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City Logistics

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Abstract City logistics aims to reduce the nuisances associated with 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. This tutorial presents an overview of city logistics concepts, ideas, and planning issues. It also attempts to identify interesting research avenues and challenges for operations research. The tactical planning and scheduling of operations and management of resources for a two-tier city logistics system illustrates these issues and challenges.

Keywords city logistics; advanced urban freight transportation; integrated short-term planning and management; service network design; vehicle routing

1. Introduction

The transportation of goods constitutes a major enabling factor for most economic and social activities taking place in urban areas. For the city inhabitants, it supplies stores and places of work and leisure, delivers mail and goods at home, provides the means to get rid of refuse, and 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 (Organisation for Economic Co-operation and Development (OECD) [67]).

Freight vehicles compete with private and public vehicles transporting people for the capacity of the streets, arteries, and parking spaces of the city, and contribute significantly to congestion and environmental nuisances, such as emissions and noise. In major French cities, for example, it has been found that freight vehicles consume, on average, 30% of the city street capacity, two-thirds representing parking for delivery and pick-up operations (Patier [68]). On average, for 13 American cities, freight transportation represents some 10% of the total vehicle kilometers travelled within the cities (Figliozzi [45]); the same measure for the three largest French cities varies from 13% to 20% (Patier [68]). Figures are equally telling regarding emissions. A report by the OECD [67] assigns, for example, 43% of sulphur oxide and 61% of particulate matter emissions in London to freight transportation, whereas for nitrogen oxide 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 the supply chains involving these firms. Moreover, the amplitude of freight traffic also contributes to the belief that "cities are not safe," which pushes numerous citizens to move out of the city limits. And the problem is not going to disappear any time soon.

The number of freight vehicles moving within city limits, which is already important, is growing and is expected to continue to grow at a steady rate. Major contributing factors are the current production and distribution practices based on low inventories and timely deliveries, and the explosive growth of business-to-customer electronic commerce that generates significant volumes of personal deliveries. Probably even more important, a worldwide urbanization trend is emptying the countryside and small towns and is making large cities even larger. Within the countries that are members of OECD, the urban population was 50% of the total population in 1950, 77% in 2000, and should reach the 85% mark by 2020 (OECD [67]). It is estimated that 2007 has seen, for the first time in recorded history, the worldwide urban population being larger than the rural population.

The public, industry, and officials at all levels of government are increasingly challenged by these issues and acknowledge the need 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, in particular to reduce congestion and pollution as well as to increase mobility, while not penalizing the city center activities. More precisely, one aims to reduce and control the number, dimensions, and characteristics of freight vehicles operating within the city limits, improve the efficiency of freight movements, and reduce the number of empty vehicle kilometers. This has resulted in several initiatives, proposals, and projects, mostly in Europe and Japan. But interest is steadily growing, as witnessed, in particular, by studies being reported in Australia and the conferences organized in North America in recent years addressing these issues. Interest is also increasing because, although developed independently, city logistics concepts are convergent with the sustainable-development principles and the environmental concerns (e.g., attempting to reach the Kyoto targets for emission reductions or, at least, to conform to the spirit of the accord) that are increasingly characterizing the development of transportation systems and urban areas.

City logistics initiatives follow from the acknowledgment that, although necessary, traffic and parking regulations are no longer sufficient and "new" organizational models of urban freight transportation activities must be set up. The fundamental idea underlying these new models 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.

For operations research and transportation science, city logistics constitutes both a challenge and an opportunity in terms of methodological developments and actual social impact. Currently, however, there are few models that address city logistics issues. Concepts are proposed and pilot studies are undertaken, yet the corresponding operations research literature related to the design, evaluation, planning, management, and control of such systems is still scarce. The objective of this tutorial is to present an overview of city logistics concepts, issues, and challenges, focusing on the models and methods required to evaluate city logistics systems and plan their activities. The field is young and evolving rapidly. This tutorial is thus also an invitation to join in the efforts to develop these models and methods and help in making our transportation systems more efficient and our cities more pleasant to live in.

This tutorial is organized as follows. Section 2 describes the main city logistics concepts and experiences. Associated planning issues and operations research challenges are examined in §3. The tactical planning problem for two-tier city logistics systems and the associated models and solution avenues are recalled in §§4 and 5 to illustrate these issues and challenges. Section 6 concludes the tutorial.

2. City Logistics

Logistics, as currently understood, targets the analysis, planning, and management of the integrated and coordinated physical, informational, and decisional flows within a potentially multipartner value network. It is from this view that the term *city logistics* has been coined to emphasize the need for a systemic view of the issues related to freight movements within urban areas, that is, a system characterized by an optimized consolidation of loads of different shippers and carriers within the same delivery vehicles and the coordination of freight transportation activities within the city.

A review of practice and literature reveals, however, that (1) the "optimization" component of the city logistics concept is not yet very developed, and (2) not all countries and regions are at the same level of analysis and action, as most documents and projects are currently still to be found in Europe and Japan. This section reviews the main business models and elements of city logistics systems. Associated analysis and planning issues are addressed in the next section. More information on the former may be found on the websites of a number of European initiatives, proposals, and projects, e.g., Trendsetter [89], PORTAL [72], CITY PORTS [19], BESTUFS [10], CIVITAS Initiative [20], and Transports de Marchandises en Ville [88], the proceedings books of the city logistics conferences available through the Institute of City Logistics [53], as well as Dablanc [33], Russo and Comi [76], and Taniguchi et al. [84].

2.1. City Logistics Business Models and Main Components

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

Data-collection activities confirmed that freight transportation within urban areas generates large numbers of movements of freight vehicles of various dimensions, that the average vehicle load is low, and that many vehicles are in fact empty (Dufour [41], Dietrich [39], Patier-Marque [69], Morris et al. [65], STA [78], Ambrosini and Routhier [1]). Moreover, traffic and parking regulations do not seem to be able to cope with the problem (Morris et al. [65], Ricci and Fagiani [74], Dablanc [33]). Better fleet-management practices could partially address these issues through a more efficient utilization of vehicles with higher average load factors and fewer empty trips (the beer and soft drink delivery industry already displays such characteristics), but only partially, because such policies would concern individual carriers or shipper-customer combinations only.

The construction of automated underground systems dedicated to freight transportation has been proposed as a means to reduce the number of vehicles traveling in urban areas. However, the huge investments required make this concept unrealistic in most cases (van Duin [43], Ooishi and Taniguchi [66]). 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 with some form of *coordination* of operations within the city is among the most important means to achieve the rationalization of distribution activities. The utilization of so-called green vehicles and the integration of public-transport infrastructures (e.g., light rail or barges on rivers 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* (CDCs; the term urban freight consolidation center is also used). Long-haul transportation vehicles of various modes dock at a CDC to unload their cargo. Loads are then sorted and consolidated into smaller vehicles 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, as well as movement among origins and destinations within the city. To simplify the presentation, however, we focus on the inbound, distribution activities only. This is the general approach of most city logistics 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 those 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 (deconsolidation) 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, e.g., Browne et al. [15], van Duin [42], Janssen and Oldenburger [54], Kohler [56, 57], Ruske [75], Taniguchi et al. [84], and Thompson and Taniguchi [86].

Most city logistics 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 websites and references indicated earlier; see also Taniguchi et al. [81], Visser et al. [91]). 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 European Union 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, with 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 continuously evolving, however, and the new generation of projects combine elements from the three previous approaches (Visser et al. [91]). The city distribution center is still at the core of the system, but the private-public partnerships are stronger, and municipal traffic and parking regulations are adjusted accordingly. 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 (ITS) technologies are increasingly being contemplated and integrated.

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 centers, display high levels of population density as well as commercial, administrative, and cultural activities (Dablanc [33]). Another characteristic of large cities that plays against single-tier systems is the rather lengthy distance a vehicle must travel from the CDC on the outskirts of the city to the city center where the delivery tour begins. Two-tier systems have recently been proposed for such cities (Crainic et al. [30, 31], Gragnani et al. [52]). Two-tier city logistics systems are described briefly next and are used later in this tutorial to illustrate a number of planning issues and challenges.

2.2. Two-Tier City Logistics System

The two-tier city logistics concept builds on and expands the city distribution center idea. CDCs form the first level of the system and are located on the outskirts of the urban zone. The second tier of the system is comprised 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 that we discuss in this tutorial, satellites do not perform any vehicle-waiting or warehousing activities, vehicle synchronization and transdock trans-shipment being the operational model (see Gragnani et al. [52] for a simpler proposal). Existing facilities, e.g., underground parking lots or municipal bus garages, could thus be used for satellite activities (Crainic et al. [30]).

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 friendly. *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, because 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 highways" 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, trains, or light-rail services, and sorting and consolidation operations may be performed in CDC-type facilities located in the port, rail yard, or a rail station situated close to the center of the city (a satellite rather than a CDC would then be located at the rail station). In this case, part of the workload normally undertaken by urban trucks is performed by barges, ships, rail or light-rail cars. 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 of 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; and 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 "need-to-be-there" basis only, while providing timely delivery of loads to customers and economically and environmentally efficient operations.

3. Planning Issues

Similarly to any complex transportation system, city logistics transportation systems require planning at the strategic, tactic, and operational levels.

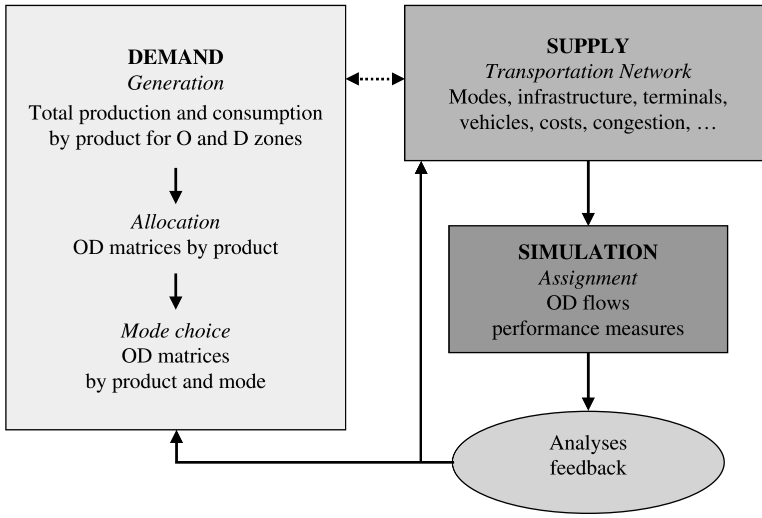
The strategic level is concerned with the design of the system and the evaluation of city logistics proposals, that is, one must evaluate the probable behavior and performance of the proposed system and operating policies under a broad range of scenarios. It also addresses the continuous analysis of the performance and behavior of deployed systems and the planning of their evolution, both as stand-alone systems and in relation to the general transportation system of the city and the larger region that encompasses it. Although very few formal models have been proposed specifically for city logistics (Taniguchi and van der Heijden [79], Taniguchi et al. [84], Taniguchi and Thompson [80]), these issues are generally part of transportation-system planning methodologies, which are well known, particularly for passenger transportation within urban zones, but also for passenger and freight regional/national planning (Cascetta [16], Crainic and Florian [26, 27], Florian [46], Florian and Hearn [47]). Their main components are as follows:

1. *supply modeling* to represent the transportation modes, infrastructure, carriers, services, and lines; vehicles and convoys; terminals and intermodal facilities; capacities and congestion; and economic, service, and performance measures and criteria;
2. *demand modeling* to capture the product definitions, identify producers, shippers, and intermediaries, and represent production, consumption, and point-to-point distribution volumes, as well as *mode choices* for transportation; relations of demand and mode choice to the performance of economic policies and transportation system performance are also addressed here;
3. *assignment* of multicommodity flows (from the demand model) to the multimode network (the supply representation); this procedure simulates the behavior of the transportation system and its output forms the basis for the strategic analyses and planning activities.

A number of methods and tools for the analysis, fusion, validation, and updating of information, as well as result-analysis capabilities for, e.g., cost-benefit, environmental impact, and energy consumption policies, complement the methodology.

Figure 1 presents the classical combination of these models and methods into the so-called *four-step planning* method. Such an approach starts from the economic, demographic, social, and political current or forecast data in a given region. For city logistics systems, this step should also include considerations relative to the organizational and managerial framework of the contemplated system, the involvement of all stakeholders, including final customers

FIGURE 1. Four-step transportation planning methodology.



Note. O, origination; D, destination.

as well as the local and central governments, and the contemplated business models must be defined. The initial step also determines the geographical division of the region into zones and identifies the product groups to be considered. Notice that all activity—production, consumption, shipping, and reception of cargo—within a zone is represented in aggregated form associated to a single point, the so-called *centroid* of the zone. This step thus reflects, and specifies for all the other steps of the planning procedure, the degree of aggregation of the data available for the region under study. The product-specific demand is then generated in two steps: first, the total production and consumption volumes (as well as imported and exported volumes, if relevant), and then the distribution of these quantities among the origin-destination (zone-to-zone) pairs of the region. These phases are called *generation* and *allocation*, respectively. The last step of the demand-generation process corresponds to the determination of the modal choice specifying the set of modes—type of infrastructure and services—that may move the demand of each product and origin-destination pair. The *assignment* step then determines the actual itineraries used to move the demand for each product, each origin-destination pair, and each mode choice, thus performing the simulation of the global behavior of the system given the particular scenario studied. The last two steps require the definition of the transportation supply in the region, in particular the multimodal infrastructure and service network available to move the demand and its attributes in terms of costs, travel and terminal operation times, energy consumption or level of emissions, etc. The assignment step also requires the specification of the criteria used to select itineraries and to measure performance, as well as the rules to translate volumes of demand of given products into vehicle and convoy utilization for each transportation mode specified in the corresponding mode-choice set.

The actual planning process is rarely linear, however. Thus, for example, many analyses are usually performed on a given set of supply and demand data, both current and forecast, by varying the parameters (e.g., vehicular technology or system utilization policies) of the future scenarios contemplated. On a more general scale, feedback mechanisms are used to modify the parameters of the demand generation steps, including allocation and mode choice, for future scenarios given the simulated performance of the transportation system.

A few demand models are proposed for evaluating the demand for freight movements within urban areas (see Gentile and Vigo [49] for a recent review). Most are descriptive models based on extensive surveys in large cities and economic principles. Thus, *FRETURB*

(Patier [68]) and *WIVER* (Meimbresse and Sonntag [63], Ambrosini and Routhier [1]), currently integrated into *VISEVA* (Friedrich et al. [48]) are based on surveys within major French and German cities, respectively, whereas *GOOD TRIP* (Boerkamps and van Binsbergen [12]) has been developed in The Netherlands. A gravity-based methodology is presented in Gentile and Vigo [49]. The models integrate elements representing the cities topologies and traffic regulations, as well as some representation of the logistics chains and vehicle tours used to move products within major product classes, but not many elements proper to city logistics yet. The supply and assignment aspects are even less developed.

The supply side requires decisions on the number, characteristics, layout, and location of intermodal facilities, CDC, satellites, and so on. The models should also select the city logistics network, e.g., the access corridors and the street networks open to each vehicle type and the determination of the vehicle fleets composition and size. We are aware of only two contributions (Taniguchi et al. [83], Crainic et al. [30]) targeting these important and challenging issues.

The assignment step requires to simulate the behavior of the system under various scenarios relative to the system organization and the social, economic, and regulatory environment. Dynamic traffic simulation, where passenger and other freight vehicles may be considered as well, appears the methodology of choice for such evaluations. City logistics simulators require methods to represent how vehicles and flows would circulate through the city and how the proposed infrastructures services would be used. These are the same models as those that are also required to plan and control operations for an actual system: tactical and, eventually, dynamic routing models. We are aware of only one fully developed contribution (Barceló et al. [8]), where a traffic microsimulator is coupled to a city logistics routing model. This methodology has been used to evaluate city logistics projects for small European cities, but appears difficult to scale for larger urban areas. Mezotraffic simulators (Mahut et al. [61]), addressing larger urban zones, coupled to tactical planning models offer interesting perspectives, but no contribution in this area has yet been made.

City logistics transportation systems rely on consolidation. Tactical planning for consolidation-based transportation systems aims to build a transportation plan to provide for efficient operations and resource utilization, while satisfying the demand for transportation within the quality criteria (e.g., delivery time) publicized or agreed upon with the respective customers (Crainic [24, 25], Crainic and Kim [29]). The same issues must be addressed in a city logistics context, but for a shorter planning horizon, due to the day-to-day demand variability. Tactical planning models for city logistics concern the departure times, routes, and loads of vehicles (urban trucks and city freighters for two-tier systems), the routing of demand, and, when appropriate, the utilization of the satellites and the distribution of work among them. Tactical planning models assist the deployment of resources and the planning of operations and guide the real-time 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. According to the best knowledge of this author, Crainic et al. [31] is the only contribution targeting 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. Although we are not aware of any specific contribution to the first topic, a few papers deal with the second, focusing generally on the operations of a single fleet within a limited part of the city (Taniguchi et al. [82], Thompson [85]). Again, much work is required before city logistics enjoys the same level of methodological richness as the other, more traditional transportation systems.

4. Tactical Planning for Two-Tier City Logistics

To illustrate a number of city logistics issues and operations research responses to the associated challenges, we focus on the tactical planning problem for two-tier systems, also denoted the *day-before planning problem*. Modeling issues are of prime interest. We follow Crainic et al. [31], who provide a more detailed presentation of the topic.

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 resources of the city logistics system, and, of course, the customer requirements in terms of delivery period and conditions.

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.

Given the issues considered and the associated time frame, a number of hypotheses are made. First, the logistics structure and resources of the system are given. Satellites have been established, customers have been assigned to one or several satellites, and corridors for urban trucks have been determined. The types and number of vehicles available and their characteristics are known for both urban trucks and city freighters. Second, most demand is known, and eventual modifications as well as any additional demand are to be handled in "real-time" during actual operations. The characteristics of demand in terms of volume, product type, origin (external zone) and destination (customer), time window at the customer, etc., are also assumed known. Finally, intelligent transportation systems and e-business infrastructures and procedures are implemented, providing the means for traffic-related data collection, efficient exchange of information among participants, and the control of operations (Crainic et al. [28]).

4.1. Notation and General Formulation

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 $t = 1, \ldots, T$ periods. The planning horizon is relatively small, a few hours to a half day in most cases, and thus, each period is relatively small, of the order of the quarter or half hour, for example. To simplify the presentation, we assume that the period is sufficiently short to provide for, at most, one departure of any service from an external zone, and that the unloading times for uran trucks are integer multiples of this period length.

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 $\mathrm{vol}(d)$ of product $p(d) \in \mathcal{P}$ available starting in period $t(d)$ at the external zone $e(d)$, to be delivered to customer $c(d)$ during the time interval $[a(d), b(d)]$. The time required to actually serve (i.e., unload the freight) the customer is denoted $\delta(d)$.

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. Each vehicle has a specific capacity, u_τ for an urban truck of type τ, and u_ν for a city freighter type ν. The fleet dimensions are given by n_τ, $1,\ldots,|\nu|$, and n_ν, $1,\ldots,|n_\nu|$, for each type of urban truck and city freighter, respectively. Some products may use the same type of vehicle but cannot be loaded together (e.g., food and hardware products). We thus define vehicle types that include the identification of the products they may carry. 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) that 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.

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 with 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 subsystem, 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 $\mathcal{G} = \{g\}$.

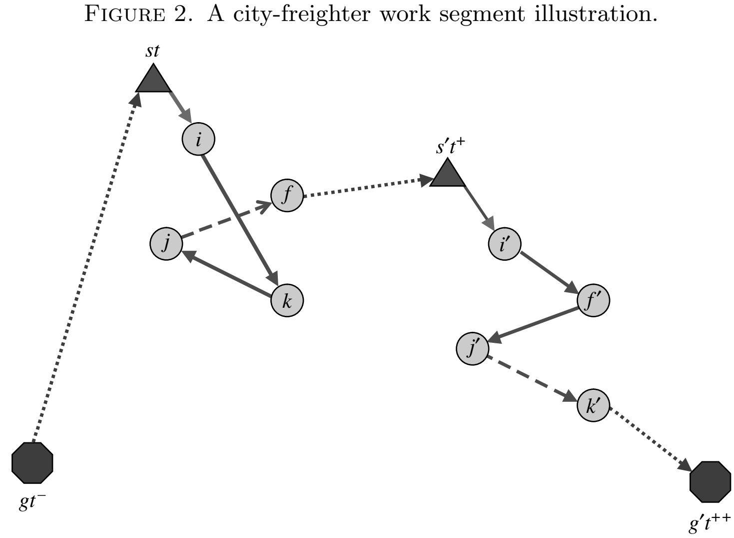
Let $\mathcal{W} = \{w\}$ be the set of feasible work segments for city freighters. A feasible *work segment* $w \in \mathcal{W}(\nu)$ for a city freighter of type $\nu(w) \in \mathcal{V}$, $\mathcal{W} = \bigcup_\nu \mathcal{W}(\nu)$ starts at period $t(w)$ at the first satellite on its route, and visits 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 2 illustrates a two-leg work segment, where $s_1 = s$, and $s_2 = s'$, $s_1, s_2, \in \sigma(w)$, and $\mathcal{C}_1(w) = \{i, k, j, \ldots, f\}$ and $\mathcal{C}_2(w) = \{i', f', j', \ldots, k'\}$. The dashed lines stand for undisplayed customers, whereas the dotted lines indicate the empty arrival from a depot (not included in segment), the empty movement from the last customer demand 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 2). 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* $h \in \mathcal{H}(\nu)$ ($\mathcal{H} = \bigcup_\nu \mathcal{H}(\nu)$).

FIGURE 2. A city-freighter work segment illustration.



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

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. One still has to select how (the itinerary) and when (vehicle departure time) each customer is served, however. Then, to allow for an uniform presentation, we consider that all these itineraries include the service r_0 from the external zone to itself, with 0 travel time. This is equivalent to assuming that each external zone includes a virtual satellite served by a service route r_0.

Three sets of decision variables are defined 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 as not to overload the presentation.

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

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

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

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

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

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

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

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

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

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

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

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

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

The objective function (1) computes the total cost of operating the system as the sum of the costs of the selected urban-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, $\mathcal{R}(s,t) = \{r\in\mathcal{R} \mid s\in\sigma(r)$ and $t_s(r)=t\}$, the set of urban-truck services that stop at satellite s at time t, and $\mathcal{H}(s,t) = \{h\in\mathcal{H} \mid s\in\sigma(w)$ for one $w\in\sigma(h)$ 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.

4.2. Model Variants and Utilization

Tactical planning models may be used in both project-*evaluation* and system-*planning* modes, and the day-before model just presented is no exception. We address this issue in discussing model variants in the following and algorithmic perspectives in the next section.

We focus on the availability and operations of the fleets of urban trucks and city freighters (split-delivery issues are discussed in Crainic et al. [31]). As described in the first sections of this tutorial, 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 mixed-fleet case being rather straightforward. The main difference with the uncontrolled 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), and 0 otherwise,

and capacity

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

and urban-truck work-assignment linking constraints

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

must be added to the model, which would yields 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.

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 to operate. However, 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 §4.1 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 then eliminates 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 it was 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 the satellite and the arrival time at the final customer are then straightforward.

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

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

and the formulation becomes

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

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

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

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

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, the 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, e.g., Barnhart et al. [9], Desrosiers et al. [38], Desaulniers et al. [36, 37]) 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.

4.3. Problem and Formulation Analysis

The formulations introduced in the previous sections 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 multiechelon 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, and long-course maritime liners are examples of consolidation carriers. The goal of the planning process is to determine the transportation, or load, plan and 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 [60], Minoux [64], Balakrishnan et al. [7], Crainic [24]). 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 in, e.g., Christiansen et al. [18, 17] for maritime transportation, Cordeau et al. [22] for rail transportation, Crainic [25] for long-haul transportation, and Crainic and Kim [29] for intermodal transportation.

Vehicle routing problems, however, 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 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 [35]. Similarly to this pioneer contribution, practical applications have prompted many research efforts and significant progress has been achieved in the last 49 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 et al. [11], Bräysy and Gendreau [13, 14], Cordeau et al. [23], Desaulniers et al. [36], Laporte and Semet [58], and the collection of papers in Toth and Vigo [87].

The underlying routing element of the proposed formulations is the series of VRPTW associated with each satellite potentially for all city-freighter types and time periods. Referring to the main model of §4, 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 (§4.2), the urban-truck service design problem may also be cast as a scheduled multidepot 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, multidepot, multiple-tour, heterogeneous vehicle routing problem with time windows* (*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 multiechelon system design and planning (e.g., Ambrosino and Scutellà [2], Pirkul and Jayaraman [71], Verrijdt and de Kok [90]), planning of logistics systems (e.g., Daganzo [34]), cross-dock distribution systems (e.g., Croxton et al. [32], Donaldson et al. [40], Ratliff et al. [73], Wen et al. [92]), and express-courier services (where the time and space scale of the first tier—interurban—is very different from those of the second tier focusing on within-city pickup and delivery activities). Inventories are part of most problem settings of these fields but are 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 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 §5.2 (path-based formulations somewhat understate the issue). They also increase the difficulty of the 2SS-MDMT-VRPTW compared with (and set 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 metaheuristic 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 metaheuristics 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 presents considerable challenges. A few efforts (Feliu et al. [44], Mancini et al. [62]) have begun to be dedicated to the development of heuristics for a simplified version of the problem considering a single period, a single distribution center, and no time elements. Much work is still evidently required. 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. The hierarchical decomposition approach presented in the following section contributes to achieving this goal.

5. Algorithmic Perspectives

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. A hierarchical approach decomposes the global problem according to these two main issues and yields two formulations (see Crainic [31] for details):

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 5.1 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) reposition city freighters at satellites, or depots, for their next assignment within the time restrictions imposed by the synchronization with the urban-truck schedules. Section 5.2 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. In evaluation mode, system-design models that select satellite locations and attributes also determine customer-satellite allocation policies (e.g., Crainic et al. [30]). 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. Historical data, as well as the current status of the system resource availability and transportation demands, may be used to refine the prediction.

The hierarchical approach may be used in single- or multiple-pass settings. The former appears appropriate for a general evaluation of the system. The second should improve the results by iteratively solving the two problems using the results of the city-freighter fleet-management model to adjust the customer-to-satellite assignments and costs. More importantly, the two problems defined by this decomposition should appear as subproblems in most exact or metaheuristic solution methods for the 2SS-MDMT-VRPT.

5.1. The Urban-Truck Service Network Design Model

The goal is to determine 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 is explicitly taken into account, whereas the duration and cost attributes of the final leg, the distribution from satellites to customers, are approximated. The focus is 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.

We start from the general case described in §4.1. 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 delivered 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, whereas 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 with each demand itinerary and urban-truck service is included in their respective definitions.

$$\text{Minimize} \quad \sum_{r\in\mathcal{R}} k(r)\rho(r) + \sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d)} \tilde{c}(d,s,t)\text{vol}(d)\zeta(m) \tag{17}$$

$$\text{subject to} \quad \sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d,\,r)} \text{vol}(d)\zeta(m) \le u_\tau \rho(r) \quad r\in\mathcal{R}, \tag{18}$$

$$\sum_{m\in\mathcal{M}(d)} \zeta(m) = 1 \quad d\in\mathcal{D}, \tag{19}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{r\in\mathcal{R}(s,\,t^-)} \rho(r) \le \pi_s \quad s\in\mathcal{S},\ t=1,\ldots,T, \tag{20}$$

$$\sum_{\nu\in\mathcal{V}} \left[\sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d,\,s,\,t)} \text{vol}(d)\zeta(m)\right] \Big/ u_\nu \le \lambda_s \quad s\in\mathcal{S},\ t=1,\ldots,T, \tag{21}$$

$$\rho(r)\in\{0,1\} \quad r\in\mathcal{R} \tag{22}$$

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

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 (17) that sums up the costs relative to the total number of urban trucks and delivery of demand to customers. Relations (18) enforce the urban-truck capacity restrictions on the selected services. Equations (19) indicate that each demand must be satisfied by a single itinerary. Constraints (20) and (21) enforce the satellite capacity restrictions in terms of urban trucks and city freighters, respectively. The term

$$\sum_{d\in\mathcal{D}} \sum_{m\in\mathcal{M}(d,\,s,\,t)} \text{vol}(d)\zeta(m) \tag{24}$$

in constraints (21) 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 $t_s^{\text{in}}(m) \le t \le t_s^{\text{out}}(m)$).

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 (§5.2) 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 (24) becomes

$$\sum_{d\in\mathcal{C}_{st}^{\nu}} \sum_{m\in\mathcal{M}(d,\,s,\,t)} \text{vol}(d). \tag{25}$$

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 studies indicated in §5. 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 reformulate the problem by defining new variables that account for more than one activity. Time-related aggregations appear appropriate, as in Joborn et al. [55], 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 in Armacost et al. [6], where combinations of services and demands reduced the dimensions of the problem and implicitly accounted for the flow distribution. The last two ideas may be combined, of course.

With respect to solution methods, heuristics will be required for actual applications even if problem dimensions may be reduced. The cycle-based metaheuristics (Ghamlouche et al. [50, 51]), 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 with 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 metaheuristic 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 predefined customer zones are used instead (see the discussion in Crainic et al. [30], 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 (17)–(23), 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 with 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 (§4.2). 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 et al. [70]). The developments for this class of models are recent and few (see, e.g., Andersen et al. [4, 3, 5], Smilowitz et al. [77]), 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.

5.2. City-Freighter Circulation Models

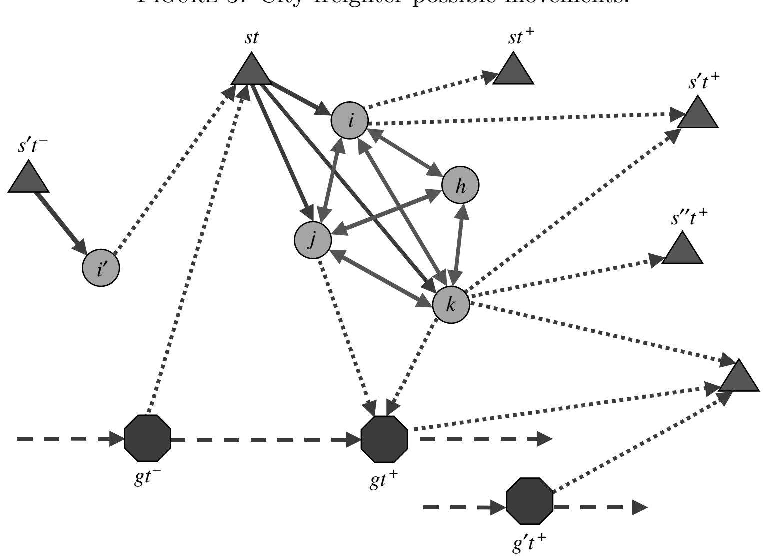
The service design formulation of the preceding section yields workloads for city freighters at satellites. For each satellite, period, and type of city freighter, the workload takes the form of customer demands that have to be served. Once all customer demands are serviced, the city freighters move 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 subsection is the planning of the city-freighter fleet operations, that is, to ensure that city freighters 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 that 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 *rendezvous* points at particular satellites and time periods. We denote this operating mode, apparently seen for the first time in the context of planning city logistics operations, the *synchronized, scheduled, multidepot, multiple-tour, heterogeneous vehicle routing problem with time windows* (*SS-MDMT-VRPTW*).

Formally, the service network design formulation yields 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 $\mathcal{ST}(\nu) \subseteq \mathcal{S} \times \mathcal{T}$ 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 of the designated city freighter and it must be delivered by a single vehicle.

Figure 3 illustrates the dynamics of the system in a somewhat aggregated form, where full and dotted lines denote possible loaded and empty city-freighter movements, respectively. Operations are illustrated starting from a satellite s at time t (node st) for one type of city freighter. Triangles and octagons denote satellites and city-freighter depots, respectively, at various time periods, whereas disks identified with letters i, j, h, and k represent customers in $\mathcal{C}^{\nu}_{st}$ (whereas $i' \in \mathcal{C}^{\nu}_{s't^-}$, $t^- < t$). 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) rendezvous 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) rendezvous 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 3. The restrictions on the time instances that city freighters must arrive at satellites and customers determine the actual feasible movements.

FIGURE 3. City-freighter possible movements.



The city-freighter SS-MDMT-VRPTW formulation is thus 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 metaheuristic 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 with each (satellite, time period) rendezvous 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 with 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

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

- 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, $a(d) \le t + \delta_{sd}(t) \le b(d)$, 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 3, $\mathcal{A}^{SD}_{st}(\nu) = \{(st,i), (st,j), (st,k)\}$.
- 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 $t' - \delta(\nu) \le T$ such that city freighters may be loaded and leave by time t': $a(d) \le t' - \delta(\nu) - \delta(d) - \delta_{ds'}(t) \le b(d)$. In Figure 3, $\mathcal{A}^{DS}_{st}(i,\nu) = \{(i, st^{+}), (i, s't^{+})\}$, for example.
- We may now define the backstar of node st with respect to customer demands as the set $\mathcal{A}^{S-}_{st}(\nu) = \{(d, st) \mid d \in \mathcal{C}^{\nu}_{s't^{-}},\, s't' \in \mathcal{ST}(\nu),\, t' < t,\, a(d) \le t - \delta(\nu) - \delta(d) - \delta_{ds}(t') \le b(d)\}$, $\nu \in \mathcal{V}$. Arc (i', st) of Figure 3 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 3, $\mathcal{A}^{G-}_{st}(\nu) = \{(gt^{-}, st)\}$.

From a depot point of view, the same arcs are grouped into the sets $\mathcal{A}^{GS}_{gt}(\nu) = \{(gt, s't') \mid s't' \in \mathcal{ST}(\nu),\, t + \delta_{gs}(t) = t' - \delta(\nu)\}$, $g \in \mathcal{G}$, $t = 0, \ldots, T$ (initial movements out of depots to start service at satellites at $t = 1$ take place arbitrarily at $t = 0$). Set $\mathcal{A}^{GS}_{gt^{-}}(\nu) = \{(gt^{-}, st)\}$ illustrates this definition in Figure 3.

- 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 $b(d) + \delta(d) + \delta_{dj}(t) \le b_j$ (plus $a_j \le a(d) + \delta(d) + \delta_{dj}(t)$ 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, whereas 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 3, $\mathcal{A}^{DD}_{st}(i,\nu) = \{(i,j), (i,k), (i,h)\}$ 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 3, $\mathcal{A}^{DG}_{st}(k,\nu) = \{(k, gt^+)\}$.

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

Referring to the notation introduced in §4, 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 $\mathcal{ST}(\nu)$ rendezvous points. In particular, sets of visited satellites are restricted to $\sigma(w) = \{s_l \in \mathcal{S}, l = 1, \ldots, |\sigma(w)| \mid t_l(w) < t_{l+1}(w)$ 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 §4. The general model (1)–(10) then reduces to the following path-based formulation of the city-freighter SS-MDMT-VRPTW:

$$\text{Minimize} \quad \sum_{h \in \mathcal{H}} k(h)\varphi(h) \tag{26}$$

$$\text{subject to} \quad \sum_{d \in \mathcal{C}^\nu_{st}} \alpha_{st}(h,d)\mathrm{vol}(d) \leq u_\nu \varphi(h) \quad (s,t) \in \sigma(w),\ \ w \in \sigma(h),\ \ h \in \mathcal{H}, \tag{27}$$

$$\sum_{h \in \mathcal{H}(\nu)} \alpha_{st}(h,d)\varphi(h) = 1 \quad d \in \mathcal{C}^\nu_{st},\ \ (s,t) \in \mathcal{ST}(\nu), \tag{28}$$

$$\sum_{t^- = t - \delta(\tau)+1}^{t} \sum_{h \in \mathcal{H}} h(s, t^-)\varphi(h) \leq \lambda_s \quad s \in \mathcal{S},\ \ t = 1, \ldots, T, \tag{29}$$

$$\sum_{h \in \mathcal{H}(\nu)} \varphi(h) \leq n_\nu \quad \nu \in \mathcal{V}, \tag{30}$$

$$\varphi(h) \in \{0,1\} \quad h \in \mathcal{H}. \tag{31}$$

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 with 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 rendezvous 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 $\bar{\mathcal{A}} = \mathcal{A} \backslash \mathcal{A}^G$, 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 with 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 with operating a city freighter of type ν at a satellite.

Two types of decision variables are defined:

- Flow variables $\theta^\nu_\phi(i,j)$, $(i,j) \in \mathcal{A}$, $\phi = 1, \ldots, n_\nu$, $\nu \in \mathcal{V}$, which equal 1 if arc (i,j) is used by the city freighter ϕ of type ν, and 0 otherwise;

- Time variables $\omega^{\nu}_{\phi}(i)$, $i \in \mathcal{N}$, $\phi = 1, \ldots, n_{\nu}$, $\nu \in \mathcal{V}$, 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 as follows:

$$\text{Minimize} \sum_{\nu \in \mathcal{V}} \sum_{\phi=1}^{n_{\nu}} \left[\sum_{(i,j) \in \bar{\mathcal{A}}} k_{\nu}(i,j) \theta^{\nu}_{\phi}(i,j) + k_{\nu} \sum_{(s,t) \in \mathcal{ST}(\nu)} \sum_{d \in \mathcal{C}^{\nu}_{st}} \theta^{\nu}_{\phi}(s,d) \right] \tag{32}$$

subject to

$$l_{st}(\nu) \le \sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d) \le u_{st}(\nu) \quad (s,t) \in \mathcal{ST}(\nu), \;\; \nu \in \mathcal{V}, \tag{33}$$

$$\sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d) \le 1 \quad (s,t) \in \mathcal{ST}(\nu), \;\; \phi = 1, \ldots, n_{\nu}, \;\; \forall \nu \in \mathcal{V}, \tag{34}$$

$$\sum_{\phi} \left[\sum_{(d,i) \in \mathcal{A}^{DD}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,i) + \sum_{(d,s't') \in \mathcal{A}^{DS}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,s') + \sum_{(d,g) \in \mathcal{A}^{DG}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,g) \right] = 1$$
$$d \in \mathcal{C}^{\nu}_{st}, \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \nu \in \mathcal{V}, \tag{35}$$

$$\sum_{\phi} \left[\theta^{\nu}_{\phi}(s,d) + \sum_{(i,d) \in \mathcal{A}^{D-}_{st}(d,\nu)} \theta^{\nu}_{\phi}(i,d) \right] = 1 \quad d \in \mathcal{C}^{\nu}_{st}, \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \nu \in \mathcal{V}, \tag{36}$$

$$\sum_{(gt',st) \in \mathcal{A}^{G-}_{st}(\nu)} \theta^{\nu}_{\phi}(g,s) + \sum_{(d,st) \in \mathcal{A}^{S-}_{st}(\nu)} \theta^{\nu}_{\phi}(d,s) = \sum_{(st,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d)$$
$$(s,t) \in \mathcal{ST}(\nu), \;\; g \in \mathcal{G}, \;\; \phi = 1, \ldots, n_{\nu}, \;\; \nu \in \mathcal{V}, \tag{37}$$

$$\sum_{\phi} \left[\theta^{\nu}_{\phi}(g(t-1), g(t)) + \sum_{(d,g) \in \mathcal{A}^{DG}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,g) \right] \tag{38}$$

$$= \sum_{\phi} \left[\theta^{\nu}_{\phi}(g(t), g(t+1)) + \sum_{(g,s) \in \mathcal{A}^{GS}_{gt}(\nu)} \theta^{\nu}_{\phi}(g,s) \right] \quad g \in \mathcal{G}, \;\; \nu \in \mathcal{V}, \;\; t = 1, \ldots, T \tag{39}$$

$$\sum_{d \in \mathcal{C}^{\nu}_{st}} \mathrm{vol}(d) \theta^{\nu}_{\phi}(s,d) + \sum_{(i,j) \in \mathcal{C}^{\nu}_{st}} \mathrm{vol}(j) \theta^{\nu}_{\phi}(i,j) \le u_{\nu}$$
$$\phi = 1, \ldots, n_{\nu}, \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \nu \in \mathcal{V}, \tag{40}$$

$$\omega^{\nu}_{\phi}(i) + \delta(i) + \delta_{ij}(t) - \omega^{\nu}_{\phi}(j) \le (1 - \theta^{\nu}_{\phi}(i,j))(b_i + \delta(i) + \delta_{ij}(t) - a_j)$$
$$\phi = 1, \ldots, n_{\nu}, \;\; (i,j) \in \mathcal{A}^{DD}_{st}(i,\nu), \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \nu \in \mathcal{V}, \tag{41}$$

$$a(d) \left[\theta^{\nu}_{\phi}(s,d) + \sum_{(i,d) \in \mathcal{A}^{D-}_{st}(d,\nu)} \theta^{\nu}_{\phi}(i,d) \right]$$
$$\le \omega^{\nu}_{\phi}(d) \le b(d) \left[\sum_{(d,i) \in \mathcal{A}^{DD}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,i) + \sum_{(d,s't') \in \mathcal{A}^{DS}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,s') + \sum_{(d,g) \in \mathcal{A}^{DG}_{st}(d,\nu)} \theta^{\nu}_{\phi}(d,g) \right]$$
$$d \in \mathcal{C}^{\nu}_{st}, \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \phi = 1, \ldots, n_{\nu}, \;\; \nu \in \mathcal{V}, \tag{42}$$

$$\omega^{\nu}_{\phi}(st) = t - \delta(\nu) \sum_{(s,d) \in \mathcal{A}^{SD}_{st}(\nu)} \theta^{\nu}_{\phi}(s,d) \quad (s,t) \in \mathcal{ST}(\nu), \;\; \phi = 1, \ldots, n_{\nu}, \;\; \nu \in \mathcal{V}, \tag{43}$$

$$(\omega^{\nu}_{\phi}(d) + \delta(d) + \delta_{ds}(t') - \omega^{\nu}_{\phi}(st)) = (1 - \theta^{\nu}_{\phi}(d,s))(\omega^{\nu}_{\phi}(d) + \delta(d) + \delta_{ds}(t') - \omega^{\nu}_{\phi}(st))$$
$$(d,s) \in \mathcal{A}^{S-}_{st}(\nu), \;\; (s,t) \in \mathcal{ST}(\nu), \;\; \phi = 1, \ldots, n_{\nu}, \;\; \nu \in \mathcal{V}, \tag{44}$$

$$(\omega_\phi^\nu(gt') + \delta_{gs}(t') - \omega_\phi^\nu(st)) = (1 - \theta_\phi^\nu(g,s))(\omega_\phi^\nu(gt') + \delta_{gs}(t') - \omega_\phi^\nu(st))$$
$$(g,s) \in \mathcal{A}_{st}^{G-}(\nu),\ (s,t) \in \mathcal{ST}(\nu),\ \phi = 1,\ldots,n_\nu,\ \nu \in \mathcal{V}, \quad (45)$$

$$(\omega_\phi^\nu(st) + \delta(\nu) + \delta_{sd}(t) - \omega_\phi^\nu(d)) = (1 - \theta_\phi^\nu(s,d))(\omega_\phi^\nu(st) + \delta(\nu) + \delta_{sd}(t) - \omega_\phi^\nu(d))$$
$$(s,d) \in \mathcal{A}_{st}^{SD}(\nu),\ (s,t) \in \mathcal{ST}(\nu),\ \phi = 1,\ldots,n_\nu,\ \nu \in \mathcal{V}, \quad (46)$$

$$\theta_\phi^\nu(i,j) \in \{0,1\} \quad (i,j) \in \mathcal{A},\ \phi = 1,\ldots,n_\nu,\ \forall \nu \in \mathcal{V}. \quad (47)$$

The objective function (32) 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 §5.1 assigns, for each city-freighter type, customer demands $\mathcal{C}_{st}^\nu$ to each (satellite, time period) rendezvous 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., $l_{st}(\nu) = \sum_{d \in \mathcal{C}_{st}^\nu} \mathrm{vol}(d)/u_\nu$ and $u_{st}(\nu) = \min\{|\mathcal{C}_{st}^\nu|, n_\nu\}$). Constraints (33) enforce these restrictions.

Constraints (34) ensure that each vehicle leaving a satellite goes to one customer only, whereas constraints (35) 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 $\mathcal{C}_{st}^\nu$, a satellite, or a depot. These two sets of constraints, together with (36), 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 rendezvous point of a city-freighter type is completed by Equations (37). Equations (38) represent the conservation of flow at depots. Relations (40) enforce the restrictions on the city-freighter capacities, each time a vehicle leaves a (satellite, time period) rendezvous point to deliver customer demands.

Constraints (41) and (42) enforce schedule feasibility with respect to the service time consideration for movements between customers. Service must start within the time windows associated with the customer demand, but no restrictions are imposed on when the vehicle actually arrives (so-called soft time windows).

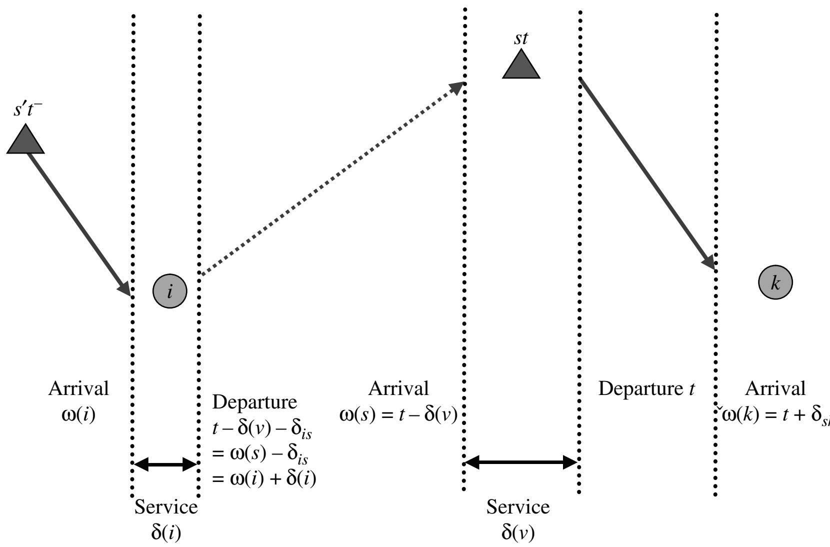
Constraints (43)–(46) impose the synchronization of city-freighter arrivals at the (satellite, time period) rendezvous points, characteristic of SS-MDMT-VRPTW. Constraints (43) specify the time service must start at the satellite. In practice, there is a small interval of arrival feasibility, δ, which transforms the constraint into

$$(t - \delta(\nu) - \delta) \sum_{(s,d) \in \mathcal{A}_{st}^{SD}(\nu)} \theta_\phi^\nu(s,d) \le \omega_\phi^\nu(st) \le t - \delta(\nu) \sum_{(s,d) \in \mathcal{A}_{st}^{SD}(\nu)} \theta_\phi^\nu(s,d)$$
$$(s,t) \in \mathcal{ST}(\nu),\ \phi = 1,\ldots,n_\nu,\ \nu \in \mathcal{V}. \quad (48)$$

Given the service starting time at the satellite, constraints (44) and (45) impose the departure time t' from the previous customer or depot, respectively. Similarly, constraints (46) impose the arrival time to the first customer demand out of the (satellite, time period) rendezvous point. Figure 4 illustrates constraints (43), (44), and (46). Finally, conditions (47) impose binary values on the flow variables.

We have elaborated in §4.3 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 §4.3 provide reasons, however, to be confident in our capabilities to develop appropriate metaheuristics 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

FIGURE 4. City-freighter synchronization requirements.



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 (Cordeau et al. [21]) and the cooperative search (Le Bouthillier et al. [59]) methods illustrate this trend.

Such methods would be particularly required for planning activities of in-function systems, as is the formulation (32)–(47), 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.

A simpler approximation scheme that takes advantage of the context and characteristics of the problem can be proposed. The general idea is based on decomposing the problem at the (satellite, time period) rendezvous 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 proceeds in two phases:

1. *Routing.* Solve *independently* each 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 rendezvous times $1 \le t \le T$.
2. *Circulation.* Solve the problem of moving city freighters among activities at (satellite, time period) rendezvous 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 §5.1 yields the sets $\mathcal{C}_{st}^{\nu}$ associated with the $(s,t) \in \mathcal{ST}(\nu)$ rendezvous 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 with each (satellite, time period) rendezvous point and is bounded by $|\mathcal{ST}(\nu)|\,|\mathcal{V}|$. The size of each problem is relatively small, however, with 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 metaheuristics 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) rendezvous 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 $\mathcal{C}^\nu_{st}$, $(s,t) \in \mathcal{ST}(\nu)$. Let $\Delta^\nu_\phi(st)$ and $k^\nu_\phi(st)$, $\phi = 1, \ldots, F_\nu(st)$ represent the duration and cost of route ϕ, respectively, and $d(st_\phi)$ denote the last customer demand served by the route. Then, $t + \Delta^\nu_\phi(st)$ represents the moment the city freighter on route ϕ becomes available for repositioning 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. Details are given in Crainic et al. [31].

6. 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 with these activities, 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 tutorial, we presented an overview of city logistics concepts, issues, and challenges, focusing on the models and methods required to evaluate city logistics systems and plan their activities. The field is young and evolving rapidly. This tutorial is thus also an invitation to join in the efforts to develop these models and methods and help in making our transportation systems more efficient and our cities more pleasant to live in.

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