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Teodor Gabriel Crainic
Nicoletta Ricciardi
Giovanni Storchi

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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

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Models for Evaluating and Planning City Logistics Transportation 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 facility 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.

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

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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-third 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-km travelled within the cities (Figliozzi 2007); the same measure for the three largers French cities varies from 13% to 20% (Patier 2002). Figures are equally telling regarding emissions. An OECD report (2003) assigns, for example, 43% of sulphur oxides (SOx) and 61% of particulate matter (PM) emissions in London, UK, to freight transportation, while for nitrogen oxides (NO) emissions, the figures are 28% for London, 50% for Prague, and 77% for Tokyo. These nuisances impact the life of all 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. Moreover, the amplitude of freight traffic also contributes to the belief that "cities are not safe" that pushes numerous citizens to move out of the city limits. And the problem is not going to disappear any time soon. In fact, the 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 world-wide urbanization trend is emptying the countryside and small towns and making large cities even larger. Within the countries members of OECD, the urban population was 50% of the total population in 1950, was 77% in 2000, and should reach the 85% mark by 2020 (OECD 2003). It is estimated that 2007 has seen the world-wide urban population being larger than the rural population.

The public, industry, and officials at all levels of government are increasingly challenged by these issues. Not all countries and regions are at the same level of analysis and action. Up to now, most documents and projects are to be found in Europe and Japan. The movements is spreading out, however, and gaining strength as witnessed, in particular, by the conferences organized in North America in recent years addressing these issues. The general consensus is that one needs to analyze, understand, and control freight transportation within urban areas. The goal is to reduce the impact of freight transportation on the city living conditions, reduce congestion and pollution, increase mobility, improve living conditions, and, in general, contribute to reach the Kyoto targets for emission reductions (the spirit of the accord, at least), while not penalizing the city center activities. More precisely, one aims to reduce and control the number and dimensions of freight vehicles operating within the city limits, improve the efficiency of freight movements, and reduce the number of empty vehicle-km. This has resulted in several initiatives, proposals, and projects (see, e.g., the websites of the projects Trensetter, CITY PORTS, Bestufs, CIVITAS, and Transports de Marchandises en Ville and the proceeding books of the City Logistics conferences available through the Institute of City Logistics).

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

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

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

We focus on one of the most challenging issues in planning City Logistics systems, the integrated short-term scheduling of operations and management of resources. We present the developments for the general case of two-tier City Logistics systems, where satellite platforms are used to transship loads from vehicles arriving from the CDCs to smaller, center-city-friendly vehicles. The problem addresses 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 and the formulations proposed. This yields what appears to be a new problem class, which we denote the *two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* problem (*2SS-MDMT-VRPTW*).

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. On the one hand, the actual planning of resource utilization and operations for the next activity period (the next "day"). On the other hand, 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 three-fold. It identifies and analyzes a set of emerging issues that are both methodologically challenging and timely. It proposes a general approach to what appears to be a new problem and formulations for its main components. It analyzes these models both with respect to possible utilization modes and in relations to other major problem classes encountered in service network design and vehicle routing settings. Based on these analyzes, the paper also identifies promising algorithmic avenues.

The paper is organized as follows. Section 1 briefly presents the City Logistics concepts, challenges, and needs in terms of models and methods for the evaluation of proposed systems and the planning of activities. The description and associated literature review focus on single and two-tier systems based on City Distribution Centers. Section 2 introduces the core planning problem addressed in this paper, the *day-before* problem, and defines the general notation used throughout the paper. The general methodology we propose is presented in Sections 3 and 4, which introduce and analyze the main formulation and variants and propose solution approaches, respectively. To emphasize the generality of our work, we also adapt our models to the case of single-tier City Logistics systems (Section 3.3). Sections 5 and 6 address the two major components of this methodology, the design of the service network to the satellite platforms and the management of the fleet of city vehicles providing service from satellites to customers, 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, and challenges of City Logistics, together with a brief history of previous studies and projects. We then focus on two-tier City Logistics and describe the main ideas, system components, and functioning principles. The section concludes with an overview of the principal sets of planning issues associated to these systems.

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 vehicle and coordination of freight transportation activities within the city. As a review of existing literature reveals, however, the "optimization" component of the City Logistics concept is not very developed yet. This paper aims to contributes to fill this gap.

1.1 General concepts

Historically, one finds a brief period of intense activity at the beginning of the 70's dedicated to urban freight transportation issues. This period yielded traffic regulation to avoid the presence of heavy vehicles in cities in order to limit the impact of freight transport on automobile movements. Very little activity took place from 1975 to the end of 80's. 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 continue to operate.

Data-collection activities confirmed that freight transportation within urban areas generates large numbers of movements of freight vehicles of various dimensions (e.g., Dufour 2001, Dietrich 2001, Patier-Marque 2001, Morris, Kornhauser, and Kay 1999, STA 2000, Ambrosini and Routier 2004). The average vehicle load is generally low and many vehicles travel empty. Moreover, traffic and parking regulations do not seem to be able to cope with the problem (e.g., Morris, Kornhauser, and Kay 1999, Ricci and Fagiani 2001). Better fleet management practices could partially address this problem. But only partially, since it would concern individual carriers or shipper-customer combinations only.

The fundamental idea of City Logistics is that the number of vehicles traveling in urban areas could be reduced through a more efficient utilization of vehicles: higher average load factors and fewer empty trips. The construction of automated underground systems dedicated to freight transportation has been proposed, but the huge investments required make this concept unrealistic in most cases (e.g., van Duin 1998 and 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. 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 this rationalization of distribution activities. The utilization of so-called green vehicles and the integration of public-transport infrastructures (e.g., light rail or 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). Long-haul transportation vehicles of various modes dock at a CDC to unload their cargo. Loads are then sorted and consolidated into smaller vehicles that deliver them to their final destinations. Of course, a City Logistics system would address the reverse movements, from origins within the city to destinations outside. To simplify the presentation, however, we focus on the in-bound, distribution activities only. This is the general approach of most City Logistic work and derives from the imbalance between entering and exiting flows that characterize most cities.

A city distribution center is thus a facility where shipments are consolidated prior to distribution. It is noteworthy that the CDC concept as physical facility is close to that of intermodal logistic platforms (and freight villages) that link the city to the region, country, and the world. Intermodal platforms receive large trucks and smaller vehicles dedicated to local distribution, and offer storage, sorting, and consolidation (de-consolidation) facilities, as well as a number of related services such as accounting, legal counsel, brokerage, and so on. Intermodal platforms may be stand-alone facilities situated close to the access or ring highways, or they may be part of air, rail or navigation terminals. The city distribution center may then be viewed as an intermodal platform with enhanced functionality to provide coordinated and efficient freight movements within the urban zone. CDCs are thus an important step toward a better City Logistics organization and they are instrumental in most proposals and projects so far(e.g., Browne *et al.* 2006, van Duin 1997, Janssen and Oldenburger 1991, Kohler 1997, 2001, Ruske 1994, Taniguchi *et al.* 2001, Thompson and Taniguchi, 2001).

Most City Logitics projects were undertaken in Europe and Japan and involved only one CDC facility and a limited number of shippers and carriers. Different business models and strategies have been tested (other than the web sites indicated in the Introduction, see, e.g., Browne *et al.* 2006, Kohler 2001, Taniguchi, Kawakatsu, and Tsuji 2000, Taniguchi *et al.* 2001, Thompson and Taniguchi 2001, Visser, v. Binsbergen, and

Nemoto 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 are no, or very few, privileges granted to participating enterprises (in terms of access and parking regulations, for example) and the project being a private initiative is supposed to become profitable over a short period. These characteristics explain why most such projects did not continue once the financing secured through the EU projects was over The policy introduced by the Dutch ministry of transportation and public works is based on strict licensing practices that impose restrictions on vehicle loads and the total number of vehicles entering the city on any given day (as well as promote the use of electric vehicles). This policy has resulted in carriers initiating collaboration activities to consolidate shipments and reduce the number of trips. There is a significant involvement of local and central government in these projects (e.g., traffic regulations were modified to permit longer delivery hours), which may explain the success and continuation of these projects within the Netherlands. A third major approach was first introduced in Monaco where urban freight delivery is considered a public service. Large trucks are banned from the city and deliver to a CDC, a single 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 license-based systems have not gained much acceptance outside the Netherlands. The private City Logistics projects have yielded mixed results. 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 practices by authorities and short-term profitability requirements. The 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 still going strong, however, and the new generation of projects combine elements from the three previous approaches. The city distribution center is still at the core of the system, but the private-public partnerships are stronger. Moreover, most projects for small and medium-sized cities integrate the idea to designate a single operator for the operations within the city. One also observes that Intelligent Transportation Systems technologies start to be integrated. 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 exception of a few contribution to real-time vehicle routing models and methods (e.g., Taniguchi, Yamada, and Tamaishi 2001 and Thompson 2004)

Most City Logistics projects address single-tier CDC-based systems, i.e., systems where delivery circuits are performed directly from a single CDC. When more than one CDC is involved, the city is usually partitioned and each CDC serves a given partition. Such approaches have not been successful for large cities, however, in particular when the large areas, usually identified as the city center, display high levels of population density as well as commercial, administrative, and cultural activities. Another characteristic of large cities that plays against single-tier systems one may mention is the rather lengthy distance a vehicle must travel from the CDC on the outskirts of the city until the city center where the delivery tour begins. Two-tier systems have been recently proposed for such cities (Crainic, Ricciardi, and Storchi 2004, Gragnani, Valenti, and Valentini 2004). Few studies dedicated to two-tier systems may be found and, to the authors knowledge, no models not procedures have been proposed for their evaluation and planning. The present paper is a contribution to this field. The following subsections describe the general two-tier City Logistics system structure and the main planning issues, respectively.

1.2 Two-Tier City Logistics System

Two questions are particularly relevant when addressing distribution rationalization policies and the associated goal of enhancing the quality of life in cities through reduced vehicular traffic and negative environmental impacts: 1) where and how to perform the consolidation and coordination activities and 2) what vehicles should perform the transportation activities. Other than the usual requirement that vehicles be environmentally friendly (e.g., with respect to the type of engine), the latter issue refers to the dimensions of the vehicles and the trade-off between capacity, the ability to travel narrow streets characteristic of many city centers, and the number of vehicles traveling long distances from CDCs to the city center. relative to the first issue, consolidation does take place at the CDCs. These facilities are few, however, even for major cities and are usually located rather far from the city center. Then, for example, consolidating into one vehicle "all" traffic originating at various locations around the city and bound for a certain street in the city center would require all the traffic to be first brought to a given platform, generating significant levels of extra heavy-truck traffic. Moreover, not all freight destined or originating in a city passes through a CDC.

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

Two types of vehicles are involved in a two-tier City Logistics system, urban-trucks and city-freighters, and both are supposed to be environmentally firendly. *Urban-trucks* move freight to satellites, possibly by using corridors (sets of streets) specially selected to facilitate access to satellites and reduce the impact on traffic and the environment.

Moreover, since the goal is to minimize the truck movements within the city, rules may be imposed to have them travel as much as possible around the city, on the "ring highway"'s surrounding the city, and enter the city center as close to destination as possible. Urban-trucks may visit more than one satellite during a trip. Their routes and departures have to be optimized and coordinated with satellite and city-freighter access and availability.

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

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

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

From an information and decision point of view, it all starts with the demand for loads to be distributed within the urban zone. The corresponding freight will be consolidated at external zones yielding the actual demand for the urban-truck transportation and the satellite transdock transfer activities. These, in turn, generate the input to the city-freighter circulation which provides the last leg of the distribution chain as well as the timely availability of empty city-freighters at satellites. The objective is to have urban-trucks and city-freighters on the city streets and at satellites on a "needs-to-be-there" basis only, while providing timely delivery of loads to customers and economically and environmentally efficient operations. The following subsection examines a number of planning issues and modeling challenges associated to the design, evaluation, and planning of two-tier City Logistics Systems.

1.3 Planning Issues

Similarly to any complex transportation system, City Logistics transportation systems require planning at strategic, tactic, and operational levels. Moreover, because in most cases, City Logistics systems have to be imagined and built up “from scratch”, proposal evaluation models and procedures need to be developed as well.

In *planning mode*, challenging strategic issues concern the location, layout, and operation of the distribution centers and satellites, as well as of the entire City Logistics network, e.g., the selection of access corridors and the street networks open to each vehicle type and the determination of the vehicle fleets composition and size. Taniguchi *et al.* (1999) and Crainic, Ricciardi, and Storchi (2004) present methodology to address some of these issues. 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. While 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, Yamada, and Tamaishi 2001 and Thompson 2004).

City Logistics transportation system rely significantly 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 a City Logistics context, but for a shorter planning horizon due to the day-to-day demand variability. For two-tier systems, tactical planning concerns the departure times, routes, and loads of urban-trucks and city-freighters, the routing of demand, and the utilization of the satellites and the distribution of work among those. According to the best knowledge of the authors, there are no published contributions targeting these issues.

Tactical planning models assist the deployment of resources and the planning of operations and guide the real-time operations 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. Indeed, the conception and evaluation of the City Logistics proposals is an essential but complex process, for which very few formal models have been proposed (Taniguchi and van der Heijden 2000, Taniguchi et al. 2001, and Taniguchi and Thompson 2002). On the one hand, one needs to focus on the organizational and managerial framework of such systems. The involvement of all stakeholders, including final customers as well as the local and central governments, must be clarified and business models must be defined. On the other hand, one must evaluate whether the proposed system will "work", that is, one must evaluate the behavior and performance of the proposed system and operating policies under a broad range of scenarios. Simulation appears as the methodology of choice for such evaluations. City Logistics simulators require, however, methods to represent how vehicles and flows would circulate through the city and how the proposed infrastructures services would be used. In *evaluation mode*, tactical models and methods provide this capability.

Very few contributions target these issues and, at our best knowledge, all address single-tier systems of rather limited dimensions (e.g., Barceló, Grzybowska, and Pardo and Boerkamps and Binsbergen 1999). None addresses the more complex two-tier City Logistics systems that require not only models for the operations of vehicles at each tier, but also the explicit consideration of the synchronization and coordination of the fleets and terminal operations. Our work addresses this issue and focuses on the tactical planning process that we identify as the *day-before* problem. In the next sections, we define the day-before planning problem for two-tier City Logistics systems and introduce models to address it in both planning and evaluation modes.

2 Problem Description and General Notation

This section is dedicated to the presentation of the problem addressed by the models discussed in the remaining sections of this paper. We also introduce hypotheses, definitions, and notation that apply to all cases and formulations.

2.1 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. This corresponds to the classical objective of tactical planning: plan the allocation and utilization of the resources of the system for best performance in terms of customer satisfaction and system costs (and profits). For freight transportation systems with consolidation, this translates into a transportation plan indicating the routes and schedules of the transportation services (and, thus, vehicles), the itineraries used to transport the freight, the terminal workloads, and the general policies regulating the empty vehicle movements. The plan then determines regular operations for a period varying from a few weeks to a few month, according to the particular type of freight carrier (for a more comprehensive discussion of these issues see, e.g., Crainic 2000 or Crainic and Kim 2007).

Satellites, city-freighters, and urban-trucks are the resources of the system addressed in this paper. The length of time targeted by tactical planning is much shorter, however, than for other consolidation-based freight transportation systems. Indeed, while a number of requests for transportation may appear on a regular basis, most will not. Recall that distribution already performed by well-loaded vehicles (e.g., soft drinks or supplying large retail stores) is supposed to be regulated by but not use the "public" vehicles of the City Logistics system. 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-truck, through which satellite, and on what type of city-freighter. One must also determine when to dispatch each urban-truck, the loads carried and the satellites serviced. Finally, one must determine the circulation of the city-freighter fleet, which corresponds to planning the routing and scheduling of city-freighters during the contemplated period. The output of the process determines the fleet and personnel deployment for the *next-day* period of activities and provides users the schedules of freight delivery. 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 and stakeholders.

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

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

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

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

4. Intelligent Transportation System 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 and Gendreau 2007).

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 use 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 not necessarily be the case. Thus, for example, following some intensive period of simulation the system operation, once could design and implement a more regular urban-truck service. Then, most urban-truck 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. Before proceeding with the presentation and discussion of these models and algorithmic development directions, we introduce the notation used in this paper. The particular notation of each model is presented in the corresponding section.

2.2 Global Definitions and Notation

Table 1 summarizes the notation that is relevant for all the models presented in this paper.

Let $\mathcal{E} = \{e\}$ be the set of external zones where freight is sorted and consolidated into urban-trucks. 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 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 at) the customer is denoted $\delta(d)$.

Fleets of heterogeneous urban-trucks and city-freighters provide transportation services. Let $\mathcal{T} = \{\tau\}$ and $\mathcal{V} = \{\nu\}$ represent the sets of urban-truck and city-freighter types, respectively. The fleet sizes are given by $n_\tau,\ 1, \ldots, |\nu|$, and $n_\nu,\ 1, \ldots, |n_\nu|$, for each type of urban-truck and city-freighter, respectively. This information is particularly useful when actual planning activities are carried on. When the day-before models are used to evaluate a proposed City Logistics system, fleet dimension restrictions may be relaxed. Indeed, in such situations fleets may not have been dimensioned yet and the models will yield information on the numbers of vehicles of various types required by operate. Each vehicle has a specific capacity, u_τ for an urban-truck of type τ, and u_ν for a city-freighter type ν.

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

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

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

Travel times are also assumed to be based on historical or simulation data (or both) which reflect the circulation rules proper to each particular application. It is clear, however, that travel times are intimately linked to congestion conditions and, thus, vary with time and the particular city zone where one travels (e.g., congestion propagates from the exterior toward the center of the city during morning rush hour). Moreover, according to the particular time of the day, the path between two points in the city might be different, due either to traffic regulation or to a policy aiming to avoid heavily congested areas. The $\delta_{ij}(t)$ travel times are thus defined given the routing rules and estimated congestion conditions at departure time t. They are not necessarily symmetric and the triangle inequality conditions cannot be assumed.

We conclude this section by examining how to define the period length. Planning is performed for $t = 1, \ldots, T$ periods. The planning horizon is relatively small, a few hours

$\mathcal{E} = \{e\}$	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-truck types
u_τ	Capacity of urban-truck type τ
n_τ	Number of urban-trucks of type τ
$\mathcal{T}(p)$	Set of urban-truck 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-trucks it may accommodate simultaneously
λ_s	Capacity of satellite s in terms of number of city-freighters it may accommodate simultaneously
$\delta(\tau)$	Time required to unload an urban-truck 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

to a half day in most cases. Consequently, each period should be relatively small, of the order of the quarter or half hour, for example. The precise definition of the planning horizon is application-specific, but a number of considerations may impact the modeling of the time discretization. In this paper, we consider two.

A first consideration is to select a sufficiently short period length such that all urban-trucks that leave an external zone during the same period provide different services (i.e., in terms of satellites serviced, type of vehicle, etc.). This simplifies the problem of determining urban-truck services by avoiding the need to define for the formulations of Sections 3 and 5 frequency-design variables that may take non-negative integer values. The second consideration comes from the need to account for urban-trucks and city-freighters that may take more than one period to unload and load at a satellite, respectively, and thus, have to be counted against the satellite capacity in several periods. Consequently, the *period length* is defined as the time required to unload (and transfer) the contents of the smallest urban-truck. To simplify the presentation of the formulations, we assume that all urban-truck types are so configured that the corresponding unloading time is an integer multiple of the period length and that there is still at most one departure of each urban-truck service at each period and external zone.

3 A General Modeling Framework

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

In a two-tier City Logistics system, demand is served by the integrated activities of two transportation systems operating urban-trucks and city-freighters, respectively. The two systems connect and synchronize operations at transfer points: the satellites. Freight is thus moved from origin points (external zones) to final destinations (customers) via itineraries that may be defined as a succession of a "direct" urban-truck route from an external zone to a satellite, a transshipment operation at the satellite, and a delivery route (tour) performed by a city-freighter. The day-before planning problem thus encompasses two main components. The first concerns the departure time of each urban-truck service and the satellites it visits, that is, the schedules and routes of the urban-truck fleet. The second addresses the issues of routing and scheduling city-freighters to provide the timely delivery of goods to customers and the adequate supply of vehicles at satellites. The two problems are linked by decisions regarding how each demand is to be routed from an external zone, through a satellite, to the customer.

This section is dedicated to the presentation of a general modeling framework for the day-before planning problem. The framework integrates the entire set of decision issues identified above and is introduced in the first subsection. We examine a number of variants of this formulation 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 in the context of the single-tier City Logistics systems.

3.1 The Model

We first present the notation for the urban-truck and city-freighter transportation systems, followed by the demand-itinerary notation and the model formulation.

Consider the set of urban-truck *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 $i < j\}$. Together with the access and egress corridors, $\sigma(r)$ defines a route through the city.

Let $t(r)$ be the departure time of the service from its origin $e(r)$. The urban-truck 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 $t_{|\sigma(r)|+1}$. The cost associated to offering and 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-truck in the city at the particular time of the service.

Consider now the city-freighter transportation sub-system, which provides the distribution of freight from satellites to customers. City-freighter operations are more constrained that those of the urban-truck transportation subsystem, the main difference being that urban-trucks may wait at loading sites, whereas city-freighters cannot. Indeed, once the visit to the last satellite on their route is completed, urban-trucks proceed to the next terminal (external zone) where freight is to be loaded and they may wait there until departure time. Once a city-freighter serves a group of customers out of a satellite, however, it proceeds to another satellite only if on arrival it is scheduled to load freight from incoming urban-trucks. It cannot wait at the satellite. Consequently, when waiting is required between service routes out of two consecutive satellites, it has to occur at a specially-designated place, either the actual depot of the vehicle or any other suitable space (e.g., a parking lot; emergency vehicles are operating out of such designated parking spaces, for example). To simplify the presentation, we denote all such spaces as *depots* and represent them through set $\mathcal{G} = \{g\}$.

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, however.) 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 l on its route, the city-freighter takes loads to deliver to a set of customers identified by the set $\mathcal{C}_l(w)$. We identify the component of the work segment that starts at satellite l, serves the customers in $\mathcal{C}_l(w)$, and then proceeds to satellite $l + 1$ (or a depot $g(w)$ when satellite l is last in $\sigma(w)$) as the route *leg* l. The set $\mathcal{L}(w)$ contains all route legs l of the work segment w sorted in the same order as $\sigma(w)$.

Figure 1 illustrates a two-leg work segment, where $s_1 = s$, and $s_2 = s'$, $s_1,\ s_2, \in \sigma(w)$, while $\mathcal{C}_1(w) = \{i, k, j, \ldots, f\}$ and $\mathcal{C}_2(w) = \{i', f', j', \ldots, k'\}$. The dashed lines stand for undisplayed customers, while the dotted lines indicate the empty arrival from a depot (not included in segment), the empty movement from the last customer-demand 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 time 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 $\delta(w)$.

Given a city-freighter type ν, a sequence of work segments $\sigma(h) = \{w_i \in \mathcal{W}(\nu),\ i = 1, \ldots, |\sigma(h)|\}$ makes up a complete city-freighter *work assignment* $h \in \mathcal{H}(\nu)$ ($\mathcal{H} = \bigcup_\nu \mathcal{H}(\nu)$). Work assignment h is feasible only if the time between two consecutive work segments is sufficiently long to accommodate the respective movements into and out of the corresponding depots. The set of all legs making up a work assignment is denoted

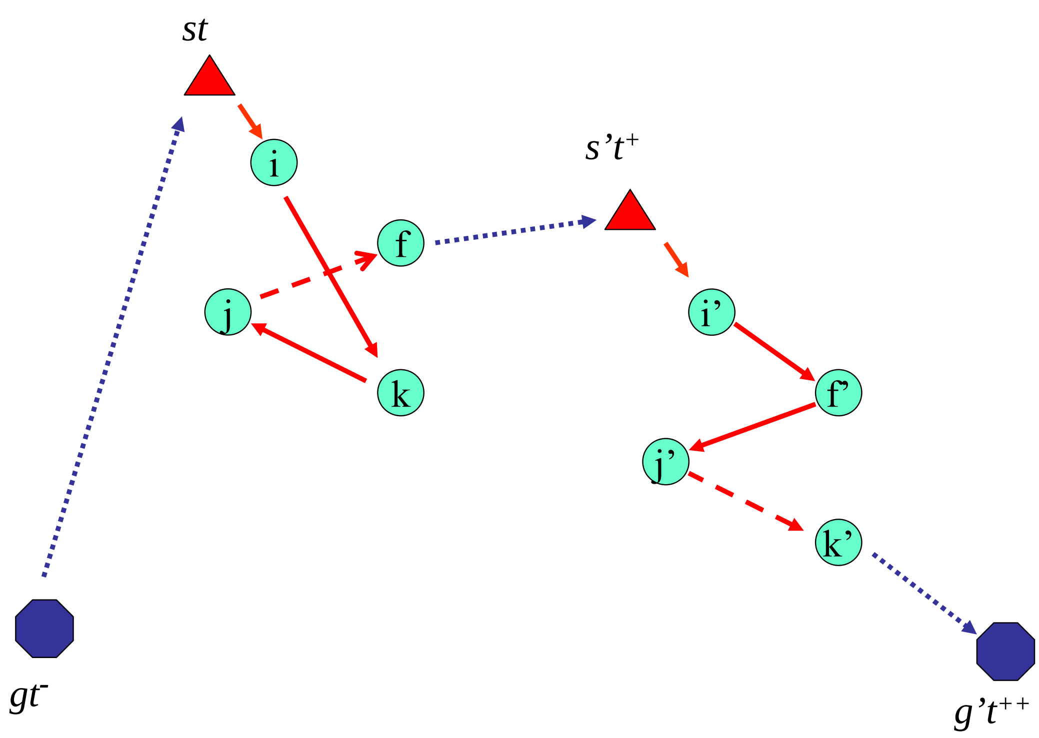

Figure 1: A City-Freighter Work Segment Illustration

$\mathcal{C}_l(h) = \bigcup_{w \in \sigma(h)} \mathcal{C}_l(w)$.

The cost of operating a city-freighter work segment $w \in \mathcal{W}(\nu)$ is denoted $k(w)$ and equals the sum of the corresponding costs of its legs, $k(w) = \sum_{l \in \mathcal{L}(w)} k_l(w)$. Similarly, the cost of a city-freighter work assignment is denoted $k(h)$ and equals the sum of the corresponding costs of its work segments. 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.

Let $\mathcal{M}(d) = \{m\}$ stand for the set of *itineraries* that may be used to satisfy customer-demand $d \in \mathcal{D}$. An itinerary $m \in \mathcal{M}(d)$ specifies how freight is to be transported:

- From its external zone $e(d) \in \mathcal{E}$;
- Using an urban-truck service $r(m) \in \mathcal{R}$, of type $\tau(r(m)) \in \mathcal{T}(p(d))$ appropriate for its product $p(d) \in \mathcal{P}$, which leaves later than the availability time of the demand, i.e., $t(d) < t(r)$;
- To a satellite (in most cases) $s(m) \in \sigma(r(m))$, where it is transferred to
- A city-freighter of type $\nu \in \mathcal{V}(p(d))$, appropriate for the demand product $p(d) \in \mathcal{P}$, which is operating leg $l(h(m))$ of the work assignment $h(m) \in \mathcal{H}(\nu)$, on its work segment $w(h(m))$, and
- Which delivers it to the final customer $c(d)$, within its time window $[a(d), b(d)]$.

The schedule of itinerary $m \in \mathcal{M}(d)$ is then specified by

- $t_e(m) = t(r(m))$, the departure time from the external zone of demand d on urban-truck service $r(m)$;
- $t_s^{\text{in}}(m) = t_{s(m)}(r(m))$, the arrival time at satellite $s(m)$ by service $r(m)$;
- $t_s^{\text{out}}(m) = t_{l(w(h(m)))}(w(h(m))) + \delta(\nu)$, the departure time from satellite $s(m)$ by a city-freighter operating leg $l(w(h(m)))$ of segment $w(h(m))$ of work assignment $h(m) \in \mathcal{H}(\nu)$, and
- $t_c(m) \in [a(d), b(d)]$, the arrival time at the final customer $c(d)$; The precise value of $t_c(m)$ depends upon the sequence of customers in $\mathcal{C}_{l(w(h(m)))}(w(h(m)))$.

When customers are "close" to an external zone, they may be served directly from this "adjacent" external zone. The service of such customers is then similar to the case of single-tier City Logistics systems and itineraries do not include an urban-truck component (see Section 3.3). One still has to select how (the itinerary) and when (vehicle departure time) each customer is served, however. Then, in order 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 corresponding to the selection of urban-truck services, city-freighter work assignments, and demand itineraries, respectively:

$\rho(r) =$ 1, if the urban-truck 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 model 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-trucks, in particular, while satisfying demand requirements (demand cannot be split between itineraries):

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

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

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

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

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

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

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

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

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

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

The objective function (1) computes the total cost of operating the system as the sum of the costs of the selected urban-truck services and city-freighter work assignments. Relations (2) enforce the urban-truck 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 time 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-truck services that stop at satellite s at time 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 time t. Then, constraints (5) and (6) enforce the satellite capacity restrictions in terms of urban-trucks and city-freighters, respectively, where the number of vehicles using a satellite at any given time t equals those that arrive at time 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-trucks 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 availability and operations of the fleets of urban-trucks and city-freighters. As described in the first sections of the paper, it is assumed that, within the urban zone of interest, the fleet of city-freighters is centrally managed for best operational and environmental performance. Moreover, for the planning period considered, the city-freighter fleet is confined to the urban zone under City Logistics control (the so-called *controlled zone*). This hypothesis has led to the explicit description of work assignments for city-freighters and consideration of the corresponding fleet capacity restrictions.

No such hypotheses are made regarding the urban-truck fleets to reflect the higher variability in ownership and operations of these vehicles. In particular, urban-trucks are not confined to the controlled zone and are not necessarily centrally managed. Indeed, as already mentioned, some may come from distant origin points, the system deciding "only" on their entry time and point into the city and the satellites where the freight is to be delivered to the city-freighter system. Consequently, urban-trucks are not "followed" once all their freight has been delivered to satellites and no fleet capacities are included in the formulation.

When this hypothesis is not true and urban-truck fleets are controlled, a path-based modeling approach similar to that of the city-freighter fleets may be used. To simplify the presentation, we consider that the entire fleet is controlled, the extension to the mix-fleet case being rather straightforward. The main difference with the un-controlled setting concerns the definition of an urban-truck work assignment as a sequence of services performed by the same vehicle and connected by returns to external zones for reloading or end-of-day termination of service.

Let Γ stand for the set of urban-truck work assignments. A work assignment for an urban-truck of type τ, $\gamma \in \Gamma(\tau)$, may then be defined 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. In somewhat more detailed form, the sequence of services may be written as an ordered sequence of external zones and satellites $\{(e_j(r), \sigma_j(r)) \mid j = 1, \ldots, n^{\mathrm{e}}(r)\}$, where $\{e_j(r),\ j = 1, \ldots, n^{\mathrm{e}}(r)\}$ is the sequence of external zones from where the service leaves to deliver to the associated satellites in sets $\sigma_j(r)$. An urban-truck 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-trucks may arrive to their next designated external zones 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 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-truck work assignment $\gamma \in \Gamma(\tau),\ \tau = 1, \ldots, \mathcal{T}$, is selected (operated), 0, otherwise,

while capacity

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

and urban-truck work-assignment linking constraints

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

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

Once the system is established, the size of the controlled fleets and the number of corresponding personnel are known. Moreover, on any given day, operators have good estimates of the vehicles and crews ready for service on the next day. Formulation (1) - (10), plus, eventually, (11), is appropriate for system-planning, particularly when the number of available vehicles is limited. The same formulation could also be used in system-evaluation mode, but it would require an *a priori* evaluation of the fleet sizes and could thus be too complex for the requirements of the evaluation process.

A somewhat simpler formulation could be used in system-evaluation mode, when the system is not implemented yet and its main operating characteristics are still to be defined. In such a case, the urban-truck fleet is considered unconstrained and the representation of Section 3.1 applies. The city-freighter fleets are also considered not limited in size. The focus is then on the volume of vehicles present in the city and not on the entire working assignments of these vehicles. The space-time synchronization of operations is still essential, however, to capturing the core characteristics of the City Logistics system. The simplified formulation eliminates then the work assignments and defines the city-freighter operations and the customer-demand itineraries directly in terms of work segments. The definition of an itinerary $m \in \mathcal{M}(d)$ is the same as previously, except for the leg out of the satellite where the load is transferred to:

> a city-freighter of type $\nu \in \mathcal{V}(p(d))$ operating leg $l(w(m))$ of work segment $w \in \mathcal{W}(\nu)$,

which will deliver it on time to the final customer. The corresponding simplifications to the definitions of the departure time from satellite and the arrival time at the final customer are then straightforward.

The sets of decision variables associated to the selection of city-freighter routes have also to be modified:

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

and the formulation becomes:

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

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

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

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

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-truck 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, assuming a "normal" situation where 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, corresponding schedules at each terminal, external zone or satellite, and the demand distribution strategy. The complete schedule of each vehicle and crew may then be obtained by solving rather standard crew-scheduling-type problems (see surveys by, e.g., Barnhart *et al.* 1999, Desrosiers *et al.* 1995, and Desaulniers *et al.* 1998a,b) for each vehicle fleet, where the tasks to be covered are the urban-truck service routes from one external zone to another and the city-freighter routes between two consecutive visits at the depot, respectively.

One of the issues often encountered in planning freight transportation services is whether loads may be split or not during delivery. Splitting loads among vehicles allows 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. Indeed, a number of firms impose very strict conditions to their suppliers of transportation services including no-split deliveries.

Formulations (1) - (10) and (13) - (16) 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 origin (external zone). This case also requires the largest number of vehicles compared to that of any of split-delivery scenarios 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-truck 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

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

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

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

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

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

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

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

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

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

where constraints (21) enforce the selection of an unique urban-truck service (and, thus, satellite), while relations (22) force the splitting of demand among itineraries to use the selected single urban-truck 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 distribution centers. Note that, when multiple distribution centers exist, each serving exclusively a particular territory of the city, the problem reduces to solving several single-distribution-center applications. 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 platforms and satellites do not belong to the single-tier problem class. Consequently, a single fleet needs to be considered and, given the environmental concerns of City Logistics, we assume city-freighters are used. The problem then reduces to planning the distribution of demand from external zones, distribution centers and similar facilities, to customers. The goal is to deliver the goods to customers in time, i.e., within the specified time windows, through an optimal utilization of the fleet of city-freighters in terms of cost and vehicle load.

The problem structure still combines service network design and vehicle routing aspects, but the service-coordination and time-synchronization characteristics of the two-tier system operations is not present in the single-tier setting. The service network design aspect comes from the requirement to select the best set of city-freighter work assignments and determine when each selected work assignment starts, as well as 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 re-loading to the same or a different external zone. When several distribution centers exist, the city-freighter circulation aspect must also be considered to decide where, i.e., to what distribution center, each vehicle must go once the last customer of the route has been serviced.

We assume the case of a controlled fleet of city-freighters, and adjust the definitions of Section 3.1. (As previously, movements out of and into depots are not included in route descriptions.) Let $\mathcal{W} = \{w\}$ be again 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 now at period $t(w)$ at an external zone and visits a sequence of customers identified by the set $\mathcal{C}_l(w)$. The work assignment is feasible if all the customer time restrictions are respected and the vehicle-capacity restrictions are enforced at all times. Once customers in $\mathcal{C}_l(w)$ are served, the city-freighter proceeds to the next external zone on its work assignment or to the depot is the work assignment is finished. With respect to the previous sections, all work segments are single legged and, thus, one does not need to define route legs.

Given a city-freighter type ν, a sequence of work segments $\sigma(h) = \{w_i \in \mathcal{W}(\nu),\ i = 1, \dots, |\sigma(h)|\}$ makes up a complete city-freighter *work assignment* $h \in \mathcal{H}(\nu)$ ($\mathcal{H} = \bigcup_\nu \mathcal{H}(\nu)$). The work assignment h is feasible only 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. As previously, $k(w)$ and $k(h)$ stand for the costs of operating a city-freighter work segment $w \in \mathcal{W}(\nu)$ and work assignment $h \in \mathcal{H}(\nu)$, respectively, the latter being equal to the sum of the corresponding costs of its work segments.

The definition of the demand *itinerary* $m \in \mathcal{M}(d)$ that may be used to satisfy customer-demand $d \in \mathcal{D}$ 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 are the selection of 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 distribution center case with unsplit delivery problem 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 the set partitioning formulations, for which a significant literature and methodology exists (e.g., Barnhart *et al.* 1998; Desrosiers *et al.* 1995; Desaulniers *et al.* 1998; Gentili 2003).

4 Solution Methodology Issues

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

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, or load, plan select the services that will be offered and their attributes, that is, their types (speed, priority, and so on), routes, intermediary stops (if any), 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, Magnanti, and Mirchandani 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, Fagerholt, and Ronen (2004 and Christiansen *et al.* (2007) for maritime transportation, Cordeau, Toth, and Vigo (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 the last forty six years 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 are the so-called Vehicle Routing Problem with Time Windows (VRPTW) problem settings specifying restrictions on when customers may be served and, eventually, depots may be visited. Surveys of routing problems may be found in, e.g., Bodin, Manienzzo, and Mingozzi (2003), Bräysy and Gendreau (2005a,b), Cordeau *et al.* (2007), Desaulniers *et al.* (1998), 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-truck services. When urban-trucks may call at more than two or three satellites during a single route or when the urban-truck fleet is limited in size and controlled (Section 3.2), the urban-truck service design problem may also be cast as a scheduled multi-depot scheduled multiple-tour VRPTW.

These problems are not independent, however. The route of each city-freighter out of each satellite and time period must be designed and scheduled not only to serve customers within their respective time windows, but also to bring the vehicle at a designated satellite at the appointed time to meet the urban-trucks bringing its future loads. Moreover, the routes and schedules or the urban-trucks and city-freighters must be strictly synchronized to provide the means for the direct transshipment satellite operations: no storage facilities at satellites and no waiting for the appointed connection.

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 Kook 1995), planning of logistics systems (e.g., Daganzo 2005), and cross-dock distribution systems (e.g., Croxton, Gendron, and Magnanti 2003, Donalson *et al.* 1998, Ratliff, Vate, and Zhang 1999, and Wen *et al.* 2007). Inventories are considered in most problem-settings of these last fields, which is not allowed in ours. The synchronization of fleets and activities is not present in the surveyed literature. Even the issue of coordinated multiple tours performed by in sequence by the same vehicle is rarely present in the literature. These time-related characteristics are central to our problem and are detailed in Section 6 (path-based formulations somewhat understate the issue). They also increase the difficulty of the 2SS-MDMT-VRPTW compared to and sets it apart from most vehicle routing problems encountered in the literature.

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. Given the state-of-the-art in vehicle routing and network design, we expect the development of column-generation-based branch-and-price algorithms for the former case. The field of meta-heuristics is too broad for safe predictions, but combining neighborhood and population-based methods into cooperation search strategies (that could also include exact solution methods for partial solutions) 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. Based on an earlier version of this paper (Crainic, Ricciardi, and Storchi 2005), Feliu, Perboli, and Tadei (2006) have initiated the development of heuristics for a simplified version of the problem (single period, single distribution center, no time considerations). Independently of the solution methodology that will be eventually selected, a better understanding of the building blocks of the formulation is certainly required before more elaborate formulations may be addressed. This is one of goals of this paper.

4.2 A hierarchical decomposition approach

Two main issues make up the day-before planning problem, the scheduling of the urban-truck 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-truck service network design* model that determines for each urban-truck its schedule (departure time) and route (satellites served), as well as the first-level demand distribution strategy: the urban-truck service, the satellite, and the type of city-freighter to use for each demand considered. Section 5 details this formulation.
2. Given the results of the previous model, a *city-freighter fleet management* formulation 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 the urban-truck schedules. Section 6 is dedicated to this issue.

The decomposition approach and the urban-truck 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-satellite allocation policies (Crainic, Ricciardi, and Storchi 2004). A number of methods may then be used to approximate satellite-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 solve 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.

5 The Urban-Truck Service Network Design Model

The models described in this section address the issues of determining when urban-trucks leave the external zones and the satellites they serve, as well as the itineraries used to move the freight from the external zones toward their destinations. At this level, the type of city-freighter used by each itinerary by is explicitly taken into account, while the duration and cost attributes of the final leg, the distribution from satellites to customers, are approximated. The focus in on the selection, for each customer-demand, of a set of urban-truck services and satellites that will provide on-time delivery at minimum total system cost which, in this case, implies a minimum number of vehicle movements in the city. The issues and models presented belong to the first level of the hierarchical decomposition approach of Section 4.

We start from the general case described in Section 3.1. Most notation and the definitions of the urban-truck services introduced in that section apply without modification to the present case. City-freighter routes are not considered, however, and, thus, the definition of demand itineraries must be modified to reflect the approximation of the delivery from satellites to customers by city-freighters.

Associate each customer-demand to the satellites that may serve it as determined, for example, at the strategic level of planning. Define $\tilde{\delta}(d, s, t)$, the approximation of the delivery time of the demand of customer-demand $d \in \mathcal{D}$ by a city-freighter tour leaving satellite s at time t, given the congestion conditions at that time, and $\tilde{c}(d, s, t)$, the corresponding approximate delivery cost. The definition of an itinerary $m \in \mathcal{M}(d)$ that may be used to satisfy customer-demand $d \in \mathcal{D}$ then becomes:

- From the external zone $e(d) \in \mathcal{E}$;
- Using an urban-truck service $r(m) \in \mathcal{R}$, of appropriate type $\tau(r(m)) \in \mathcal{T}(p(d))$ for the product $p(d) \in \mathcal{P}$, which leaves later than the availability time of the demand, i.e., $t(d) < t(r)$;
- To a satellite $s(m) \in \sigma(r(m))$ from where it is deliverred to the final customer $c(d)$, within its time window $[a(d), b(d)]$.

The associated schedule is then specified by

- $t_e(m) = t(r(m))$, the departure time from the external zone of demand d on urban-truck service $r(m)$;
- $t_s^{\text{in}}(m) = t_{s(m)}(r(m))$, the arrival time at satellite $s(m)$ by service $r(m)$;
- $t_s^{\text{out}}(m) = t_s^{\text{in}}(m) + \delta(\nu)$, the departure time from satellite $s(m)$ following unloading from the urban-truck and loading into a city-freighter;
- $t_c(m) = t_s^{\text{out}}(m) + \tilde{\delta}(d, s, t) \in [a(d), b(d)]$, the arrival time at the final customer.

Two sets of decision variables are defined. The first determines the urban-truck service network, while the second selects itineraries for each customer-demand:

$\rho(r) =$ 1, if the urban-truck service $r \in \mathcal{R}$ is selected (dispatched), 0, otherwise;

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

The problem may be formulated as a path-based scheduled service network design problem, where the specification of the time associated to each demand itinerary and urban-truck service is included in their respective definitions. We present the formulation for the case when demand cannot be split between itineraries (the formulations allowing demand to be split follow straightforwardly as indicated in Section 3.2 and are not included):

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

$$\text{Subject to} \quad \sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,r)} vol(d)\zeta(m) \leq u_\tau \rho(r) \qquad r \in \mathcal{R}, \tag{30}$$

$$\sum_{m \in \mathcal{M}(d)} \zeta(m) = 1 \qquad d \in \mathcal{D}, \tag{31}$$

$$\sum_{t^- = t - \delta(\tau)+1}^{t} \sum_{r \in \mathcal{R}(s,t^-)} \rho(r) \leq \pi_s \qquad s \in \mathcal{S},\ t = 1, \ldots, T, \tag{32}$$

$$\sum_{\nu \in \mathcal{V}} \left[\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,s,t)} vol(d)\zeta(m) \right] / u_\nu \leq \lambda_s \qquad s \in \mathcal{S}, \quad t = 1, \ldots, T, \tag{33}$$

$$\rho(r) \in \{0, 1\} \qquad r \in \mathcal{R} \tag{34}$$

$$\zeta(m) \in \{0, 1\} \qquad m \in \mathcal{M}(d),\ d \in \mathcal{D} \tag{35}$$

The model minimizes the total cost of the system, and thus the number of urban-trucks in the city, as captured by the objective function (29) that sums up the costs relative to the total number of urban-trucks and delivery of demand to customers. Relations (30) enforce the urban-truck capacity restrictions on the selected services. Equations (31) indicate that each demand must be satisfied by a single itinerary. Constraints (32) and (33) enforce the satellite capacity restrictions in terms of urban-trucks and city-freighters, respectively. The term

$$\sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}(d,s,t)} vol(d)\zeta(m) \tag{36}$$

in constraints (33) represents the total volume to be delivered to customers by city-freighters of type ν from satellite s at time t (set $\mathcal{M}(d,s,t)$ includes all itineraries of demand d that include satellite s at time $t_s^{\text{in}}(m) \leq t \leq t_s^{\text{out}}(m)$).

The results of the formulation are the design of the urban-truck service network and the selection of the satellite, time period, and city-freighter type for each customer-demand. The latter is 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 time period t from satellite s. The associated total demand of (36) becomes

$$\sum_{d \in \mathcal{C}_{st}^{\nu}} \sum_{m \in \mathcal{M}(d,s,t)} vol(d). \tag{37}$$

As indicated in Section 4, the model may be seen as a fixed-cost, multicommodity, capacitated network design formulation over a time-space network representing the possible departures of urban-trucks from external zones during the considered planning horizon. Service network design problems are difficult. They usually exhibit weak relaxations and are of very large dimensions. As a result, the field is dominated by various heuristics 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 that context.

We expect the problem size to be quite large due to the expected dimensions for a system representing a medium or large city and the number of periods. To reduce the size, we notice that the customer time windows and the impossibility to wait at satellites imply that the feasible itineraries for any given 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, Barnhart, and Ware (2002) where combinations of services and demands reduced the dimensions of the problem and implicitly accounted for the flow distribution. The last two idea 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, Crainic, and Gendreau (2003, 2004), which are among the current-best heuristics for the fixed-cost, capacitated, multicommodity network design problem, offer interesting perspectives. Indeed, urban-truck itineraries are relatively short, most services visiting one or two satellites (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-truck 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.

We close this section with two remarks. First, in evaluation mode, one does not have a detailed, customer-by-customer demand. Rather, estimations of demand in pre-defined customer zones are used instead (see the discussion in Crainic, Ricciardi, and Storchi 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) - (35), which would be smaller and, thus, easier to address. Of course, such an aggregation could also be used in planning mode for a faster but, potentially, less-precise result. 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.

The second remark concerns the case when urban-truck fleets are limited and controlled (Section 3.2). The specialization of urban-truck 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-truck 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, Crainic, and Madsen 2006). The developments for this class of models are recent and few (see, e.g., Andersen, Crainic, and Christiansen 2007a,b and Smilowitz, Atamtürk, and Daganzo 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. For each satellite, period, and type of city-freighter, the workload takes the form of customer-demands that have to be served. 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, that is, to ensure that city-freighter deliver the goods on time and that they arrive at satellites on time for their next assignments.

Recall that there are no waiting areas at satellites. Thus, city-freighters must arrive at the designated satellite just-in-time to load the designated freight and depart according to the schedule planned by the service design formulation (schedule which reflects the time constraints of the customer-demands). 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 see 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* problem (*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 could 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, time 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

The service network design formulation yields the city-freighter workloads at each satellite and time period. That is, it specifies one or more customer-demands $d \in \mathcal{C}^{\nu}_{st} \subseteq \mathcal{D}$ that must be served by city-freighters of type ν, leaving at time period t from satellite s. Let $\mathcal{ST}(\nu) \subseteq \mathcal{S}\text{x}\mathcal{T}$ be the set of (satellite, time-period) combinations where loads are assigned to city-freighters of type $\nu \in \mathcal{V}$, that is $\mathcal{ST}(\nu) = \{(s,t) \mid \mathcal{C}^{\nu}_{st} \neq \infty,\ s \in \mathcal{S},\ t = 1,\ldots,T\},\ \nu \in \mathcal{V}$. We assume that each customer-demand is less or equal to the capacity

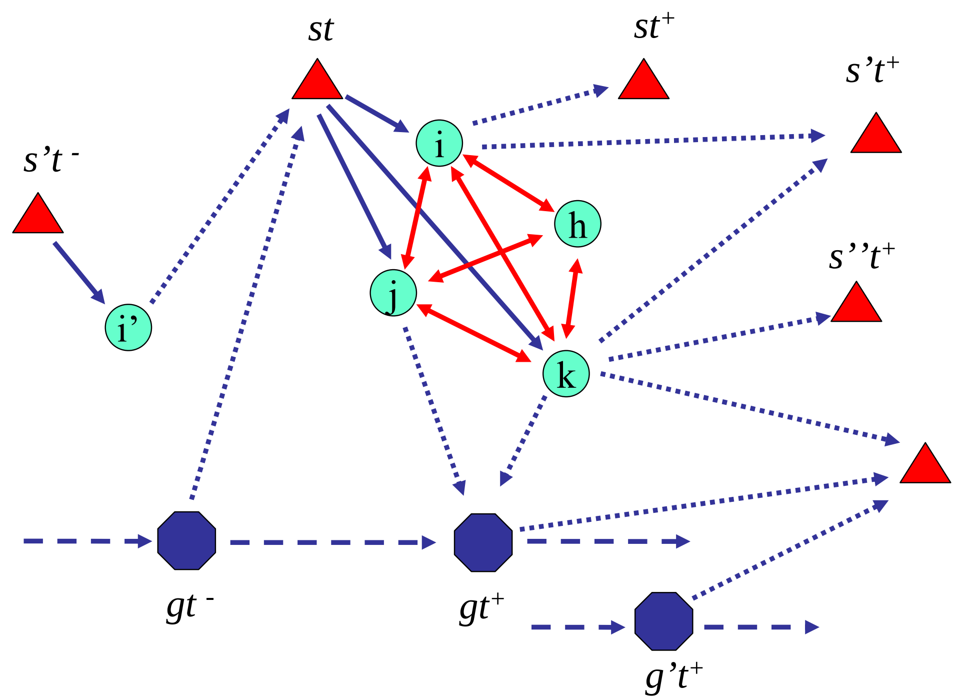

Figure 2: City-freighter Possible Movements

of the designated city-freighter and it must be delivered by a single vehicle.

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 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 time 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 serve one or more customers in $\mathcal{C}^{\nu}_{st}$. Once the last customer is served, the city-freighter goes either to a depot, e.g., the (j, gt^+) movement, or to a satellite (the requirements of operations at (satellite, time period) rendez-vous points forbid movements to customer-demands not in $\mathcal{C}^{\nu}_{st}$). 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 time period as determined by the total travel and customer service time. Given the (satellite, time 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 served on a previous service route, e.g., the (i', st) movement in Figure 2. The restrictions on the time instances city-freighters must arrive at satellites and customers determine the actual feasible movements.

6.2 The general city-freighter 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 time periods, arcs in $\mathcal{A}$ standing for the movements between these nodes which are feasible with respect to time and demand-itinerary definitions. The formulations presented in this subsection, as well as the contemplated exact and meta-heuristic solution methods, require the specification of this network.

Set $\mathcal{N}$ is made up of three subsets. The first represents the (satellite, time-period) pairs with loads to be distributed by city-freighters to customers. Other node sets stand for the customers associated to each (satellite, time-period) rendez-vous point and the city-freighter depots at all time periods. Formally:

- st representing the (satellite, time-period) pair $(s, t) \in \mathcal{ST}(\nu)$ for all city-freighter types ν;
- d for the customer-demands associated to the nodes 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 time $t = 0, \ldots, T+1$, 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

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

- An arc (st, d) goes from satellite st to each customer-demand $d \in \mathcal{C}^{\nu}_{st}$, such that the service time-window restriction, $a(d) \leq t + \delta_{sd}(t) \leq b(d)$, is satisfied. Identify $\mathcal{A}^{SD}_{st}(\nu) = \{(st, d) \mid d \in \mathcal{C}^{\nu}_{st}\},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$. In Figure 2, $\mathcal{A}^{SD}_{st}(\nu) = \{(st, i), (st, j), (st, k)\}$.
- Arcs link each customer $d \in \mathcal{C}^{\nu}_{st}$ to satellites in later periods. The set $\mathcal{A}^{DS}_{st}(d,\nu) = \{(d, s't'),\ s't' \in \mathcal{ST}(\nu)\},\ d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, contains the arcs corresponding to such feasible movements, that is, arcs that leaving the customer, arrive at a satellite $s' \in \mathcal{S}$ at time $t' - \delta(\nu) \leq T$, such that city-freighters may be loaded and leave by time t': $a(d) \leq t' - \delta(\nu) - \delta(d) - \delta_{ds'}(t) \leq b(d)$. In Figure 2, $\mathcal{A}^{DS}_{st}(i,\nu) = \{(i, st^{+}), (i, s't^{+})\}$, for example.

- We may now define the backstar of node st with respect to customer-demands as the set $\mathcal{A}^{S-}_{st}(\nu) = \{(d, st) \mid d \in \mathcal{C}^{\nu}_{s't^-},\ s't' \in \mathcal{ST}(\nu),\ t' < t,\ a(d) \leq t - \delta(\nu) - \delta(d) - \delta_{ds}(t') \leq b(d)\},\ \nu \in \mathcal{V}$. 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 that 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 back-star arcs (i.e., arriving at customer d at time 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 link each customer $d \in \mathcal{C}^{\nu}_{st}$ to depots in later periods. The set $\mathcal{A}^{DG}_{st}(d, \nu) = \{(d, gt^+),\ d \in \mathcal{C}^{\nu}_{st},\ g \in \mathcal{G},\ t^+ > t\},\ (s, t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}$, contains these arcs arriving at depot g at time 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-freighters may be held at depots, which yields the set $\mathcal{A}^G = \{(gt, gt + 1),\ t = 0, \dots, T,\ \forall g \in \mathcal{G}\}$.

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 $\sigma(w) = \{s_l \in \mathcal{S},\ l = 1, \dots, |\sigma(w)| \mid t_l(w) < t_{l+1}(w)$ 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 deliver the loads of the customer-demands in $\mathcal{C}^{\nu}_{st}$.

Define $\alpha_{st}(h, d) = 1$, if work assignment $h \in \mathcal{H}(\nu)$ serves 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:

$$\text{Minimize} \quad \sum_{h \in \mathcal{H}} k(h)\varphi(h) \tag{38}$$

$$\text{Subject to} \quad \sum_{d \in \mathcal{C}^{\nu}_{st}} \alpha_{st}(h,d) vol(d) \leq u_{\nu}\varphi(h) \quad (s,t) \in \sigma(w),\ w \in \sigma(h),\ h \in \mathcal{H}, \tag{39}$$

$$\sum_{h \in \mathcal{H}(\nu)} \alpha_{st}(h,d)\varphi(h) = 1 \quad d \in \mathcal{C}^{\nu}_{st},\ (s,t) \in \mathcal{ST}(\nu), \tag{40}$$

$$\sum_{t^- = t - \delta(\tau)+1}^{t} \sum_{h \in \mathcal{H}} h(s,t^-)\varphi(h) \leq \lambda_s \quad s \in \mathcal{S},\ t = 1, \ldots, T, \tag{41}$$

$$\sum_{h \in \mathcal{H}(\nu)} \varphi(h) \leq n_{\nu} \quad \nu \in \mathcal{V}, \tag{42}$$

$$\varphi(h) \in \{0,1\} \quad h \in \mathcal{H}. \tag{43}$$

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 modest-dimensioned problem instances. This elegance is hiding, however, the increased complexity of the SS-MDMT-VRPTW, compared to the more "regular" VRPTW problem 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.

Recall that n_ν represents the number of available city-freighters of type ν and let $k_\nu(i,j)$ stand for the unit transportation cost for a city-freighter of type ν, between two points $i,j \in \mathcal{N}$ in the city, where each point may be a customer, a satellite, or a depot at a given point in time; i.e., $k_\nu(i,j)$ is defined for each arc (i,j) of $\bar{\mathcal{A}} = \mathcal{A} \setminus \mathcal{A}^G$, the set of all arcs except those for holding vehicles at depots. Travel on arc (i,j) is initiated at period t specified by the time associated to node $i \in \mathcal{N}$ and its duration is adjusted for the congestion conditions generally prevalent at that moment. Let also k_ν represent the cost associated to operating a city freighter of type ν at a satellite.

Two types of decision variables are defined:

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

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

$$\text{Minimize} \quad \sum_{\nu \in \mathcal{V}} \sum_{\phi=1}^{n_\nu} \left[\sum_{(i,j) \in \bar{\mathcal{A}}} k_\nu(i,j)\theta^\nu_\phi(i,j) + k_\nu \sum_{(s,t) \in \mathcal{ST}(\nu)} \sum_{d \in \mathcal{C}^\nu_{st}} \theta^\nu_\phi(s,d) \right] \tag{44}$$

$$\text{Subject to} \quad l_{st}(\nu) \leq \sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^\nu_\phi(s,d) \leq u_{st}(\nu) \quad (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{45}$$

$$\sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^\nu_\phi(s,d) \leq 1 \quad (s,t) \in \mathcal{ST}(\nu),\ \phi = 1,\dots,n_\nu,\ \forall \nu \in \mathcal{V}, \tag{46}$$

$$\sum_\phi \left[\sum_{(d,i) \in \mathcal{A}^{DD}_{st}(d,\nu)} \theta^\nu_\phi(d,i) + \sum_{(d,s't') \in \mathcal{A}^{DS}_{st}(d,\nu)} \theta^\nu_\phi(d,s') + \sum_{(d,g) \in \mathcal{A}^{DG}_{st}(d,\nu)} \theta^\nu_\phi(d,g) \right] = 1$$
$$d \in \mathcal{C}^\nu_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{47}$$

$$\sum_\phi \left[\theta^\nu_\phi(s,d) + \sum_{(i,d) \in \mathcal{A}^{D-}_{st}(d,\nu)} \theta^\nu_\phi(i,d) \right] = 1 \quad d \in \mathcal{C}^\nu_{st},\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{48}$$

$$\sum_{(gt',st) \in \mathcal{A}^{G-}_{st}(\nu)} \theta^\nu_\phi(g,s) + \sum_{(d,st) \in \mathcal{A}^{S-}_{st}(\nu)} \theta^\nu_\phi(d,s) = \sum_{(st,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^\nu_\phi(s,d)$$
$$(s,t) \in \mathcal{ST}(\nu),\ g \in \mathcal{G},\ \phi = 1,\dots,n_\nu,\ \nu \in \mathcal{V}, \tag{49}$$

$$\sum_\phi \left[\theta^\nu_\phi(g(t-1),g(t)) + \sum_{(d,g) \in \mathcal{A}^{DG}_{st}(d,\nu)} \theta^\nu_\phi(d,g) \right] \tag{50}$$

$$= \sum_\phi \left[\theta^\nu_\phi(g(t),g(t+1)) + \sum_{(g,s) \in \mathcal{A}^{GS}_{gt}(\nu)} \theta^\nu_\phi(g,s) \right] \quad g \in \mathcal{G},\ \nu \in \mathcal{V},\ t = 1,\dots,T \tag{51}$$

$$\sum_{d \in \mathcal{C}^\nu_{st}} vol(d)\theta^\nu_\phi(s,d) + \sum_{(i,j) \in \mathcal{C}^\nu_{st}} vol(j)\theta^\nu_\phi(i,j) \leq u_\nu$$
$$\phi = 1,\dots,n_\nu,\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{52}$$

$$\omega^\nu_\phi(i) + \delta(i) + \delta_{ij}(t) - \omega^\nu_\phi(j) \leq (1 - \theta^\nu_\phi(i,j))(b_i + \delta(i) + \delta_{ij}(t) - a_j)$$
$$\phi = 1,\dots,n_\nu,\ (i,j) \in \mathcal{A}^{DD}_{st}(i,\nu),\ (s,t) \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{53}$$

$$a(d)\left[\theta^{\nu}_{\phi}(s,d)+\sum_{(i,d)\in\mathcal{A}^{D-}_{st}(d,\nu)}\theta^{\nu}_{\phi}(i,d)\right]\leq\omega^{\nu}_{\phi}(d)$$

$$\leq b(d)\left[\sum_{(d,i)\in\mathcal{A}^{DD}_{st}(d,\nu)}\theta^{\nu}_{\phi}(d,i)+\sum_{(d,s't')\in\mathcal{A}^{DS}_{st}(d,\nu)}\theta^{\nu}_{\phi}(d,s')+\sum_{(d,g)\in\mathcal{A}^{DG}_{st}(d,\nu)}\theta^{\nu}_{\phi}(d,g)\right]$$

$$d\in\mathcal{C}^{\nu}_{st},\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \qquad (54)$$

$$\omega^{\nu}_{\phi}(st)=t-\delta(\nu)\sum_{(s,d)\in\mathcal{A}^{SD}_{st}(\nu)}\theta^{\nu}_{\phi}(s,d)\quad (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \qquad (55)$$

$$(\omega^{\nu}_{\phi}(d)+\delta(d)+\delta_{ds}(t')-\omega^{\nu}_{\phi}(st))=(1-\theta^{\nu}_{\phi}(d,s))(\omega^{\nu}_{\phi}(d)+\delta(d)+\delta_{ds}(t')-\omega^{\nu}_{\phi}(st))$$

$$(d,s)\in\mathcal{A}^{S-}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \qquad (56)$$

$$(\omega^{\nu}_{\phi}(gt')+\delta_{gs}(t')-\omega^{\nu}_{\phi}(st))=(1-\theta^{\nu}_{\phi}(g,s))(\omega^{\nu}_{\phi}(gt')+\delta_{gs}(t')-\omega^{\nu}_{\phi}(st))$$

$$(g,s)\in\mathcal{A}^{G-}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \qquad (57)$$

$$(\omega^{\nu}_{\phi}(st)+\delta(\nu)+\delta_{sd}(t)-\omega^{\nu}_{\phi}(d))=(1-\theta^{\nu}_{\phi}(s,d))(\omega^{\nu}_{\phi}(st)+\delta(\nu)+\delta_{sd}(t)-\omega^{\nu}_{\phi}(d)$$

$$(s,d)\in\mathcal{A}^{SD}_{st}(\nu),\ (s,t)\in\mathcal{ST}(\nu),\ \phi=1,\ldots,n_{\nu},\ \nu\in\mathcal{V}, \qquad (58)$$

$$\theta^{\nu}_{\phi}(i,j)\in\{0,1\}\quad (i,j)\in\mathcal{A},\ \phi=1,\ldots,n_{\nu},\ \forall\nu\in\mathcal{V} \qquad (59)$$

The objective function (44) minimizes the total transportation-related cost, as well as the number of city freighters used (through their utilization costs at satellites). As mentioned earlier, the service network design model of Section 5 assigns, for each city-freighter type, customer-demands $\mathcal{C}^{\nu}_{st}$ to each (satellite, time period) rendez vous point. 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 this demand (e.g., $l_{st}(\nu) = \sum_{d\in\mathcal{C}^{\nu}_{st}} vol(d)/u_{\nu}$ and $u_{st}(\nu) = \min\{|\mathcal{C}^{\nu}_{st}|, n_{\nu}\}$). Constraints (45) enforce these restrictions..

Constraints (46) ensure that each vehicle leaving a satellite goes to one customer only, while constraints (47) 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 (48) also enforce the flow conservation at customer nodes (at least one arc must serve each customer-demand). The conservation of flow at satellites at each rendez-vous point of a city-freighter type is completed by equations (49). Equations (50) represent the conservation of flow at depots. Relations (52) enforce the restrictions on the city-freighter

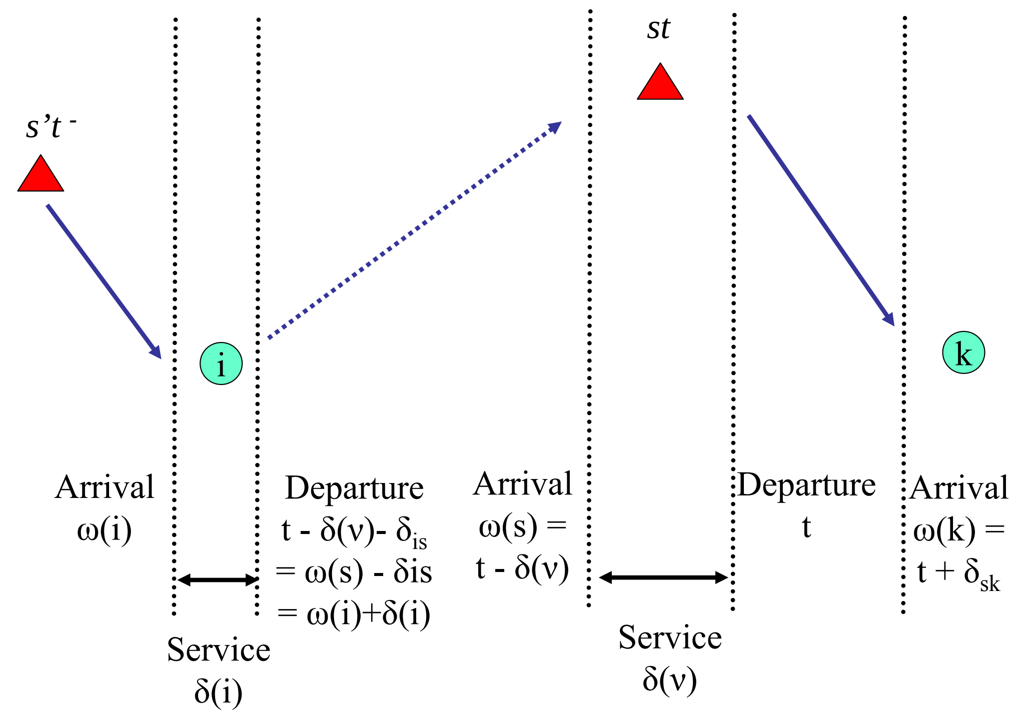

Figure 3: City-freighter Synchronization Requirements

capacities, each time a vehicle leaves a (satellite, time period) rendez-vous point to deliver customer-demands.

Constraints (53) and (54), enforce schedule feasibility with respect to the service time consideration for movements between customers. Service must start within the time windows associated to the customer-demand, but no restrictions are imposed on when the vehicle actually arrives (so-called soft time windows).

Constraints (55), (56), (57), and (58) impose the synchronization of city-freighter arrivals at the (satellite, time period) rendez-vous points, characteristic of SS-MDMT-VRPTW. Constraints (55) specify the time service must start at the satellite. In practice, there is a small interval of arrival feasibility, δ, which transforms the constraint into:

$$(t - \delta(\nu) - \delta) \sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d) \leq \omega^{\nu}_{\phi}(st) \leq t - \delta(\nu) \sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d)$$

$$(s,t) \in \mathcal{ST}(\nu),\ \phi = 1, \ldots, n_{\nu},\ \nu \in \mathcal{V}. \qquad (60)$$

Given the service starting time at the satellite, constraints (56) and (57) impose the departure time t' from the previous customer or depot, respectively. Similarly, constraints (58) impose the arrival time to the first customer-demand out of the (satellite, time period) rendez-vous point. Figure 3 illustrates constraints (55), (56), and (58) Finally, conditions (59) 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, Laporte, and Mercier (2001) and the cooperative search of Le Bouthillier, Crainic, and Kropf (2005) illustrate this trend that we intend to follow for this problem.

Such methods would be particularly required for planning activities of in-function systems as is the formulation (44) - (59), which is a "complete" and 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. The same couple model - solution method could also be used in system-evaluation mode, given an evaluation (a scenario) of the dimension of each city-freighter type fleet. It appears much too complicated for this purpose, however. For evaluation purposes, a simpler approximation scheme that takes advantage of the context and characteristics of the problem can be proposed. This is the scope of the next subsection.

6.3 A decomposition approach for the SS-MDMT-VRPTW

In this subsection, we propose an efficient approach to address the SS-MDMT-VRPTW that takes advantage of the structure of the problem. The general idea is based on decomposing the problem at the (satellite, time period) rendez-vous points and focusing on the approximate flow of city-freighters required to deliver the loads, without specifically accounting for the satellite synchronization requirements. The resulting procedure thus becomes a heuristic for the city-freighter SS-MDMT-VRPTW. It is therefore appropriate for the evaluation of contemplated two-tier City Logistics systems. In system-planning mode, it could also yield the input data to more detailed vehicle and crew scheduling methods.

The method we propose proceeds in two phases:

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

Circulation. Solve the problem of moving city-freighters among activities at (satellite, time period) rendez-vous points (loading) and, eventually, depots (to wait), to determine the city-freighter flows at minimum total cost.

The output of the service design model of Section 5 yields the sets $\mathcal{C}_{st}^{\nu}$ associated to the $(s,t) \in \mathcal{ST}(\nu)$ rendez-vous points. This information makes up the input to the Routing phase, which thus consists in solving many small VRPTW problems. The number of VRPTW subproblems depends upon the number of $\mathcal{C}_{st}^{\nu}$ sets associated to each (satellite, time period) rendez-vous point and is bounded by $|\mathcal{ST}(\nu)||\mathcal{V}|$. The size of each problem is relatively small, however, the cardinality of sets $\mathcal{C}_{st}^{\nu}$ being in the low teens. Individual VRPTW (return arcs from each customer to the satellite with 0 travel time and cost are included) 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, time period) rendez-vous point and each associated vehicle type, the number of city-freighter routes and the actual routes with their attributes. Let $F_{\nu}(st)$ represent the (integer) number of city-freighters of type ν required to serve customers in $\mathcal{C}_{st}^{\nu}$, $(s,t) \in \mathcal{ST}(\nu)$. Let $\Delta_{\phi}^{\nu}(st)$ and $k_{\phi}^{\nu}(st)$, $\phi = 1, \ldots, F_{\nu}(st)$, represent the duration and cost of route ϕ, respectively, and denote $d(st_{\phi})$ the last customer-demand served by the route. Then, $t + \Delta_{\phi}^{\nu}(st)$ represents the moment the city-freighter on route ϕ becomes available for re-positioning to a satellite or back to the depot.

A flow problem, one for each type of city-freighter, may then be defined to yield a circulation plan for the city-freighters during the planing period. The network used to define this 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. The set of nodes $\mathcal{N}$ is made up of the sets of

- st representing the (satellite, time-period) pair $(s,t) \in \mathcal{ST}(\nu)$ (e.g., $F_{\nu}(st) = 4$ in Figure 4);
- st_{ϕ} for the route $\phi = 1, \ldots, F_{\nu}(st)$, $(s,t) \in \mathcal{ST}(\nu)$ (e.g., nodes st_i and st_j in Figure 4);

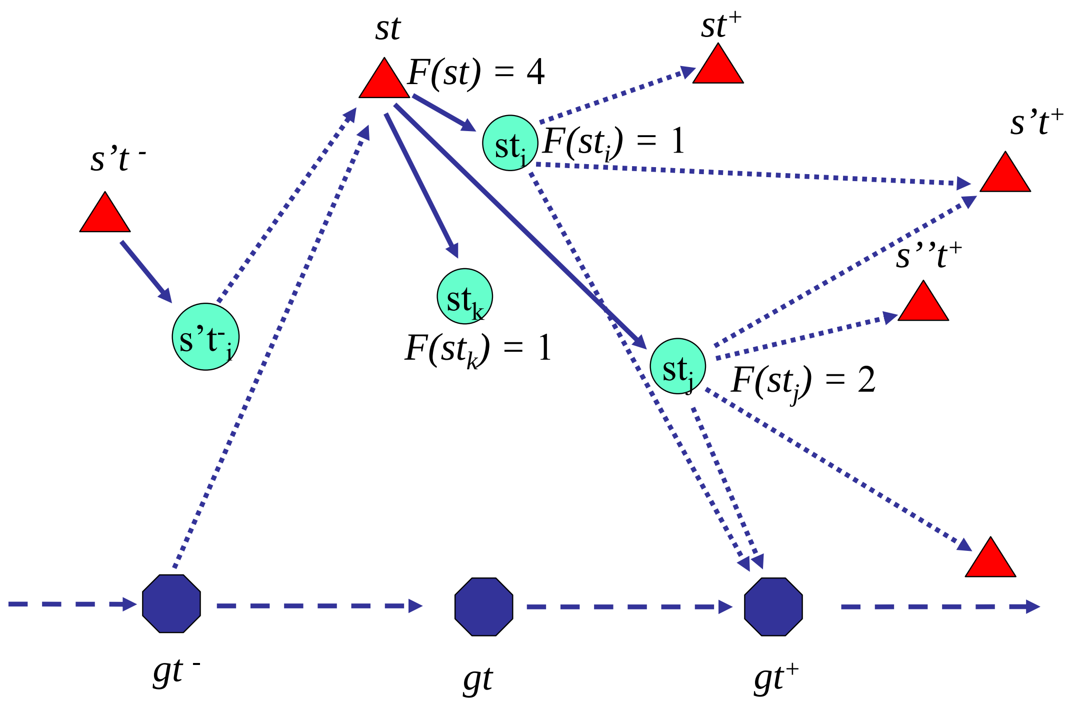

Figure 4: Disaggregated City-freighter Network

- $gt \in \mathcal{G}(t)$, representing the city-freighter depots at time $t = 0, \ldots, T+1$.

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_ϕ) go from satellite st to each route-node $st_\phi,\ \phi = 1, \ldots, F_\nu(st),\ (s,t) \in \mathcal{ST}(\nu)$. Identify $\mathcal{A}^{SD}_{st}(\nu)$ as the set of these arcs, three of which are illustrated in Figure 4.

- Arcs link each route-node st_ϕ to satellites in later periods. Only arcs to nodes $s't'$ such that $t + \Delta^\nu_\phi(st) + \delta_{d(st_\phi)s't'}(t + \Delta^\nu_\phi(st)) = t' - \delta(\nu)$ are included in this set denoted $\mathcal{A}^{DS}_{st}(st_\phi, \nu)$. In Figure 4, $\mathcal{A}^{DS}_{st}(st_i, \nu) = \{(st_i, st^+), (st_i, s't^+)\}$, for example.

  The backstar of node st with respect to route-nodes is the set $\mathcal{A}^{S-}_{st}(\nu) = \{(s't'_\phi, st)\}$ including links to st from all 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 link each route-node $st_\phi,\ \phi = 1, \ldots, F_\nu(st),\ (s,t) \in \mathcal{ST}(\nu)$ to depots in later periods. The set $\mathcal{A}^{DG}_{st}(d, \nu) = \{(st_\phi, gt^+)\}$, contains these arcs (e.g., (st_i, st^+) in Figure 4) arriving at depot g at time $t^+ = t + \Delta^\nu_\phi(st) + \delta_{d(st_\phi)g}(t + \Delta^\nu_\phi(st))$.

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 city-freighter type ν then becomes:

$$\text{Minimize} \quad \sum_{(i,j)\in\mathcal{A}} k_\nu(i,j) f_\nu(i,j) \tag{61}$$

Subject to

$$\sum_{(st,st_\phi)\in\mathcal{A}^{SD}_{st}(\nu)} f_\nu(st, st_\phi) = F_\nu(st) \quad st \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{62}$$

$$f_\nu(st, st_\phi) = 1 \quad (st, st_\phi) \in \mathcal{A}^{SD}_{st}(\nu) \quad st \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V}, \tag{63}$$

$$\sum_{gt'} f_\nu(gt', st) + \sum_{(i,j)\in\mathcal{A}^{S-}_{st}(\nu)} f_\nu(i,j) = \sum_{(st,st_\phi)\in\mathcal{A}^{SD}_{st}(\nu)} f_\nu(st, st_\phi) \quad st \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V} \tag{64}$$

$$f_\nu(st, st_\phi) = \sum_{(st_\phi, gt^+)\in\mathcal{A}^{DG}_{st}(d,\nu)} f_\nu(st_\phi, gt^+) + \sum_{(st_\phi, s't'))\in\mathcal{A}^{DS}_{st}(st_\phi,\nu)} f_\nu(st_\phi, s't')$$
$$st \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V},\ st \in \mathcal{ST}(\nu),\ \nu \in \mathcal{V} \tag{65}$$

$$f_\nu(g(t-1), gt) + \sum_{(i,j)\in\mathcal{A}_{st}^{DG}(d,\nu)} f_\nu(st_\phi, gt^+)$$
$$= f_\nu(gt, g(t+1)) + \sum_{(i,j)\in\mathcal{A}_{gt}^{GS}(\nu)} f_\nu(gt', st) \quad g\in\mathcal{G},\ \nu\in\mathcal{V},\ t=1,\ldots,T+1 \quad (66)$$
$$f_\nu(i,j) \geq 0 \quad (i,j)\in\mathcal{A} \quad (67)$$

Constraints (62) and (63) fix the number of city-freighters that must arrive at each (satellite, time period) rendez-vous point and enforce the single vehicle per route condition, respectively. Constraints (64) and (65) then enforce the flow conservation conditions at (satellite, time period) rendez-vous points and route-nodes, respectively. Conservation of flow at depot nodes $g(t)$ are enforced by constraints (66), with 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, which we denoted the *two-echelon, synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* problem (*2SS-MDMT-VRPTW*).

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

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