathcal{G}(t)$, representing the city-freighter depots at period $t = 0,\dots,T+1$, where the opening and closing hours for all depots are indicated as time 0 and $T+1$, respectively.

Several sets of arcs represent feasible movements among these nodes and make up set

$$\begin{aligned}\mathcal{A} \ =\ & \bigcup_{\nu\in\mathcal{V}} \bigcup_{(s,t)\in\mathcal{ST}(\nu)} \left[\mathcal{A}^{SD}_{st}(\nu) \bigcup \mathcal{A}^{DS}_{st}(d,\nu) \bigcup \mathcal{A}^{DD}_{st}(\nu) \bigcup \mathcal{A}^{DG}_{st}(d,\nu)\right] \\ & \bigcup_{\nu\in\mathcal{V}} \bigcup_{g\in\mathcal{G},\ t=0,\dots,T} \mathcal{A}^{GS}_{gt}(\nu) \bigcup \mathcal{A}^{G}\end{aligned}$$

- Arcs in $\mathcal{A}^{SD}_{st}(\nu) = \{(st,d) \mid d \in \mathcal{C}^{\nu}_{st}\},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, go from a satellite st to each customer-demand $d \in \mathcal{C}^{\nu}_{st}$, such that the service time-window restriction, $a(d) \le t + \delta_{sd}(t) \le b(d)$, is satisfied. In Figure 2, $\mathcal{A}^{SD}_{st}(\nu) = \{(st,i),(st,j),(st,k)\}$.
- Arcs is $\mathcal{A}^{DS}_{st}(d,\nu) = \{(d, s't'),\ (s',t') \in \mathcal{ST}(\nu)\},\ d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, link customers $d \in \mathcal{C}^{\nu}_{st}$ to satellites in later periods $s't'$, such that city freighters may be loaded and leave by time t': $a(d) \le t' - \delta(\nu) - \delta(d) - \delta_{ds'}(t) \le b(d)$. In Figure 2, $\mathcal{A}^{DS}_{st}(i,\nu) = \{(i, st^{+}), (i, s't^{+})\}$.
- Define the backstar of node st with respect to customer-demands as the set $\mathcal{A}^{S-}_{st}(\nu) = \{(d, st) \mid d \in \mathcal{C}^{\nu}_{s't^{-}},\ (s',t') \in \mathcal{ST}(\nu),\ t' < t,\ a(d) \le t - \delta(\nu) - \delta(d) - \delta_{ds}(t') \le b(d)\},\ \nu \in \mathcal{V}$. Arc (i', st) of Figure 2 belongs to $\mathcal{A}^{S-}_{st}(\nu)$.
- When needed, city freighters may be dispatched out of depots to satellites. To complete the backstar of node st, arcs in $\mathcal{A}^{G-}_{st}(\nu) = \{(gt', st) \mid g \in \mathcal{G},\ t' = t - \delta(\nu) - \delta_{gs}(t)\},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, represent these movements, which must arrive at satellite s on time for the next assignment. In Figure 2, $\mathcal{A}^{G-}_{st}(\nu) = \{(gt^{-}, st)\}$.

  From a depot point of view, the same arcs are grouped into the sets $\mathcal{A}^{GS}_{gt}(\nu) = \{(gt, s't') \mid (s',t') \in \mathcal{ST}(\nu),\ t + \delta_{gs}(t) = t' - \delta(\nu)\},\ g \in \mathcal{G},\ t = 0,\dots,T$ (initial movements out of depots to start service at satellites at $t = 1$ take arbitrarily place at $t = 0$). Set $\mathcal{A}^{GS}_{gt^{-}}(\nu) = \{(gt^{-}, st)\}$ illustrates this definition in Figure 2.

- An arc exists between each pair of customer-demands $(i,j),\ i,j \in \mathcal{C}^{\nu}_{st}$, for which the movement is feasible with respect to the respective time-window constraints. Given the time window $[a(d), b(d)]$ and the service time $\delta(d)$ of customer $d \in \mathcal{C}^{\nu}_{st}$, one considers only the arcs to customers j such that $b(d) + \delta(d) + \delta_{dj}(t) \leq b_j$ (plus $a_j \leq a(d) + \delta(d) + \delta_{dj}(t)$ when waiting "at" the customer site is not allowed). Set $\mathcal{A}^{DD}_{st}(\nu) = \bigcup_{d\in\mathcal{C}^{\nu}_{st}} \mathcal{A}^{DD}_{st}(d,\nu)$ contains these arcs, while set $\mathcal{A}^{D-}_{st}(\nu) = \bigcup_{d\in\mathcal{C}^{\nu}_{st}} \mathcal{A}^{D-}_{st}(d,\nu)$ holds the corresponding backstar arcs (i.e., arriving at customer d at period t) for $d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$. In Figure 2, $\mathcal{A}^{DD}_{st}(i,\nu) = \{(i,j),(i,k),(i,h)\}$ and $\mathcal{A}^{D-}_{st}(i,\nu) = \{(j,i),(k,i),(h,i)\}$.
- Arcs in $\mathcal{A}^{DG}_{st}(d,\nu) = \{(d, gt^+),\ d \in \mathcal{C}^{\nu}_{st},\ g \in \mathcal{G},\ t^+ > t\},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, link customers $d \in \mathcal{C}^{\nu}_{st}$ to depots in later periods, arriving at depot g at period t^+, such that $a(d) + \delta(d) + \delta_{dg}(t) \leq t^+ \leq b(d) + \delta(d) + \delta_{dg}(t)$. For customer k of Figure 2, $\mathcal{A}^{DG}_{st}(k,\nu) = \{(k, gt^+))\}$.
- City-freighter holding arcs at depots: $\mathcal{A}^G = \{(gt, gt+1),\ t = 0,\ldots,T,\ \forall g \in \mathcal{G}\}$.

Referring to the notation introduced in Section 3, the sets of feasible work segments $\mathcal{W}(\nu)$ and assignments $\mathcal{H}(\nu)$ for city freighters of type $\nu \in \mathcal{V}$ are restricted by the $\mathcal{ST}(\nu)$ rendez-vous points. In particular, sets of visited satellites are restricted to $\sigma(w) = \{s_l \in \mathcal{S},\ l = 1,\ldots,|\sigma(w)| \mid t_l(w) < t_{l+1}(w) \text{ and } (s_l, t_l(w)) \in \mathcal{ST}(\nu)\}$ (with $t_{|\sigma(w)|+1}(w) = t(g(w))$). Moreover, $\mathcal{C}_l(w) \subseteq \mathcal{C}^{\nu}_{st}$ and one or more city-freighter work assignments are required to service the customer-demands in $\mathcal{C}^{\nu}_{st}$.

Define $\alpha_{st}(h,d) = 1$, if work assignment $h \in \mathcal{H}(\nu)$ services customer-demand $d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu)$, that is, if $(s,t) \in \sigma(w)$ for any of the work segments $w \in \sigma(h)$. These marker functions are sufficient to determine how demand will be delivered (recall that we assume single-delivery policy) and replace the demand itinerary definition of Section 3. The general model (1) - (10) then reduces to the following path-based formulation of the city-freighter SS-MDMT-VRPTW:

$$\text{Minimize} \quad \sum_{h\in\mathcal{H}} k(h)\varphi(h) \tag{32}$$

$$\text{Subject to} \quad \sum_{d\in\mathcal{C}^{\nu}_{st}} \alpha_{st}(h,d)vol(d) \leq u_{\nu}\varphi(h) \qquad (s,t) \in \sigma(w),\ w \in \sigma(h),\ h \in \mathcal{H}, \tag{33}$$

$$\sum_{h\in\mathcal{H}(\nu)} \alpha_{st}(h,d)\varphi(h) = 1 \qquad d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu), \tag{34}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{h\in\mathcal{H}} h(s,t^-)\varphi(h) \leq \lambda_s \qquad s \in \mathcal{S},\ t = 1,\ldots,T, \tag{35}$$

$$\sum_{h\in\mathcal{H}(\nu)} \varphi(h) \leq n_{\nu} \qquad \nu \in \mathcal{V}, \tag{36}$$

$$\varphi(h) \in \{0,1\} \qquad h \in \mathcal{H}. \tag{37}$$

The path formulation is compact and quite elegant. Based on the considerable body of work dedicated to various types of vehicle routing problems, it should also be the starting point for developing column-generation-based exact solution methods to be applied to modestly-dimensioned problem instances. This elegance is hiding, however, the increased complexity of the SS-MDMT-VRPTW, compared to the more "regular" VRPTW settings, which comes from the requirements for the space-time synchronization of the city-freighter work assignments. An arc-based formulation provides the framework for displaying these requirements and emphasizes the combination of soft customer-demand time windows and hard satellite rendez-vous points characteristic of the city-freighter SS-MDMT-VRPTW.

Let k_ν and $k_\nu(i,j), (i,j) \in \bar{\mathcal{A}} = \mathcal{A} \setminus \mathcal{A}^G$, stand for the cost associated to handling a city freighter of type ν at a satellite and the unit transportation cost between two points $i, j \in \mathcal{N}$ in the city, respectively. Two types of decision variables are defined:

- Flow variables $\theta^\nu_\phi(i,j),\ (i,j) \in \mathcal{A},\ \phi = 1,\dots,n_\nu,\ \nu \in \mathcal{V}$, which equal 1 if arc (i,j) is used by the city freighter ϕ of type ν, and 0 otherwise;
- Time variables $\omega^\nu_\phi(i),\ i \in \mathcal{N},\ \phi = 1,\dots,n_\nu,\ \nu \in \mathcal{V}$, which indicate when the city freighter ϕ arrives, and starts service in most cases, at node i.

An arc-based mathematical programming formulation may then be written:

$$\text{Minimize} \quad \sum_{\nu\in\mathcal{V}} \sum_{\phi=1}^{n_\nu} \left[\sum_{(i,j)\in\bar{\mathcal{A}}} k_\nu(i,j)\theta^\nu_\phi(i,j) + k_\nu \sum_{(s,t)\in\mathcal{ST}(\nu)} \sum_{d\in\mathcal{C}^\nu_{st}} \theta^\nu_\phi(s,d) \right] \tag{38}$$

$$\text{Subject to} \quad l_{st}(\nu) \le \sum_{(s,d)\in\mathcal{A}^{SD}_{st}(\nu)} \theta^\nu_\phi(s,d) \le u_{st}(\nu) \quad (s,t)\in\mathcal{ST}(\nu),\ \nu\in\mathcal{V}, \tag{39}$$

$$\sum_{(s,d)\in\mathcal{A}^{SD}_{st}(\nu)} \theta^\nu_\phi(s,d) \le 1 \quad (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\dots,n_\nu,\ \forall\nu\in\mathcal{V}, \tag{40}$$

$$\sum_\phi \left[\sum_{(d,i)\in\mathcal{A}^{DD}_{st}(d,\nu)} \theta^\nu_\phi(d,i) + \sum_{(d,s't')\in\mathcal{A}^{DS}_{st}(d,\nu)} \theta^\nu_\phi(d,s') + \sum_{(d,g)\in\mathcal{A}^{DG}_{st}(d,\nu)} \theta^\nu_\phi(d,g) \right] = 1$$
$$d\in\mathcal{C}^\nu_{st},\ (s,t)\in\mathcal{ST}(\nu),\ \nu\in\mathcal{V}, \tag{41}$$

$$\sum_\phi \left[\theta^\nu_\phi(s,d) + \sum_{(i,d)\in\mathcal{A}^{D-}_{st}(d,\nu)} \theta^\nu_\phi(i,d) \right] = 1 \quad d\in\mathcal{C}^\nu_{st},\ (s,t)\in\mathcal{ST}(\nu),\ \nu\in\mathcal{V}, \tag{42}$$

$$\sum_{(gt',st)\in\mathcal{A}^{G-}_{st}(\nu)} \theta^{\nu}_{\phi}(g,s) + \sum_{(d,st)\in\mathcal{A}^{S-}_{st}(\nu)} \theta^{\nu}_{\phi}(d,s) = \sum_{(st,d)\in\mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d)$$
$$(s,t)\in\mathcal{ST}(\nu),\ g\in\mathcal{G},\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \quad (43)$$

$$\sum_{\phi}\left[\theta^{\nu}_{\phi}(g(t-1),g(t)) + \sum_{(d,g)\in\mathcal{A}^{DG}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,g)\right] \quad (44)$$
$$= \sum_{\phi}\left[\theta^{\nu}_{\phi}(g(t),g(t+1)) + \sum_{(g,s)\in\mathcal{A}^{GS}_{gt}(\nu)} \theta^{\nu}_{\phi}(g,s)\right] \quad g\in\mathcal{G},\ \nu\in\mathcal{V},\ t=1,\ldots,T \quad (45)$$

$$\sum_{d\in\mathcal{C}^{\nu}_{st}} vol(d)\theta^{\nu}_{\phi}(s,d) + \sum_{(i,j)\in\mathcal{C}^{\nu}_{st}} vol(j)\theta^{\nu}_{\phi}(i,j) \le u_{\nu}$$
$$\phi=1,\ldots,n_{\nu},\ (s,t)\in\mathcal{ST}(\nu),\ \nu\in\mathcal{V}, \quad (46)$$

$$\omega^{\nu}_{\phi}(i)+\delta(i)+\delta_{ij}(t)-\omega^{\nu}_{\phi}(j) \le (1-\theta^{\nu}_{\phi}(i,j))(b_i+\delta(i)+\delta_{ij}(t)-a_j)$$
$$\phi=1,\ldots,n_{\nu},\ (i,j)\in\mathcal{A}^{DD}_{st}(i,\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \nu\in\mathcal{V}, \quad (47)$$

$$a(d)\left[\theta^{\nu}_{\phi}(s,d) + \sum_{(i,d)\in\mathcal{A}^{D-}_{st}(d,\nu)} \theta^{\nu}_{\phi}(i,d)\right] \le \omega^{\nu}_{\phi}(d)$$
$$\le b(d)\left[\sum_{(d,i)\in\mathcal{A}^{DD}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,i) + \sum_{(d,s't')\in\mathcal{A}^{DS}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,s') + \sum_{(d,g)\in\mathcal{A}^{DG}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,g)\right]$$
$$d\in\mathcal{C}^{\nu}_{st},\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \quad (48)$$

$$(t-\delta(\nu)-\delta)\sum_{(s,d)\in\mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d) \le \omega^{\nu}_{\phi}(st) \le (t-\delta(\nu))\sum_{(s,d)\in\mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d)$$
$$(s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}. \quad (49)$$

$$(\omega^{\nu}_{\phi}(d)+\delta(d)+\delta_{ds}(t')-\omega^{\nu}_{\phi}(st)) = (1-\theta^{\nu}_{\phi}(d,s))(\omega^{\nu}_{\phi}(d)+\delta(d)+\delta_{ds}(t')-\omega^{\nu}_{\phi}(st))$$
$$(d,s)\in\mathcal{A}^{S-}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \quad (50)$$

$$(\omega^{\nu}_{\phi}(gt')+\delta_{gs}(t')-\omega^{\nu}_{\phi}(st)) = (1-\theta^{\nu}_{\phi}(g,s))(\omega^{\nu}_{\phi}(gt')+\delta_{gs}(t')-\omega^{\nu}_{\phi}(st))$$
$$(g,s)\in\mathcal{A}^{G-}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \quad (51)$$

$$(\omega^{\nu}_{\phi}(st)+\delta(\nu)+\delta_{sd}(t)-\omega^{\nu}_{\phi}(d)) = (1-\theta^{\nu}_{\phi}(s,d))(\omega^{\nu}_{\phi}(st)+\delta(\nu)+\delta_{sd}(t)-\omega^{\nu}_{\phi}(d)$$
$$(s,d)\in\mathcal{A}^{SD}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \quad (52)$$

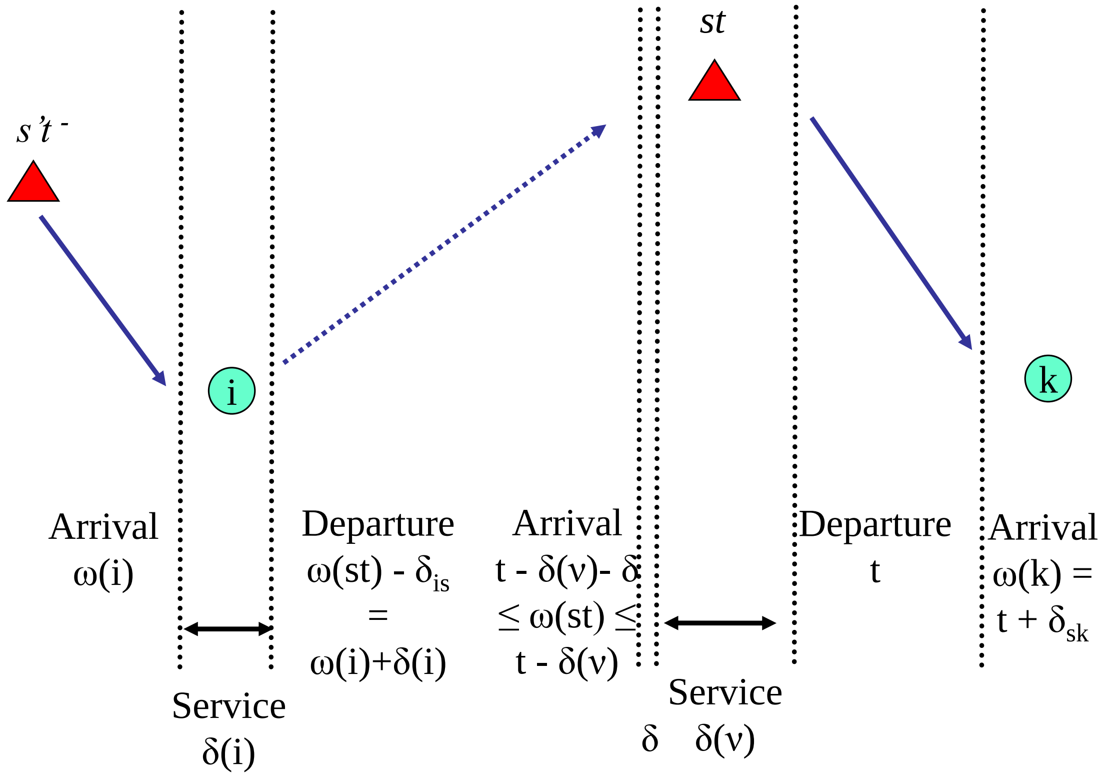

Figure 3: City-freighter Synchronization Requirements

$$\theta^{\nu}_{\phi}(i,j) \in \{0,1\} \quad (i,j) \in \mathcal{A},\ \phi = 1,\dots,n_{\nu},\ \forall \nu \in \mathcal{V} \tag{53}$$

The objective function (38) minimizes the total transportation-related cost, as well as the number of city freighters used (through their utilization costs at satellites). Lower, $l_{st}(\nu)$, and upper, $u_{st}(\nu)$, bounds on the number of city freighters of each type leaving a satellite at any given period may be derived from the demand $\mathcal{C}^{\nu}_{st}$ (e.g., $l_{st}(\nu) = vol(\mathcal{C}^{\nu}_{st})/u_{\nu}$ and $u_{st}(\nu) = \min\{|\mathcal{C}^{\nu}_{st}|, n_{\nu}\}$). Constraints (39) enforce these restrictions. Constraints (40) ensure that each vehicle leaving a satellite goes to one customer only, while constraints (41) force the single assignment of customers to routes. The latter also ensure that a city freighter leaving a customer goes either to another customer of the same set $\mathcal{C}^{\nu}_{st}$, a satellite, or a depot. These two sets of constraints together with (42) also enforce the flow conservation at customer nodes (at least one arc must service each customer-demand). The conservation of flow at satellites at each rendez-vous point of a city-freighter type is completed by equations (43). Equations (44) represent the conservation of flow at depots. Relations (46) enforce the restrictions on the city-freighter capacities, each time a vehicle leaves a (satellite, period) rendez-vous point to deliver customer-demands.

Constraints (47) and (48), enforce schedule feasibility with respect to the service time consideration for movements between customers. Service must start within the time window associated to the customer-demand, but no restrictions are imposed on when the vehicle actually arrives (so-called soft time windows). Constraints (49), (50), (51), and (52), illustrated in Figure 3, impose the synchronization of city-freighter arrivals at the (satellite, period) rendez-vous points, characteristic of SS-MDMT-VRPTW. Constraints (49) specify the period service must start at the satellite. Given this period, constraints (50) and (51) impose the departure time t' from the previous customer or depot, respectively. Similarly, constraints (52) impose the arrival time to the first customer-demand out of the (satellite, period) rendez-vous point. Finally, conditions (53) impose binary values on the flow variables.

We have elaborated in Section 4 on the 2SS-MDMT-VRPTW and perspectives for the development of solution methods. These comments apply rather straightforwardly to the SS-MDMT-VRPTW as well. To our best knowledge, both formulations are original. The path formulation of the SS-MDMT-VRPTW suggests the development of column-generation-based branch-and-price methods. We do not expect such approaches to do much better in terms of problem-size solved than the state-of-the-art methods for VRPTW. The surveys referred to in Section 4 provide reasons, however, 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 ("hybridizing" 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 et al. (2001) and the cooperative search of Le Bouthillier et al. (2005) illustrate this trend that we intend to follow for this problem.

Formulation (38) - (53) is a general model integrating all issues related to the routing of each city freighter, the coordination of the fleet, and the synchronization of activities at satellites. It could thus be used to plan the activities of deployed systems. A simpler approximation scheme, which takes advantage of the context and characteristics of the problem, can be proposed for evaluation purposes. This is the scope of the next subsection.

6.3 A decomposition approach for the SS-MDMT-VRPTW

The general idea of the heuristic we propose for the SS-MDMT-VRPTW is to decompose the problem at the (satellite, period) rendez-vous points, solve the resulting small VRPTW, and approximate the required flow of city freighters, without specifically accounting for the satellite synchronization requirements. The method proceeds in two phases:

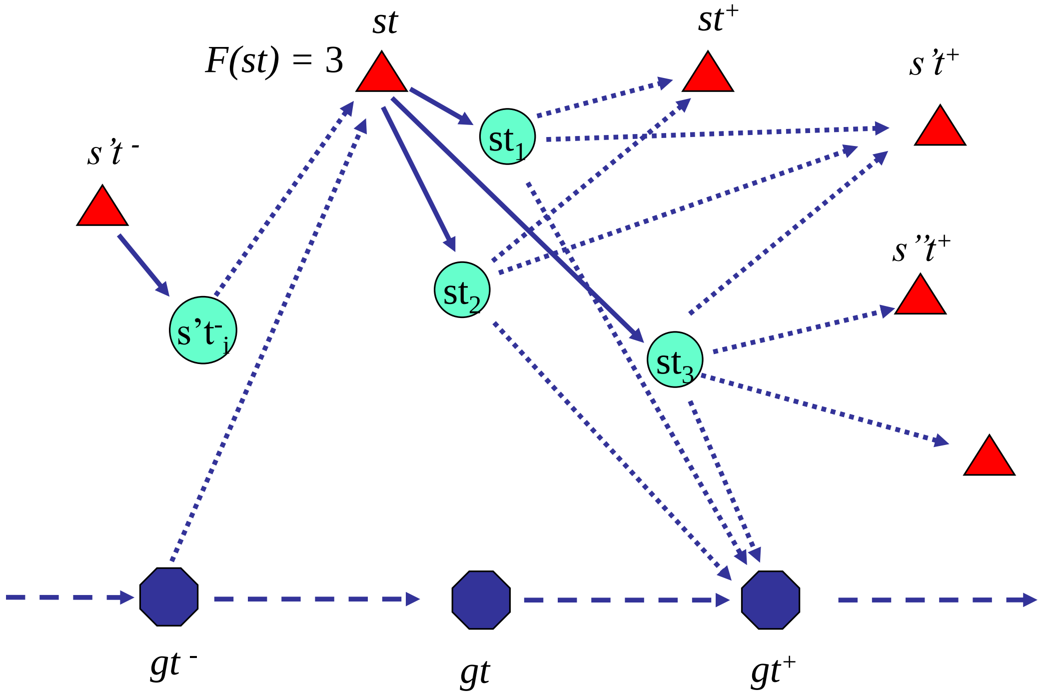

Figure 4: Disaggregated City-freighter Network

Routing. Solve *independently* each vehicle routing problem with time windows associated with customers in $\mathcal{C}_{st}^{\nu}$, $(s,t) \in \mathcal{ST}(\nu)$, $\nu \in \mathcal{V}$, $s \in \mathcal{S}$, $1 \leq t \leq T$.

Circulation. Flow city freighters among (satellite, period) rendez-vous points (and, eventually, depots) to supply them at minimum cost with the appropriate numbers of vehicles.

The number of VRPTW subproblems depends upon the number of non-empty $\mathcal{C}_{st}^{\nu}$ sets and is bounded by $|\mathcal{ST}(\nu)||\mathcal{V}|$. The size of each problem is relatively small, however, the capacity of the contemplated vehicles forcing the cardinality of sets $\mathcal{C}_{st}^{\nu}$ to be in the low teens. Individual VRPTW (return arcs from each customer to its satellite are included with suitable, e.g., 0, travel time and cost) may thus be addressed very efficiently either exactly or by one of the fast meta-heuristics present in the literature (see the surveys introduced previously). The global efficiency of this phase may be increased by solving these individual problems in parallel.

The output of the routing phase specifies for each (satellite, period) rendez-vous point (s,t), the number of city freighters $F_{\nu}(st)$ of type ν required to service the customers in

$\mathcal{C}^{\nu}_{st}$, as well as the associated routes $\phi = 1, \ldots, F_\nu(st)$ with their time $\Delta^\nu_\phi(st)$ and cost $k^\nu_\phi(st)$ attributes. Denote $d(st_\phi)$ the last customer-demand serviced by route ϕ. Then, $t + \Delta^\nu_\phi(st)$ represents the moment route ϕ is completed and the associated city freighter may proceed to a satellite or return to the depot. A minimum-cost network flow problem may then be defined to yield a circulation plan for the city freighters of each type.

The network used to define the circulation problem for each city-freighter type ν is a much simplified version of the one described in the previous section, and is illustrated in Figure 4 for a (satellite, period) rendez-vous point with three associated routes ($F_\nu(st) = 3$). The set $\mathcal{N}$ is made up of the node sets $\{gt\}$ and $\{st\}$ defined as before, plus the set of nodes $\{st_\phi\}$ standing for the routes $\phi = 1, \ldots, F_\nu(st)$ associated to each node st (e.g., nodes st_1, st_2, and st_3 in Figure 4). There are no arcs between nodes representing routes. The sets of depot-to-satellite and depot-holding arcs have the same definition $\mathcal{A}^{G-}_{st}(\nu)$ (and $\mathcal{A}^{GS}_{gt}(\nu)$) and $\mathcal{A}^G$, respectively, as in the previous subsection. The other arcs of the network are:

- Arcs $(st, st_\phi) \in \mathcal{A}^{SD}_{st}(\nu)$ go from satellite-node st to each route-node st_ϕ, $\phi = 1, \ldots, F_\nu(st)$, $(s,t) \in \mathcal{ST}(\nu)$. Three such arcs are illustrated in Figure 4.
- Arcs in $\mathcal{A}^{DS}_{st}(st_\phi, \nu)$ link each route-node st_ϕ to satellite-nodes $s't'$ in later periods, such that $t + \Delta^\nu_\phi(st) + \delta_{d(st_\phi)s't'}(t + \Delta^\nu_\phi(st)) = t' - \delta(\nu)$. $\mathcal{A}^{DS}_{st}(st_i, \nu) = \{(st_1, st^+), (st_1, s't^+)\}$ in Figure 4.

  The set $\mathcal{A}^{S-}_{st}(\nu) = \{(s't'_\phi, st)\}$ represents the backstar of node st with respect to route-nodes $s't'_\phi$, such that $t' + \Delta^\nu_\phi(s't') + \delta_{d(s't'_\phi)st}(t' + \Delta^\nu_\phi(s't')) = t - \delta(\nu)$.
- Arcs $\mathcal{A}^{DG}_{st}(d, \nu) = \{(st_\phi, gt^+)\}$ link each route-node st_ϕ to depots g in later periods $t^+ = t + \Delta^\nu_\phi(st) + \delta_{d(st_\phi)g}(t + \Delta^\nu_\phi(st))$, e.g., arc (st_2, gt^+) in Figure 4.

Define the decision variables $f_\nu(i,j)$ to stand for the number of city freighters of type ν that move between nodes $i, j \in \mathcal{N}$. The associated unit cost is $k_\nu(i,j)$. The minimum cost network flow formulation for each city-freighter type ν then becomes:

$$\text{Minimize} \quad \sum_{(i,j)\in\mathcal{A}} k_\nu(i,j) f_\nu(i,j) \tag{54}$$

Subject to

$$\sum_{(st,st_\phi)\in\mathcal{A}^{SD}_{st}(\nu)} f_\nu(st, st_\phi) = F_\nu(st) \quad (s,t) \in \mathcal{ST}(\nu), \tag{55}$$

$$f_\nu(st, st_\phi) = 1 \quad (st, st_\phi) \in \mathcal{A}^{SD}_{st}(\nu) \quad (s,t) \in \mathcal{ST}(\nu), \tag{56}$$

$$\sum_{gt'} f_\nu(gt', st) + \sum_{(i,j)\in\mathcal{A}^{S-}_{st}(\nu)} f_\nu(i,j) = \sum_{(st,st_\phi)\in\mathcal{A}^{SD}_{st}(\nu)} f_\nu(st, st_\phi) \quad (s,t) \in \mathcal{ST}(\nu), \tag{57}$$

$$f_\nu(st, st_\phi) = \sum_{(st_\phi, gt^+) \in \mathcal{A}_{st}^{DG}(d,\nu)} f_\nu(st_\phi, gt^+) + \sum_{(st_\phi, s't')) \in \mathcal{A}_{st}^{DS}(st_\phi,\nu)} f_\nu(st_\phi, s't') \quad (s,t) \in \mathcal{ST}(\nu), \tag{58}$$

$$\begin{aligned} f_\nu(g(t-1), gt) &+ \sum_{(i,j) \in \mathcal{A}_{st}^{DG}(d,\nu)} f_\nu(st_\phi, gt^+) \\ &= f_\nu(gt, g(t+1)) + \sum_{(i,j) \in \mathcal{A}_{gt}^{GS}(\nu)} f_\nu(gt', st) \quad g \in \mathcal{G},\ t = 1, \dots, T+1 \end{aligned} \tag{59}$$

$$f_\nu(i,j) \geq 0 \quad (i,j) \in \mathcal{A} \tag{60}$$

Constraints (55) and (56) fix the number of city-freighters that must arrive at each (satellite, period) rendez-vous point and enforce the single-vehicle-per-route condition, respectively. Constraints (57) and (58) then enforce the flow conservation conditions at (satellite, period) rendez-vous points and route-nodes, respectively. Conservation of flow at depot nodes $g(t)$ are enforced by constraints (59), with given initial conditions $f_\nu(g0,\ g1)$ (number of city freighters available at each depot; alternatively, a super-source may distribute all city freighters).

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 City Distribution Centers. City Logistics explicitly refers to the *optimization* of such advanced urban freight transportation systems.

In this paper, we focused on the 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 undertook our analysis within the general case of two-tier City Logistics systems, where satellite platforms are used to transship loads from vehicles arriving from CDCs to smaller, center-city-friendly vehicles. The problem concerned the selection or routes and the scheduling of departures for the vehicles of the two fleets involved, as well as the selection of the delivery routes for customer demands from the CDCs through satellites to the final customer. Strict coordination and time-synchronization of the operations of the two fleets are central elements of the problem, which appears to belong to a new problem class that we denoted the *two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* (*2SS-MDMT-VRPTW*).

We proposed a general mathematical formulation for the problem, introduced variants and analyzed them, identified promising solution avenues and proposed methodological approaches for utilization in both planning and evaluation modes. These contributions open the way to optimization and simulation methodological developments on which we intend to report in the near future.

Acknowledgments

While working on this project, the first author was the NSERC Industrial Research Chair on Logistics Management, ESG UQAM, and Adjunct Professor with the Department of Computer Science and Operations Research, Université de Montréal, and the Department of Economics and Business Administration, Molde University College, Norway. 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 (NSERC), through its Industrial Research Chair and Discovery Grants programs, by the partners of the Chair, CN, Rona, Alimentation Couche-Tard and the Ministry of Transportation of Québec, by the Fonds québécois de recherche sur la nature et les technologies (FQRNT Québec) through its Team Research grants program, and by MIUR, Ministero Istruzione Universitá Ricerca, through project PRIN 2003 *Infomobility and design of integrated system for urban transport* prot. 2003095533.

We want to take this opportunity to thank our colleagues and friends, Professors Lucca Bertazzi, Michel Gendreau, Guido Perboli, and Maria Grazia Speranza, as well as our students Abderrahim Benjelloun, Jesus Gonzales Feliu, Lorraine Cauquil, and Simona Mancini, for enlighting exchanges, help with the literature search, and starting the exploration of algorithmic developments for the problems introduced in this paper. We also want to thank the Editor of the Journal and the anonymous Associate Editor and referees for their comments, critics, and suggestions, which all helped us write a better paper.

References

C. Ambrosini and J.-L. Routhier. Objectives, Methods and Results of Surveys Carried out in the Field of Urban Freight Transport: An International Comparison. *Transport Reviews*, 24:55–77, 2004.

D. Ambrosino and M.G. Scutellà. Distribution Network Design: New Problems and Related Models. *European Journal of Operational Research*, 155(3):610–624, 2005.

J. Andersen, T.G. Crainic, and M. Christiansen. Service Network Design with Asset Management: Formulations and Comparative Analyzes. *Transportation Research Part C: New Technologies*, 2008. on line at Articles in Advance DOI:10.1016/j.trc.2008.10.005.

J. Andersen, T.G. Crainic, and M. Christiansen. Service Network Design with Management and Coordination of Multiple Fleets. *European Journal of Operational Research*, 193(2):377–389, 2009.

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

A.P. Armacost, C. Barnhart, K.A. Ware, and A.M. Wilson. UPS Optimizes Its Air Network. *Interfaces*, 34(1):15–25, 2004.

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

J. Barceló, H. Grzybowska, and S. Pardo. Vehicle Routing and Scheduling Models, Simulation and City Logistics. In Zeimpekis, V., Tarantilis, C.D., Giaglis, G.M., and Minis, I., editors, *Dynamic Fleet Management Concepts - Systems, Algorithms & Case Studies*, pages 163–195. Springer, 2007.

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

C. Barnhart, E.L. Johnson, G.L. Nemhauser, and P.H. Vance. Crew Scheduling. In Hall, R.W., editor, *Handbook of Transportation Science*, pages 517–560. Kluwer Academic Publishers, Norwell, MA, second edition, 2003.

A. Benjelloun and T.G. Crainic. Trends, Challenges, and Perspectives in City Logistics. In *Transportation and Land Use Interaction, Proceedings TRANSLU'08*, pages 269–284. Editura Politecnica Press, Bucharest, Romania, 2008.

BESTUFS. Best Urban Freight Solutions. European Union project, http://www.bestufs.net.

L.D. Bodin, V. Maniezzo, and A. Mingozzi. Street Routing and Scheduling Problems. In Hall, R.W., editor, *Handbook of Transportation Science*, pages 413–449. Kluwer Academic Publishers, Norwell, MA, second edition, 2003.

J. Boerkamps and A. van Binsbergen. GoodTrip - A New Approach for Modelling and Evaluating Urban Goods Distributrion. In Taniguchi, E. and Thompson, R.G., editors, *City Logistics I, 1st International Conference on City Logistics*, pages 175–186. Institute of Systems Science Research, Kyoto, 1999.

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

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

M. Browne, S. Allen, S. Andersen, and A. Woodburn. Urban Freight Consolidation Centres. In Taniguchi, E. and Thompson, R.G., editors, *Recent Advances in City Logistics*, pages 253–265. Elsevier, Amsterdam, 2006.

K. Buedenbender, T. Grünert, and H.-J. Sebastian. A Hybrid Tabu Search/Branch and Bound Algorithm for the Direct Flight Network Design Problem. *Transportation Science*, 34(4):364–380, 2000.

E. Cascetta. *Transportation Systems Engineering: Theory and Methods*. Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001.

M. Christiansen, K. Fagerholt, and D. Ronen. Ship Routing and Scheduling: Status and Perspectives. *Transportation Science*, 38(1):1–18, 2004.

M. Christiansen, K. Fagerholt, B. Nygreen, and D. Ronen. Maritime Transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, pages 189–284. North-Holland, Amsterdam, 2007.

Chronopost International. Chronopost, pionnière de la livraison propre en centre ville. Dossier de presse, 2007.

CITY PORTS. A Network of Cities Following a Co-ordinated Approach to Develop Feasible and Sustainable City Logistics Solutions. European Union project, http://www.cityports.net.

CIVITAS Initiative. City-Vitality-Sustainability. European Union project, http://www.civitas-initiative.org.

J.-F. Cordeau, P. Toth, and D. Vigo. A Survey of Optimization Models for Train Routing and Scheduling. *Transportation Science*, 32(4):380–404, 1998.

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

J.-F. Cordeau, G. Laporte, M.W.F. Savelsbergh, and D. Vigo. Vehicle Routing. In Barnhart, C. and Laporte, G., editors, *Transportation*, Handbooks in Operations Research and Management Science, pages 367–428. North-Holland, Amsterdam, 2007.

T.G. Crainic. Long-Haul Freight Transportation. In Hall, R.W., editor, *Handbook of Transportation Science*, pages 451–516. Kluwer Academic Publishers, Norwell, MA, second edition, 2003.

T.G. Crainic. Network Design in Freight Transportation. *European Journal of Operational Research*, 122(2):272–288, 2000.

T.G. Crainic and M. Florian. National Planning Models and Instruments. *INFOR*, 46 (4):81–90, 2008.

T.G. Crainic and K. Kim. Intermodal Transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, chapter 8, pages 467–537. North-Holland, Amsterdam, 2007.

T.G. Crainic and M. Toulouse. Parallel Strategies for Meta-Heuristics. In Gendreau, M. and Potvin, J.-Y., editors, *Handbook of Metaheuristics*. Springer, 2009.

T.G. Crainic, N. Ricciardi, and G. Storchi. Advanced Freight Transportation Systems for Congested Urban Areas. *Transportation Research Part C: Emerging Technologies*, 12(2):119–137, 2004.

T.G. Crainic, M. Gendreau, and J.-Y. Potvin. Intelligent Freight-Transportation Systems: Assessment and the Contribution of Operations Research. *Transportation Research Part C: Emerging Technologies*, 2008. forthcoming, doi:10.1016/j.trc.2008.07.002.

K.L. Croxton, B. Gendron, and T.L. Magnanti. Models and Methods for Merge-in-Transit Operations. *Transportation Science*, 37(1):1–22, 2003.

L. Dablanc. Goods Transport in Large European Cities: Difficult to Organize, Difficult to Modernize. *Transportation Research Part A: Policy and Practice*, 41(3):280–285, 2007.

G.B. Dantzig and J.H. Ramser. The truck dispatching problem. *Management Science*, 6:80–91, 1959.

G. Desaulniers, J. Desrosiers, M. Gamache, and F. Soumis. Crew Scheduling in Air Transportation. In T.G. Crainic and G. Laporte, editors, *Fleet Management and Logistics*, pages 169–185. Kluwer Academic Publishers, Norwell, MA, 1998a.

G. Desaulniers, J. Desrosiers, I. Ioachim, M.M. Solomon, F. Soumis, and D. Villeneuve. A Unified Framework for Deterministic Time Constrained Vehicle Routing and Crew Scheduling Problems. In T.G. Crainic and G. Laporte, editors, *Fleet Management and Logistics*, pages 57–93. Kluwer Academic Publishers, Norwell, MA, 1998b.

J. Desrosiers, Y. Dumas, M.M. Solomon, and F. Soumis. Time Constrained Routing and Scheduling. In M. Ball, Magnanti, T.L., Monma, C.L., and Nemhauser, G.L., editors, *Network Routing*, volume 8 of *Handbooks in Operations Research and Management Science*, pages 35–139. North-Holland, Amsterdam, 1995.

W.J. Dietrich. Approches et pistes suivies en Suisse. In D. Patier-Marque, editor, *L'intégration des marchandises dans le système des déplacements urbains - Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000*, volume 15 of *Études et recherches*, pages 191–198. Laboratoire d'Économie des Transports, Lyon, France, 2001.

H. Donaldson, E.L. Johnson, H.D. Ratliff, and M. Zhang. Schedule-Driven Cross-Docking Networks. Georgia Tech TLI Report, The Logistics Institute, Georgia Tech., 1998.

J.-G. Dufour. L'émergence du problème des marchandises en villes en France et en Europe de l'Ouest. In D. Patier-Marque, editor, *L'intégration des marchandises dans le système des déplacements urbains - Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000*, volume 15 of *Études et recherches*, pages 19–29. Laboratoire d'Économie des Transports, Lyon, France, 2001.

M.A. Figliozzi. Analysis of the Efficiency of Urban Commercial Vehicle Tours: Data Collection, Methodology and Policy Implications. *Transportation Research Part B: Methodological*, 41(9):1014–1032, 2007.

M. Florian. Models and Software for Urban and Regional Transportation Planning: The Contribution of the Center for Research on Transportation. *INFOR*, 46(1):29–50, 2008.

M. Friedrich, T. Haupt, and K. Nökel. Freight Modelling: Data Issues, Survey Methods, Demand and Network Models. presented at the 10th International Conference on Travel Behaviour Research, Lucerne, 2003.

G. Gentile and D. Vigo. Movement Generation and Trip Distribution for Freight Demand Modelling Applied to City Logistics. Technical report, Università di Bologna, Italy, 2007.

M. Gentili. Visiting a Network of Services with Time Constraints. *Computers & Operations Research*, 30(8):1187–1217, 2003.

I. Ghamlouche, T.G. Crainic, and M. Gendreau. Cycle-based Neighbourhoods for Fixed-Charge Capacitated Multicommodity Network Design. *Operations Research*, 51(4): 655–667, 2003.

I. Ghamlouche, T.G. Crainic, and M. Gendreau. Path Relinking, Cycle-based Neighbourhoods and Capacitated Multicommodity Network Design. *Annals of Operations Research*, 131:109–133, 2004.

S. Gragnani, G. Valenti, and M.P. Valentini. City Logistics in Italy: A National Project. In Taniguchi, E. and Thompson, R.G., editors, *Logistics Systems for Sustainable Cities*, pages 279–293. Elsevier, Amsterdam, 2004.

T. Grünert and H.-J. Sebastian. Planning Models for Long-haul Operations of Postal and Express Shipment Companies. *European Journal of Operational Research*, 122(2): 289–309, 2000.

B.J.P. Janssen and A.H. Oldenburger. Product Channel Logistics and City Distribution Centers; The case of the Netherlands. In *OECD Seminar on Future Road Transport Systems and Infrastructures in Urban Areas*, pages 289–302, Chiba, 1991.

M. Joborn, T.G. Crainic, M. Gendreau, K. Holmberg, and J.T. Lundgren. Economies of Scale in Empty Freight Car Distribution in Scheduled Railways. *Transportation Science*, 38(2):459–464, 2004.

U. Kohler. How to Change Urban Traffic with City Logistics. In Schnieder, E. and Becker, U., editors, *Control in Transportation Systems 2000 - Proceedings 9th IFAC Symposium, Braunschweig, Germany*, volume 1, pages 199–201. Pergamon, Oxford, 2001.

U. Kohler. An Innovating Concept for City-Logistics. In *Proceedings 4th World Congress on Intelligent Transportat Systems*, Berlin (CD ROM), 1997.

G. Laporte and F. Semet. Classical Heuristics for the Vehicle Routing Problem. In Toth, P. and Vigo, D., editors, *The Vehicle Routing Problem*, SIAM Monographs on Discrete Mathematics and Applications, pages 109–128. SIAM, Philadelphia, PA, 2002.

A. Le Bouthillier, T. Crainic, and P. Kropf. A Guided Cooperative Search for the Vehicle Routing Problem with Time Windows. *IEEE Intelligent Systems*, 20(4):36–42, 2005.

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

M. Mahut, M. Florian, P. Tremblay, Campbell, M., Patman, D., and McDaniel, Z.K. Calibration and Application of a Simulation Based Dynamic Traffic Assignment Model. *Transportation Research Record*, 1876:101–111, 2004.

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

A.G. Morris, A.K. Kornhauser, and M.J. Kay. Getting the Goods Delivered in Dense Urban Areas: A Snapshot of the Last Link of the Supply Chain. *Transportation Research Record*, 1653:34–41, 1999.

OECD. Delivering the Goods: 21st Century Challenges to Urban Goods Transport. Technical report, Organisation for Economic Co-operation and Development, OECD Publishing, http://www.oecdbookshop.org, 2003.

R. Ooishi and E. Taniguchi. Effects and Profitability of Constructing the New Underground Freight Transport System. In Taniguchi, E. and Thompson, R.G., editors, *City Logistics I, 1st International Conference on City Logistics*, pages 303–316. Institute of Systems Science Research, Kyoto, 1999.

D. Patier. *La logistique dans la ville*. CELSE Editeur, Paris, France, 2002.

D. Patier-Marque. Diagnostique sur les enquêtes françaises : tentative de globalisation. In D. Patier-Marque, editor, *L'intégration des marchandises dans le système des déplacements urbains - Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000*, volume 15 of *Études et recherches*, pages 125–144. Laboratoire d'Économie des Transports, Lyon, France, 2001.

M.B. Pedersen, T.G. Crainic, and O.B.G. Madsen. Models and Tabu Search Metaheuristics for Service Network Design with Asset-Balance Requirements. *Transportation Science*, 2008. online at Articles in Advance DOI: 10.1287/trsc.1080.0234.

H. Pirkul and V. Jayaraman. Production, Transportation, and Distribution Planning in a Multi-Commodity Tri-Echelon System. *Transportation Science*, 30(4):291–302, 1996.

H.D. Ratliff, J.V. Vate, and M. Zhang. Network Design for Load-Driven Cross-Docking Systems. Georgia Tech TLI Report, The Logistics Institute, Georgia Tech., 1999.

A. Ricci and P. Fagiani. Régulation du Transport de Marchandises en Ville: concertation ou répression? L'expérience italienne. In D. Patier-Marque, editor, *L'intégration des marchandises dans le système des déplacements urbains - Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000*, volume 15 of *Études et recherches*, pages 199–208. Laboratoire d'Économie des Transports, Lyon, France, 2001.

W. Ruske. City Logistics - Solutions for Urban Commercial Transport by Cooperative Operations Management. In *OECD Seminar on Advanced Road Transport Technologies*, Omiya, Japan, 1994.

F. Russo and A. Comi. A state of the art on urban freight distribution at European scale. presented at ECOMM 2004, Lion, France, available from The European Conference on Mobility Management, //http:www.epomm.org/, 2004.

K.R. Smilowitz, A. Atamtürk, and C.F. Daganzo. Deferred Item and Vehicle Routing within Integrated Networks. *Transportation Research Part E: Logistics and Transportation*, 39:305–323, 2003.

STA. Studio per la mobilità delle merci nell'area centrale di Roma. Technical report, S.T.A. - Società Trasporti Automobilistici, Roma, Italia, 2000.

E. Taniguchi and R.G. Thompson. Modeling City Logistics. *Transportation Research Record*, 1790:45–51, 2002.

E. Taniguchi and R.E.C.M. van der Heijden. An Evaluation Methodology for City Logistics. *Transport Reviews*, 20(1):65–90, 2000.

E. Taniguchi, T. Noritake, T. Yamada, and T. Izumitani. Optimal Size and Location Planning of Public Logistics Terminals. *Transportation Research E*, 35(3):207–222, 1999.

E. Taniguchi, S. Kawakatsu, and H. Tsuji. New Co-Operative System Using Electric Vans for Urban Freight Transport. In Sucharov, L.J. and Brebbia, C.A., editors, *Urban Transport and the Environment for the 21st Century VI*, pages 201–210. WIT Press, Southampton, 2000.

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

E. Taniguchi, T. Yamada, and M. Tamaishi. Dynamic Vehicle Routing and Scheduling with Real Time Informations. In Taniguchi, E. and Thompson, R.G., editors, *City Logistics II, Second International Conference on City Logistics*, pages 111–125. Institute of Systems Science Research, Kyoto, 2001b.

R.G. Thompson. Intelligent Vehicle Routing and Scheduling. In Taniguchi, E. and Thompson, R.G., editors, *Logistics Systems for Sustainable Cities*, pages 97–109. Elsevier, Amsterdam, 2004.

R.G. Thompson and E. Taniguchi. City Logistics and Transportation. In *Handbook of Logistics and Supply-Chain Management*, pages 393–405. Elsevier, Amsterdam, 2001.

P. Toth and D. Vigo, editors. *The Vehicle Routing Problem.* SIAM Monographs on Discrete Mathematics and Applications. SIAM, Philadelphia, PA, 2002.

Transports de Marchandises en Ville. Ministre̊ de l'écologie, du développement et de l'aménagement durables, France, http://www.transports-marchandises-en-ville.org.

Trendsetter. Setting Trends for Sustainable Urban Mobility. European Union project, http://www.trendsetter-europe.org.org.

J.H.R. van Duin. Evaluation and Evolution of the City Distribution Concept. In *Urban Transport and the Environment for the 21st Century III*, pages 327–337. WIT Press, Southampton, 1997.

J.H.R. van Duin. Simulation of Underground Freight Transport Systems. In *Urban Transport and the Environment for the 21st Century IV*, pages 149–158. WIT Press, Southampton, 1998.

J. Verrijdt and A. de Kok. Distribution Planning for a Divergent N-Echelon Network without Intermediate Stocks under Service Restrictions. *International Journal of Production Economics*, 38:225–243, 1995.

J. Visser, A. van Binsbergen, and T. Nemoto. Urban Freight Transport Policy and Planning. In Taniguchi, E. and Thompson, R.G., editors, *City Logistics I, 1st International Conference on City Logistics*, pages 39–69. Institute of Systems Science Research, Kyoto, 1999.

M. Wen, J. Larsen, J.-F. Cordeau, and G. Laporte. Vehicle Routing with Cross-Docking. *Journal of the Operational Research Society*, 2008. on line at Articles in Advance DOI:10.1057/jors.2008.108.

Annex - Summary of Notation

Table 1 summarizes the notation relevant for all formulations in the paper, while Table 2 focuses on the notation of the main model of Section 3.

$\mathcal{E} = \{e\}$	Set of external zones
$\mathcal{P} = \{p\}$	Set of products
$\mathcal{C} = \{c\}$	Set of customers
$\mathcal{D} = \{d\}$	Set of customer-demands: Volume $vol(d)$ of product $p(d)$ available starting in period $t(d)$ at the external zone $e(d)$, to be delivered to customer $c(d)$ during the time interval $[a(d), b(d)]$; $\delta(d)$: service time at the customer;
$\mathcal{T} = \{\tau\}$	Set of urban-vehicle types
u_τ	Capacity of urban-vehicle type τ
n_τ	Number of urban vehicles of type τ
$\mathcal{T}(p)$	Set of urban-vehicle types that may be used to transport product p
$\mathcal{V} = \{\nu\}$	Set of city-freighter types
u_ν	Capacity of city-freighter type ν
n_ν	Number of city freighters of type ν
$\mathcal{V}(p)$	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 vehicles it may accommodate simultaneously
λ_s	Capacity of satellite s in terms of number of city freighters it may accommodate simultaneously
$\mathcal{G} = \{g\}$	Set of city-freighter depots
$\delta(\tau)$	Time required to unload an urban vehicle of type τ at any satellite
$\delta(\nu)$	Loading time (continuous operation) at any satellite for a city freighter of type ν
$\delta_{ij}(t)$	Travel time between two points i, j in the city, where each point may be a customer, an external zone, a satellite, or a depot; Travel is initiated in period t and duration is adjusted for the corresponding congestion conditions

Table 1: General Notation

$\mathcal{R} = \{r\}$	Set of urban vehicle services
$\tau(r)$	vehicle type of r
$e(r)$	external zone of r
$\sigma(r) \subset \mathcal{S}$	ordered set of visited satellites for r
$\bar{e}(r)$	terminal external zone for r
$t(r)$	departure period for r
$t_i(r)$	period service r visits satellite s_i
$\mathcal{W} = \{w\}$	Set of feasible work segments for city freighters
$\nu(w)$	vehicle type of w
$\sigma(w) \subset \mathcal{S}$	ordered set of visited satellites for w
$k(w)$	cost to operate w
$t(w)$	starting period of w
$t_l(w)$	period work segment w arrives at satellite s_l
$\delta(w)$	duration of w
$\mathcal{L}(w) = \{l\}$	Set of legs of w
$\mathcal{C}_l(w)$	set of customers of leg l of w
$\delta_l(w)$	duration of l
$k_l(w)$	cost of operating l of w
$\mathcal{H}(\nu) = \{h\}$	Set of city-freighter work assignments
$\mathcal{M}(d) = \{m\}$	Set of itineraries for customer-demand d
$t_s^{\text{in}}(m)$	arrival period at satellite $s(m)$ of service $r(m)$ of m
$h(m)$	work assignment of m
$w(h(m))$	work segment of work assignment $h(m)$ of m
$l(w(h(m)))$	leg of $w(h(m))$ of $h(m)$ of m
$t_s^{\text{out}}(m)$	departure period from satellite $s(m)$ of $h(m)$ of m
$t_c(m)$	arrival time of m at $c(d)$

Table 2: Notation for the General Model (Section 3)