City Logistics

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1 Introduction

The political, economic, and social evolution of society challenges transportation and logistics with new objectives, challenges, and constraints. Efficiency of operations, consistently bringing freight at the designated destination, within the agreed upon time, at the lowest possible cost and with the highest possible quality of service is still, of course, a major goal, as are the profitability of the firms and the economic development of the cities, regions, and countries involved. Increasingly, however, the long-term sustainability of the industry and the society it supports is challenged by citizens and governments alike, bringing into focus the need to reduce the negative externalities of transportation and logistics, in particular, the high levels of congestion in many cities and regions of the world, the environmental damage through emissions and consumption of fossil fuels, and the safety and security of the people. A number of new organization and business models have been proposed to address these issues and aim to conciliate, better still, to jointly ”optimize” the economic and social goals of transportation and logistics. City Logistics, the Physical Internet, and their recent combination into Hyperconnected City Logistics, belong to this group. They also share a number of fundamental characteristics, including multi and intermodality, cooperation among stakeholders, consolidation, synchronization of operations, resource sharing, and the separation of commercial

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transactions generating cargo movements from the planning and execution of the corresponding activities, the degree and way of inclusion of each defining variants and applications.

We focus on *City Logistics* in this chapter, as it has a history going back to the 90's and has generated a good number of studies, implementations, and discussions on success and failure factors. In fact, even though not all proposals and implementations were successful, the City Logistics concepts and proposals are influencing the development and deployment of urban freight transportation and logistics systems. It influences national policy in several countries in Europe and Asia, brings new systems to several cities around the world, and is the source of new forms of private distribution networks (e.g., last-mile service providers, express couriers, and large retail chains).

In its most fundamental meaning, City Logistics aims to reduce the externalities and nuisances, e.g., emissions and, more generally, the environmental footprint, associated to the transportation of freight within urban areas, while sustaining the social and economic development of the organizations and cities involved. City Logistics encompasses several dimensions, and may target demand estimation or the design and organization of the supply activities servicing it. City Logistics studies may focus on a single organization or on several organizations interacting in a city.

The operations research-based research and development of models and methods to support the planning and management of City Logistics systems really got started in the first years of the millennium and it is steadily growing ever since. Network design is one the main methodologies used in this context, the particular settings and characteristics of City Logistics systems bringing modeling challenges and conducting to new formulations, e.g., several layers of facilities and operations, time-dependency of demand and activities, synchronization of fleets at terminals, integration of private and public transportation and logistic means, and combining network design and vehicle routing, to name but a few. It appears that network design models for City Logistics are mainly directed at the strategic and tactical planning of the system. This chapter aims to capture these characteristics and present the network design methodology currently available.

The chapter is organized as follows. Section 2 recalls the two-tier City Logistics setting we use this chapter to describe issues and models, together with the tactical and strategic planning issues that call for network design methodologies. Section 3 proposes a general scheduled service network design modeling framework for strategic and tactical planning of City Logistics systems. Section 4 then focuses on how one may use the modeling framework, as well as a number of important problem and model variants, including the connection to multi-echelon routing, the representation of delivery and pickup operations and costs, the selection of particular corridors or infrastructures, and the explicit consideration of uncertainty. Bibliographical notes are the topic of Section 5, recalling the historic developments and the main contributions to the field. We discuss perspectives for other new transportation concepts proposed, identify a number of challenging research avenues, and conclude in Section 6

2 City Logistics, Planning, and Design

We describe a “general” *Two-Tier City Logistics*, *2T-CL*, system setting in Section 2.1, which includes the most important characteristics found in literature and practice, even though not all characteristics are currently found within the same systems. We use the 2T-CL setting to illustrate City Logistics planning issues and models.

Two-tier systems have been proposed both for single organizations and for multiple organizations, e.g., carriers and other service providers, operating in (parts of) cities under some form of cooperation and resource sharing. We therefore assume in this chapter that the 2T-CL system is planned and managed by a single manager/decision maker, even though resources may be provided and operated by several private and public stakeholders involved in some form of cost/profit/risk-sharing collaboration. We discuss a number of possible modeling consequences of such collaborations in Section 5.

2T-CL are consolidation-based systems involving multiple resources in complex interactions, and thus require advanced planning methods, particularly at the tactical and strategic levels where system-wide decisions are made for medium to long-term planning horizons. These planning issues are recalled in Section 2.2.

2.1 A two-tier setting

Figure 1 illustrates the structure of a 2T-CL system that, similar to any transportation system, 2T-CL has a demand and a supply component. The latter, composed of facilities and the transportation modes and services moving freight among them and customers, is designed and planned to answer the requests of the former according to some performance criteria. In particular, a 2T-CL system aims to satisfy demand and contribute to the sustainable development of the city, that is, to deliver goods from origins to destinations, on time, economically in monetary terms, and efficiently from the societal point of view of the impact on the city. This impact accounts for the street or neighborhood characteristics, e.g., touristic, residential, social (schools, hospitals, leisure, culture, etc.), administrative, etc., and can be defined in terms of emissions, noise, visual degradation, contribution to congestion, and so on. The particular measures considered, as well as their estimation processes, are application specific. While multi-objective optimization may be used to reflect these different measures, economic and impact measures are often combined for planning purposes into a *transportation* or *city-infrastructure-utilization cost* associated to the network representation used in the model. This is the approached used in this chapter.

In all generality, the customers of a City Logistics system are all the firms, organizations, institutions, and private citizens that ship or receive freight through the system. For planning purposes, particularly at tactical and strategic levels, the many possible external origins and destinations of such shipments are aggregated into a number of *external zones* (ellipse disks in Figure 1), connected to the city by various transportation modes. Similarly, locations within the city are aggregated into

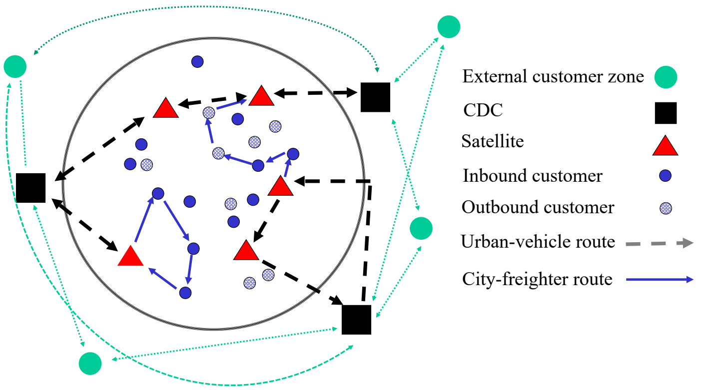

Fig. 1 Two-tier City Logistics Structure

customer-demand zones, referred to as *customer zones* in the following and represented by circular disks in Figure 1.

The *demand* side of the system thus consists of a set of freight loads that need to be moved between particular pairs of customer and external zones. Three types of demand may be identified. *Inbound demand* is to be delivered from external-zone origins to customers in the city. Symmetrically, *outbound demand* is to be picked up at customers in the city, and then be shipped to specified external-zone destinations. *Local demand* is to be picked up from a customer within the city and delivered to another customer within the city. Each individual origin-destination (*OD*) demand is characterized by a volume to be moved and time-related features, e.g., its *availability* time representing when the demand would enter the system and could start to be handled, as well as delivery and pick-up *time windows* at customers (locations within the city). More than one physical product is generally handled. To simplify the presentation, but without loss of generality, we assume that the 2T-CL system makes use of smart containers, as those developed within the Physical Internet initiatives, which can be loaded together irrespective of their content; such boxes are referred to as π*-containers* (Montreuil, 2011). In modeling terms, this yields problems that are single product, the loading container, but multicommodity in the OD demand treated.

The supply side of a 2T-CL system consists of two layers of terminals and the transportation means linking them and the customer and external zones. *City distribution centers* (*CDC*s) are generally located at the border of the city, close to main interurban transportation infrastructures or intermodal facilities. Inbound and outbound loads are sorted and consolidated at CDCs for distribution into the city or long-haul transportation to external zones destinations. Consolidated inbound demand is shipped, using *urban vehicles*, to intermediary facilities called *satellites* located close to the parts of the city where traffic is controlled and certain vehicle types, e.g., large trucks, are not allowed to penetrate. It is at satellites, illustrated through triangles in Figure 1, that the junction between first and second-tier vehicles takes place, freight being generally transferred between synchronized vehicles according to transdock principles, with little or no temporary storage. *City freighters*, second-tier vehicles, bring inbound freight from satellites to customers, and pick up outbound and local freight at customers delivering it to satellites and destination customers, respectively. The outbound loads brought to a satellite at the ”same” time by several city freighters are loaded into urban vehicles to be moved to the appropriate CDC from where the goods are shipped to their final external zones. First and second-tier vehicles carrying inbound or outbound cargo could thus be present simultaneously at a satellite, competing for the capacity it offers for vehicle docking, parking, and cargo transfer.

Several modes and vehicles types make up the *multi/intermodal transportation system* (π-containers make the system intermodal) connecting the facilities and the customers. City freighters, operating at the second tier, may be small vans, eco-friendly electric or hydrogen small vans, traditional or cargo bikes, canal or river barges, individuals using their own cars, etc. The spectrum of possible modes is even larger on the first tier as, increasingly, the utilization of what may be described as massive-flow modes and vehicles, e.g., regular and light rail, is contemplated or tested. We distinguish between *line-based* and *no-line* transportation modes and services. The latter include the various trucks and barges for which one may define services along any path within their admissible network (e.g., a city “trucking network” is often defined to restrict circulation). Line-based modes are often captive of particular infrastructure, such as passenger buses, which are “captive” of their predefined lines, regular and light rail (tramways, subways, etc.) captive of their tracks, and trolleybuses captive of their aerial power lines. This characteristic restricts the definition of line-based services to the network of the corresponding infrastructure, but not necessarily to the service lines and stops operated for passengers. Two main approaches for line-based services are being contemplated within City Logistics projects around the world. On the one hand, regular vehicles may be equipped with special compartments for the transportation of goods while, on the other hand, freight-dedicated vehicles may be operated on the same infrastructure, either independently or as parts of regular convoys.

When different demand types, inbound, outbound, local, may be loaded into urban vehicles and city freighters, loading/unloading rules must be defined. To keep the presentation simple, we assume in the following a *pseudo-backhaul* policy, which means that a vehicle completes the current type of activity before initiating a different one. Thus, for example, a vehicle may leave the depot, perform a sequence of pickup and delivery activity for local demand, and then move to a satellite to synchronize with arriving first-tier urban vehicles and load for a delivery phase of inbound demand. This policy is based on the idea that operations at satellites and customers should be streamlined. Indeed, capacity, time-window, and synchronization restrictions and requirements, as well as the goal of reducing the presence of vehicles in the city, implies efficient vehicle unloading and loading activities, which makes searching for and resorting of loads undesirable.

2.2 Planning and design

City Logistics belongs to the important class of consolidation-based transportation systems that include rail and less-than-truckload carriers, high-sea navigation lines, intermodal systems, postal services, and so on. Such complex systems require planning at all levels. We briefly recall the issues associated to tactical and strategic planning, as this is where the interactions with network design are the strongest.

Tactical planning for consolidation freight carriers aims to select and schedule services, together with the itineraries used to move freight flows from origins to destinations in the resulting service network. The goal is to satisfy the regular demand in the most cost- and resource-utilization efficient way possible, while satisfying the service-quality levels set by the carrier to answer customer requirements. The tactical plan is thus also generally yielding activity profiles of terminals and the resources required to support the selected services. The service network and plan is determined for a rather short period called *schedule length*, e.g., a day or a week, and it is then repeatedly applied over a certain medium-term planning horizon, the *season*, e.g., six months. Note that this decision process assumes that the major elements of the plan, the demand, selected scheduled services, and main resource assignments to services and terminals, will not be modified during regular operations for the length of the planning horizon. Adjustments of the plan to actual demand are then mostly performed through modifications to the routing of demand flows at operation time.

In City Logistics terms, tactical planning targets the regular demand and is about selecting the services and resources that will be operated regularly and repeatedly. In this sense, first-tier service operations should be more stable, particularly for line-based services, as they move larger loads between CDCs and satellites. With this regularity comes the regularity in using the terminal facilities and assigning customers to satellites, while the actual routing may vary from day to day according to the particular demand. The goal is to determine the most cost-effective plan to satisfy forecast demands with the available resources, where the generalized transportation costs account for operations-related costs and city-impact considerations. With such a plan, material and human resources can be allocated for the duration of the planning horizon, which makes management easier and lowers costs.

Strategic planning generally addresses longer-term decisions than tactical ones, with impacts normally valid for years. Setting up a City Logistics system within a given city or part thereof is certainly strategic in nature, as well as the associated decisions on zones covered, partnerships, network and service type (e.g., single or two-tier), legal and financial framework, etc. Most of these issues are generally not of an Operations Research type. Yet, they may be, and hopefully are supported by Operations Research models providing quantitative evaluations and analyses of contemplated systems and policies. Network design is at the core of such methodologies. On the one hand, tactical-planning models provide performance-evaluation tools for contemplated or existing City Logistics system and policy designs. On the other hand, network design models may be built to answer strategic-level decisions such as the number, locations, and characteristics of facilities, CDCs and satellites to built or select, the construction of dedicated infrastructure or the connection of the City Logistics facilities to public transport infrastructure and services, the types of vehicles to use and the dimensions of the fleets, etc.

In the next section, we present a general scheduled service network design model, incorporating the main tactical-planning issues previously discussed. We then discuss specializations and extensions able to address particular settings of the tactical and strategic planning problems.

3 A General SSND Modeling Framework

Scheduled service network design (*SSND*) formulations defined over time-space networks are generally used to model tactical planning problems for consolidation-based freight carriers (Chapter 12). We present in this section a general SSND model for the tactical planning of the 2T-CL system described in Section 2.1, addressing the activities at both tiers and their synchronization at satellites, for a time-dependent demand. This path-based SSND formulation thus addresses the main issues of 1) selecting a subset of scheduled services out of the set of possible line- and no-line-based multimodal services; 2) building the multi-tour routes of the second-tier city freighters, 3) determining the itineraries of each demand through the selected City Logistics service network, including the assignment to a CDC and a satellite for inbound and outbound demands; and 4) managing the terminals and the multimodal fleets of urban vehicles and city freighters, which connect and synchronize at satellites. The optimization is performed for a given schedule length, City Logistics infrastructure, potential first and second-tier services, and a deterministic estimation of demand, travel times, and activity times at facilities and customers. The formulation thus combines characteristics of classical SSND models (Chapter 12) and multi-attribute vehicle routing formulations. The goal is to minimize a total generalized cost, reflecting both the economics of operating the system and the potential impact on the city, while satisfying demand. The resulting service plan is supposed to be used repeatedly over a certain planning horizon (Section 4).

In a City Logistics context, the schedule length is relatively short, from a few hours to half a day and, thus, each of its $t = 1,\dots,T$ periods is also relatively short. To simplify the presentation, we assume that the length of any activity, vehicle movement or terminal operation, is an integer number of periods. The external and customer zones defining demand, as well as the CDC and satellite locations are modeled as nodes connected through modal arcs within a physical network representing the 2T-CL system. The scheduled service network design model is built on a time-space network, where the physical nodes are duplicated at all relevant time periods (customer-related nodes are not represented outside the corresponding temporal attributes). This yields the set of nodes $\mathscr{N}$ encompassing the sets $\mathscr{E}$ (external zones), $\mathscr{C}$ (customer zones), $\mathscr{F}$ (CDCs), and $\mathscr{Z}$ (satellites). A set of links $\mathscr{A} = \{a = (i,j)\}$ representing the modal transportation and terminal-holding activities connecting these nodes completes the network representation $\mathscr{G} = (\mathscr{A},\mathscr{N})$.

Movements are performed by vehicles of different types and modes. Let $\mathscr{M}$ be the set of transportation modes and $\mathscr{T}_m$ and $\mathscr{V}_m$ the sets of urban-vehicle and city-freighter types, respectively, for mode $m \in \mathscr{M}$; the respective vehicle capacities are $u_\tau,\ \tau \in \mathscr{T}_m$ and $u_\nu,\ \nu \in \mathscr{V}_m$. Let $n_{f\tau}$ be the fleet size of urban-vehicle type τ at CDC $f \in \mathscr{F}$, and n_ν the fleet size of city-freighter type ν at the second tier garage.

In most cases, city distribution centers are large facilities, where capacity issues are not critical and sufficient space is available for vehicles to wait for loading and unloading activities. This is, however, not the case for satellites, where the space available for transferring goods limits the number of urban vehicles and city freighters which can be present simultaneously. Furthermore, there is generally no space available for storing goods at satellites, nor for vehicles to wait. The satellite capacity may also be time dependent, due to either opening hours or operations on a shared infrastructure. For example, a passenger tramway cannot wait longer than "normal" at a station because of unloading or loading activities of another tramway with freight somewhere down the line. Several capacity measures account for these limitations for each satellite z and must be enforced at each period: 1) u_z^{T} for the total number of urban vehicles it may accommodate, with $u_{z\tau}^{\mathrm{T}}$ for the number of urban vehicles of type τ of mode m it may accommodate; for no-line modes, this is the actual number of vehicles, while for line-based modes (e.g., tramways) it is the number of available tracks (but could also be the number of cars in a convoy); 2) u_z^{V} for the total number of city freighters it may accommodate; 3) u_z^{K} for the total volume of goods the satellite may handle.

Inbound, outbound, and local requests for transportation make up the demand of the system. When the same customer location is both the origin and the destination of demand, separate nodes are created, the respective demands being then treated individually within the model. Each customer demand $k \in \mathscr{K}$ is defined between a pair $(O(k),D(k))$ of origin - destination nodes in $\mathscr{N}$, where $(O(k) \in \mathscr{E}$ and $D(k) \in \mathscr{C})$ for inbound demand, $(O(k) \in \mathscr{C}$ and $D(k) \in \mathscr{E})$ for outbound, and $(O(k),\ D(k) \in \mathscr{C})$ for local. A volume $d(k)$ is to be moved between these nodes. Time attributes specify when the volume is available at origin, $[a(O(k)),\ b(O(k))]$ and must be delivered at destination $[a(D(k)),\ b(D(k))]$ (some time windows might not be bidding). External zones, the out-of-city origins and destinations, are linked by various transportation modes to the city and the CDCs. The CDC to be used by each demand is to be selected by the model. Let $\mathscr{F}(k) \subseteq \mathscr{F}$ be the set of potential CDCs that may be used for demand k, and $c_{ft}(k)$ the cost of assigning demand k to CDC $f \in \mathscr{F}(d)$ at time t (it could account, e.g., for using another CDC rather than the closest one, using inter-CDC transportation or short-term storage).

Let $\Sigma = \{\sigma\}$ be the set of potential urban-vehicle *services*. Service σ operates a vehicle of type $\tau(\sigma)$, originates at CDC $O(\sigma)$, travels to one or several satellites $\mathscr{Z}(\sigma)$, and returns to CDC $D(\sigma)$, possibly different from $O(\sigma)$ (this may be the case even for line-based modes, when the line connects two CDCs). The urban-vehicle route is thus composed of a series of *legs*, from the CDC to the first satellite, from the latter to the second one, until the last leg from the last satellite to the destination CDC. Let $\mathscr{L}(\sigma)$ be the set of these legs. The schedule of service σ is given by $t(\sigma)$, the departure time from $O(\sigma)$, as well as by the arrival and departure times at all the

Table 1 Main notation of the SSND model

$\mathscr{G} = (\mathscr{N}, \mathscr{A})$	Time-space network for a schedule length of T periods
$\mathscr{E} = \{e\}; \mathscr{C} = \{c\}$	Sets of external & customer zones
$\mathscr{F} = \{f\};\ \mathscr{Z} = \{z\}$	Sets of facilities, CDCs & satellites
$\mathscr{M} = \{m\}$	Set of transportation modes
$\mathscr{T}_m = \{\tau\}; \mathscr{V}_m = \{\nu\}$	Sets of urban vehicles & city-freighter types of mode $m \in \mathscr{M}$
u_τ	Capacity of urban vehicle type $\tau \in \mathscr{T}_m$, $m \in \mathscr{M}$
$n_{f\tau}$	Fleet size of urban-vehicle type $\tau \in \mathscr{T}_m$, $m \in \mathscr{M}$, at CDC $f \in \mathscr{F}$
u_ν	Capacity of city-freighter type $\nu \in \mathscr{V}_m$, $m \in \mathscr{M}$
n_ν	Fleet size of city-freighter type $\nu \in \mathscr{V}_m, m \in \mathscr{M}$ at the second tier garage
u_z^{T}	Satellite z total capacity in number of urban vehicles of all types
$u_{z\tau}^{\mathrm{T}}$	Satellite z capacity in number of urban vehicles / tracks of type τ
u_z^{V}	Satellite z capacity in number of city freighters
u_z^{K}	Satellite z capacity in volume of goods it may handle
$\mathscr{K} = \{k\}$	Set of origin-destination demands
$O(k); D(k); d(k)$	Origin, destination, and quantity of demand $k \in \mathscr{K}$
$[a(O(k)), b(O(k))]$	Availability time interval of demand $k \in \mathscr{K}$ at its origin
$[a(D(k)), b(D(k))]$	Due date interval of demand $k \in \mathscr{K}$ at its destination
$\mathscr{F}(k) \subseteq \mathscr{F}$	Set of potential CDCs for demand $k \in \mathscr{K}$
$c_{ft}(k)$	Cost of assigning demand $k \in \mathscr{K}$ to CDC $f \in \mathscr{F}(d)$ at time t
$\Sigma = \{\sigma\}$	Set of potential urban-vehicle services
$O(\sigma); D(\sigma)$	Origin and destination CDCs of service $\sigma \in \Sigma$
$\mathscr{Z}(\sigma); \mathscr{L}(\sigma)$	Sets of satellites and legs of service $\sigma \in \Sigma$
$t(\sigma)$	Departure time of service $\sigma \in \Sigma$ from its origin
$c(\sigma)$	Cost (fixed) of service $\sigma \in \Sigma$
$\mathscr{H} = \{h\}$	Set of city-freighter work assignments
$\mathscr{W}(h)$	Set of work segments of city-freighter work assignment $h \in \mathscr{H}$
$c(h)$	Cost of city-freighter work assignment $h \in \mathscr{H}$
$\mathscr{I}(k) = \{i\}$	Set of itineraries, customer demand $k \in \mathscr{K}$

satellites in $\mathscr{Z}(\sigma)$, which account for the travel time along the arcs of the specific mode as well as the loading and unloading times at satellites. The cost associated to operating service $\sigma \in \Sigma$ is denoted $c(\sigma)$. The cost captures not only the monetary expenses of operating the service, but also the city-infrastructure-utilization cost reflecting the "nuisance" factors related to the presence of the urban vehicle in the city at the particular time of the service.

The second-tier pickup and delivery activities between satellites and customer zones are performed by city freighters operating multi-tour synchronized routes called *work assignments*. A city-freighter work assignment $h \in \mathscr{H}$ operates a city freighter of type $\nu(h)$ over a sequence of work *segments* $w \in \mathscr{W}(h)$, separated by returns to the garage, each segment being made up of visits to satellites to load and unload freight and one or several pickup (outbound demand), delivery (inbound demand), and pickup-and-delivery (local demand) activity phases. The schedule of a work segment starts at period $t(w)$ at the first satellite or customer on its route, and continues with the arrival and departure times at the visited satellites and customers. The cost of operating city-freighter work assignment h, $c(h)$, includes the costs of its segments, those associated to the garage (back and forth movements, idles time, etc.), a vehicle fixed cost, and the city-infrastructure-utilization cost reflecting the "nuisance" factors related to the presence of the city freighter in the city at the particular time of the service.

Freight is moved from the origin to the destination of demand via *itineraries* that include the facilities and the first and-second tier services used. Inbound-demand itineraries are thus made up of the movement from the external zone to a CDC, an urban-vehicle movement, a transshipment operation at a satellite, and the final distribution by a city-freighter work segment. Outbound-demand itineraries involve the same operations in reverse order. Local-demand itineraries are simpler as they involve the work segment performing the pickup and delivery only. Let $\mathscr{I}(k)$ stand for the set of itineraries that may be used to satisfy customer demand k, with itinerary $i \in \mathscr{I}(k)$ being defined by its selected CDC $f(i)$, urban-vehicle service $\sigma(i)$, satellite $z(i)$, and work segment $w_h(i)$ of work assignment $h(i)$.

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

- $y(\sigma) = 1$, if the urban-vehicle service $\sigma \in \Sigma$ is selected, 0, otherwise;
- $\varphi(h) = 1$, if the work assignment $h \in \mathscr{H}$ is selected, 0, otherwise;
- $\xi(i) = 1$, if itinerary $i \in \mathscr{I}(k)$ of demand $k \in \mathscr{K}$ is used, 0, otherwise.

The goal of the SSND formulation is to minimize the number, cost and impact of vehicles in the city, while satisfying demand requirements and capacity limitations. The formulation when no splitting of demand is allowed then becomes:

$$\text{Minimize} \quad \sum_{\sigma \in \Sigma} c(\sigma) y(\sigma) + \sum_{h \in \mathscr{H}} c(h) \varphi(h) \tag{1}$$

$$\text{Subject to} \quad \sum_{i \in \mathscr{I}(k)} \xi(i) = 1, \;\; \forall k \in \mathscr{K}, \tag{2}$$

$$\sum_{k \in \mathscr{K}(\sigma l)} \sum_{i \in \mathscr{I}(k) | \sigma(i) = \sigma} d(k) \xi(i) \leq u_{\tau(\sigma)} y(\sigma), \;\; \forall l \in \mathscr{L}(\sigma), \forall \sigma \in \Sigma, \tag{3}$$

$$\sum_{k \in \mathscr{K}(w(h)t)} \sum_{i \in \mathscr{I}(k) | h(i) = h} d(k) \xi(i) \leq u_{\nu(h)} \varphi(h)$$

$$\forall w \in \mathscr{W}(h), \; \forall h \in \mathscr{H}, \; t = 1, \ldots, T, \tag{4}$$

$$\sum_{\sigma \in \Sigma(z,t)} y(\sigma) \leq u^{\mathrm{T}}_{z}, \;\; \forall z \in \mathscr{Z}, \; t = 1, \ldots, T, \tag{5}$$

$$\sum_{\sigma \in \Sigma(z,t,\tau)} y(\sigma) \leq u^{\mathrm{T}}_{z\tau},$$

$$\forall z \in \mathscr{Z}, \forall \tau \in \mathscr{T}_m, \forall m \in \mathscr{M}, t = 1, \ldots, T, \tag{6}$$

$$\sum_{h \in \mathscr{H}(z,t)} \varphi(h) \leq u^{\mathrm{V}}_{z}, \;\; \forall z \in \mathscr{Z}, t = 1, \ldots, T, \tag{7}$$

$$\sum_{i \in \mathscr{I}(z,t)} d(k) \xi(i) \leq u^{\mathrm{K}}_{z}, \;\; \forall z \in \mathscr{Z}, t = 1, \ldots, T, \tag{8}$$

$$\sum_{\sigma \in \Sigma(f,t,\tau)} y(\sigma) \leq n_{f\tau},$$

$$\forall f \in \mathscr{F},\ \forall \tau \in \mathscr{T}_m,\ \forall m \in \mathscr{M},\ t = 1,\ldots,T, \tag{9}$$

$$\sum_{h \in \mathscr{H}(\nu)} \varphi(h) \leq n_\nu,\ \ \forall \nu \in \mathscr{V}_m, \forall\ m \in \mathscr{M}, \tag{10}$$

$$y(\sigma) \in \{0,1\},\ \ \forall \sigma \in \Sigma, \tag{11}$$

$$\varphi(h) \in \{0,1\},\ \ \forall h \in \mathscr{H}, \tag{12}$$

$$\xi(i) \in \{0,1\},\ \ \forall i \in \mathscr{I}(k),\ \forall k \in \mathscr{K}. \tag{13}$$

The objective function (1) computes the total generalized cost of the system (operations and negative impact on the city) as the sum of the costs of the selected urban-vehicle services and city-freighter work assignments. Constraints (2) indicate that each demand must be satisfied by a single itinerary. The formulation may be easily modified to account for the case when demand may be split by 1) using continuous itinerary flow variables instead of the selection ones, and 2) imposing in constraints (2) that the sum of these flows equals the demand volume.

Let $\mathscr{K}(\sigma l)$ be the set of all demands k that may use leg l of urban-vehicle service σ (i.e., there is at least an itinerary of k that includes leg l). Similarly, let $\mathscr{K}(w(h)t)$ be the set of all demands k that may use segment w of city-freighter work assignment h at time t. Then, constraints (3) enforce the urban-vehicle capacity restrictions for each leg of the vehicle route. Similarly, constraints (4) enforce city-freighter capacity restrictions at all time for each segment of a work assignment. These last two groups of relations are the linking constraints of network design formulations.

Define, 1) $\Sigma(z,t)$ ($\Sigma(z,t,\tau)$) and $\mathscr{H}(z,t)$, the sets of urban-vehicle services (of type τ) and city-freighter work assignments, respectively, stopping at satellite z at period t; 2) $\Sigma(f,t,\tau)$, the set of services initiated at or before period t that are still active at period t; and 3) $\mathscr{I}(z,t)$, the set of demand itineraries using satellite z at period t to load or unload freight. Then, constraints (5) - (8) enforce the satellite capacity restrictions in terms of total numbers of urban vehicles (services) (5), mode-specific urban vehicles (6), city freighters (7), and freight handled (8). Note that the coherence of the respective numbers of urban vehicles and city freighters present simultaneously at satellites is provided by the flow of freight imposed by the demand itineraries. Constraints (9) limit the number of services of each type operated out of each CDC at period t to the available fleet at the respective CDC. Constraints (10) perform the same role for the city freighters (work assignments) of each type. Constraints (11) - (13) define the range of the decision variables.

4 Using the Modeling Framework

The previous SSND formulation constitutes a modeling framework that can be adapted and extended to address a rather broad range of planning issues. We discuss a number of those in this section.

Recall that problem definitions and the corresponding models must account not only for the particular system setup and the planning issues addressed, and also the operation and management policies involved. Two aspects of the latter have a particular impact on the design of SSND formulations, the estimation of major exogenous factors, e.g., demand, travel and service times, and costs of goods and services, and the degree of freedom in managing resources. Indeed, tactical planning assumes a certain level of look-ahead capability and the inclusion of an evaluation of future events and their consequences into today's decision processes, through forecasts for the planning horizon considered. Tactical planning also implicitly assumes managerial capabilities to assign and schedule resources in a way that matches the requirements of the tactical plan. The choice of an appropriate modeling/methodological approach is then related to the magnitude of the variability of those factors, the confidence one has in the forecasts, and the amplitude of the managerial capabilities. A rather broad spectrum of problem settings and formulations is thus possible.

Consider, to illustrate, the case of high variability of demand, combined to a low or no confidence in the possibility to adequately forecast it and a high capability to manage resources, generally implies that no advanced planning of operations is possible. The system then reacts to new or varying demand by assigning and dispatching resources to service it. Such a dynamic mode of operations is not, however, within the scope of the problem settings and methodology considered in this chapter. At the other end of the spectrum, deterministic models, e.g., Sections 3 and 4.1, are appropriate in cases of high confidence in forecasts or estimated low-variability for the duration of the planning horizon. Between these cases, one finds problem settings where one represents the future through some probability distribution.

The literature is very sparse regarding the explicit integration of uncertainty in tactical-planning models and methods for City Logistics. To the best of our knowledge, duration and cost uncertainty, in particular, has not been addressed to any significant extent, a few contributions targeting demand uncertainty. The impact of demand uncertainty on the tactical plan is then generally accounted for through two-stage stochastic programs (Chapter 10), the design decisions selecting the service network appearing in the first stage, while routing is decided in the second. We illustrate such a formulation in Section 4.2.

Relative to the management environment and constraints, planning closely to operation-time is beneficial when one has little or no restrictions on mustering facilities and people on very short notice. The so-called *day-before planning* problem class and formulation of Section 3 corresponds to this situation. In most cases, however, management is significantly more constrained. Labor contracts often restrict the possible modifications to schedules. The inclusion of massive transportation means, particularly when related to passenger transportation, also involves strict scheduling of operations and advanced planning. The tactical planning formulation of Section 4.1 address these cases.

We conclude the section with a few comments on the longer-term planning of two-tier City Logistics systems in Section 4.3.

4.1 Tactical planning for medium-term horizons

Tactical planning is often concerned with structuring service, and the required resource assignment, to be repeatedly operated over a planning horizon several months long. Then, as discussed previously, including the precise routing of second-tier vehicles in the tactical plan appears less appropriate than for the day-before situation described in Section 3. One cannot neglect second-tier activities and costs, however, as they impact first-tier decisions, e.g., the freight itineraries and the synchronization with first-tier vehicles at satellites, and the global performance of the City Logistics system. The model described in this section then represents city-freighter routing through an *approximated cost* of servicing a customer zone out of each satellite to which it may be connected.

The inbound and outbound flows are thus captured together with the selection of the satellites which will service each customer zone, and the estimation of the dimensions of the city-freighter fleets required to satisfy demand, and the corresponding utilization of satellite capacity and city freighters. To simplify the presentation, the SSND tactical planning model bellow assumes, without loss of generality, a single city-freighter fleet and the same routing costs for inbound and outbound demand. As for the first-tier decisions, they are the same as before, namely, select the scheduled services to operate out of the set of possible line- and no-line-based multimodal services; determine the itineraries of each inbound and outbound demand, including the assignment to a CDC, a satellite, and a service with, possibly, a compartment; manage the multimodal fleets and terminals. For sake of simplicity, we do not repeat the notation in common with the model of Section 3 (see Table 1), and present only the new notation and modifications to the existing one.

The multicommodity demand $\mathscr{K}$ includes the inbound and outbound components, noted $\mathscr{K}^I$ and $\mathscr{K}^O$, respectively. Notice that the local demand is not considered in this model as it does not impact the design of the first-tier service network. All the characteristics defined in Section 3 are still valid. Similarly, the set of potential first-tier urban-vehicle services defined previously is also considered here, together with their characteristics, modes, types, and costs.

As indicated previously, the second tier is represented through an approximated cost of servicing customers out of satellites (delivery out of satellites to receiving customer zones and pick up at shipping customer zones to deliver at satellites and then CDCs) . To streamline the network representation and the model, however, no explicit satellite-customer arcs are added. Rather, the corresponding cost is added to the cost of the service carrying the flow of the particular demand into or out of the satellite. Let $\mathscr{Z}(k)$ be the set of satellites that may service demand k, and $c(k,z,\sigma)$ the approximated satellite-customer transportation cost of demand k moved in or out of satellite $z \in \mathscr{Z}(k)$ by a service σ (which could service the demand in time). Similar to all other costs defined in this chapter, the assignment costs $c(k,z,\sigma)$ represent not only the transport, unloading, and loading costs, but also city-disturbance factors related to these activities.

With respect to vehicles and modes, the previous definitions hold. We take the opportunity of this tactical planning SSND model, however, to introduce the notion of *compartment*. Several vehicle types have more than one cargo-holding space, as illustrated by the multiple cargo bays of river barges and several proposed cargo tramways, as well as the (vertical or horizontal) separators that may be used within motor vehicles. This definition may be broaden to a partition of a cargo-holding space (for, e.g., pallets or assemblies of smart π-containers), for as long as each compartment so defined may be accessed independently of the others. Moreover, the pseudo-backhaul policy assumed for loading and unloading vehicles implies that one can start loading outbound demand in a compartment only once all inbound freight present in the compartment has been unloaded. Such a policy facilitates streamlining operations at satellites, which is beneficial when capacities are tight as in City Logistics. We introduce compartments into the service definition through the set of *compartment services* $\mathscr{B}(\sigma)$ of service σ. To simplify the presentation, we assume all compartments of a given urban-vehicle type τ have the same capacity u^{B}_{τ}. Obviously, all compartment services are selected when the corresponding service is selected, and $|\mathscr{B}(\sigma)| = 1$ for single-compartment services.

Freight itineraries in the present context of approximated second-tier routing may be defined straightforwardly based on the service used. To illustrate, consider the itinerary of an inbound demand. It starts at the external-zone of origin from where the goods are received at the selected CDC, where the goods are loaded into an urban-vehicle (and compartment) of the selected service. The goods are then transported to the selected satellite by the selected service (with possibly intermediary stops but no work on the goods considered here), from where they are to be delivered to the final customer zone. It is noteworthy that the selection of a service (and compartment) provides all the necessary decision information, i.e., the CDC, the satellite, and the relevant time stamps, i.e., departure from CDC and arrival to satellite for delivery to the customer zone that, implicitly, takes care of the synchronization issue. Let then $c(k,b,\sigma,z)$ be the unit cost of moving freight of demand $k \in \mathscr{K}$ in compartment $b \in \mathscr{B}(\sigma)$ of service $\sigma \in \Sigma$ among its external and customer zones through satellite $z \in \mathscr{Z}(k)$.

One may therefore write an arc-based SSND formulation based on service and compartment selections and assignments to demands. The decisions variables are:

- $y(\sigma) = 1$, if the urban-vehicle service $\sigma \in \Sigma$ is selected, 0, otherwise;
- $x(b,\sigma,z,k) = 1$, if demand $k \in \mathscr{K}$ is assigned to compartment service $b \in \mathscr{B}(\sigma)$ and satellite $z \in \mathscr{Z}(k)$ (visited by service $\sigma \in \Sigma$), 0 otherwise.

The arc-based formulation of the SSND problem then becomes

$$\begin{aligned}\text{Minimize} \quad & \sum_{\sigma \in \Sigma} c(\sigma) y(\sigma) \\ & + \sum_{k \in \mathscr{K}} \sum_{\sigma \in \Sigma} \sum_{b \in \mathscr{B}(\sigma)} \sum_{z \in \mathscr{Z}(k)} \left(c(k,b,\sigma,z) + c(k,z,\sigma) \right) d(k) x(b,\sigma,z,k)\end{aligned} \tag{14}$$

$$\text{Subject to} \quad \sum_{\sigma \in \Sigma} \sum_{b \in \mathscr{B}(\sigma)} \sum_{z \in \mathscr{Z}(k)} x(b,\sigma,z,k) = 1, \; k \in \mathscr{K}, \tag{15}$$

$$x(b,\sigma,z_1,k_1)+x(b,\sigma,z_2,k_2)\leq 1,\ b\in\mathscr{B}(\sigma),\ \sigma\in\Sigma,\ k_1\in\mathscr{K}^I,\ k_2\in\mathscr{K}^O, z_1,z_2\in\mathscr{Z}(k),\ z_1\geq z_2, \tag{16}$$

$$\sum_{k\in\mathscr{K}^I}\sum_{z\in\mathscr{Z}(k)} d(k)x(b,\sigma,z,k)\leq u^{\mathrm{B}}_{\tau}(\sigma)y(\sigma),\ \sigma\in\Sigma, \tag{17}$$

$$\sum_{k\in\mathscr{K}^O}\sum_{z\in\mathscr{Z}(k)} d(k)x(b,\sigma,z,k)\leq u^{\mathrm{B}}_{\tau}(\sigma)y(\sigma),\ \sigma\in\Sigma, \tag{18}$$

$$\sum_{t=1,\ldots,T}\sum_{\sigma\in\Sigma(f,t,\tau)} y(\sigma)\leq n_{f\tau},\ f\in\mathscr{F},\ \tau\in\mathscr{T}_m,\ m\in\mathscr{M}, \tag{19}$$

$$\sum_{\sigma\in\Sigma(z,t)} y(\sigma)\leq u^{\mathrm{T}}_{z},\ z\in\mathscr{Z},\ t=1,\ldots,T, \tag{20}$$

$$\sum_{\sigma\in\Sigma(z,t,\tau)} y(\sigma)\leq u^{\mathrm{T}}_{z\tau},\ z\in\mathscr{Z},\ \tau\in\mathscr{T}_m,\ m\in\mathscr{M},\ t=1,\ldots,T, \tag{21}$$

$$\sum_{\sigma\in\Sigma(z,t)}\sum_{k\in\mathscr{K}} d(k)x(b,\sigma,z,k)\leq u^{\mathrm{K}}_{z},\ z\in\mathscr{Z}, t=1,\ldots,T, \tag{22}$$

$$y(\sigma)\in\{0,1\},\ \sigma\in\Sigma \tag{23}$$

$$x(b,\sigma,z,k)\in\{0,1\},\ k\in\mathscr{K},\ \sigma\in\Sigma,\ z\in\mathscr{Z}(k) \tag{24}$$

The objective function (14) minimizes the total generalized cost of selecting and operating services that move inbound and outbound demand flows, distributing demands from satellites and bringing outbound demands to satellites, as well as selecting a CDC for each demand.

Constraints (15) ensure that each item is assigned exactly to one compartment, while constraints (16) ensure that outbound demand is only assigned to a compartment after the inbound demand is unloaded and the compartment is empty. The compartment capacities for inbound and outbound traffic are enforced by the linking constraints (17) and (18). These constraints combined with constraints (16) enforce the capacity restriction for the entire service. Then, constraints (19) ensure that the maximum number of vehicles of each type assigned to a city distribution center is never exceeded. Constraints (20) and (21) limit the number of urban vehicles present at a satellite at each period in total and per transportation mode, respectively. Finally, constraints (22) limit the amount of demand that can be unloaded or loaded at a satellite at each period.

4.2 Demand uncertainty in tactical planning for City Logistics

We now present a stochastic scheduled service network design formulation for the tactical planning of two-tier City Logistics systems when the uncertainty on demand is explicitly taken into account. As discussed above, such formulations are required when major resources must be allocated and their utilization must be planned for the length of the planning horizon, well before the actual operations take place, while simultaneously acknowledging the strategies that are used during operations to adjust the plan to the observed demand. The tactical plan, which is built prior to the beginning of the season, then aims to determine the main structure of the service network and major resource allocation that will be executed regularly at each period of the planning horizon, but without fixing all the operational details that will be address at execution time. The goal is to optimize the overall cost (operations and environmental impact) of the system in terms of service selection and resource allocation plus an estimation of the costs involved in adjusting the plan and operating accordingly over the contemplated planning horizon. One thus expects that the explicit flexibility introduced into the tactical plan translates into the capability of the selected service network to accommodate a certain range of demand variability with no or little modification to the activities of the major resources involved. Such *a priori* optimization approaches are generally addressed through two-stage stochastic programming formulations with recourse, the latter corresponding to the strategies used to adjust the plan to given realizations of demand (Chapter 10).

In the two-stage stochastic SSND formulation with recourse described in this section, the plan is the object of the first stage and it concerns the selection of the first-tier services and schedules together with the associated demand itineraries between external zones and satellites. The later implies the allocation of customers to particular (satellite, period) combinations, the so-called *rendez-vous points*, providing strong indications on the satellite workloads and the dimensions of the city-freighter fleets required. City-freighter routing decisions are to be taken at each period the system operates, once the actual demand has been observed. They are thus the object of the second stage, and only an approximation of the corresponding costs and operations is integrated in the first-stage formulation. In this sense, the first-stage *urban-vehicle service network design* model is quite similar to the deterministic SSND model of Section 4.1. The output of this model includes the selection of services, customer-demand itineraries down to the (satellite, period) rendez-vous points (including the type of city freighter), and the customer-satellite allocations. It is this information that guides and constrains the second-stage recourse strategies, which address the city-freighter routing, determine the extra service capacity required, if any, and, eventually, slightly modify the service network.

We focus in this chapter on strategies that allow slight adjustments to the service network selected in the first stage and which, consequently, involve network-design formulations. Such a strategy aims to increase service flexibility, by fixing the "backbone" of the urban-vehicle service design identified by the first stage, while permitting to modify the corresponding urban-vehicle departure times. This may be viewed as a combined dispatching-routing decision to let the urban vehicles leave somewhat earlier or later than the planed schedule while determining the routing of the "regular" and "extra" city freighters. The presentation of the stochastic SSND model follows the deterministic path-based framework introduced in Section 3.

Let $\Omega = \{\omega\}$ be the sample space of the random event. Let $\mathscr{K}(\omega) = \{k(\omega)\}$ be the set of customer-demand realizations (0 demand corresponds to the no-demand case) for $\omega \in \Omega$, $\mathsf{K} = \{\mathscr{K}(\omega) | \omega \in \Omega\}$, and $d(k, \omega)$ the volume associated with demand k given $\omega \in \Omega$. Let $\widehat{d(k)}$ be the point forecast of the volume of customer demand $k \in \mathscr{K}$ used in the first stage of the formulation. Usually, $\widehat{d(k)}$ corresponds to the "best" estimate used in deterministic SSND, representing the "regular" demand one expects to see on a "normal" day (e.g., 80% of the maximum expected demand; no particular value is assumed for the formulation). One then desires the planned resource allocation and scheduling to be able to address this demand or, in other words, to provide at least this level of service in all cases.

The definition of the service network does not change but, as extra city freighters may be required and city-freighter routing is part of the second stage, reduced first-stage demand itineraries, $\mathscr{I}^{\mathrm{R}}(k)$, have to be defined. These include the itineraries corresponding to the possibility of CDC↔customer services through extra city-freighters ("artificial" arcs). Then, as the first-stage problem considers an approximation of routing activities and costs only, through customer-to-satellites allocations (for each city freighter type, mode, and period), regular first-stage demand itineraries include satellite↔customer links only, rather than actual city-freighter work segments. Let $\tilde{c}(k,i)$ be the cost of itinerary $i \in \mathscr{I}^{\mathrm{R}}(k)$ corresponding to these decisions, i.e., the extra city freighter usage or satellite↔customer allocation, respectively (the cost of services is captured in the corresponding term of the objective function). Similarly to the definition of all other costs, $\tilde{c}(k,i)$ reflects the handling and moving freight, as well as a measure of the "nuisance" factors related to the presence of city freighters in the city at the particular time of the delivery.

Two sets of decision variables are defined to select urban-vehicle services and first-stage demand itineraries:

$y(\sigma) = 1$, if urban-vehicle service $\sigma \in \Sigma$ is selected, 0, otherwise;
$\xi(i) = 1$, if itinerary $i \in \mathscr{I}^{\mathrm{R}}(k)$ of demand k is used, 0, otherwise.

An *a priori* plan then specifies:

- A set of urban-vehicle services $\Sigma(y^1)$ to be operated, and a set of first-stage itineraries $\mathscr{I}^{\mathrm{R}}(y^1,\zeta^1) = \{i(y^1,\zeta^1,k),\ k \in \mathscr{K}\}$ bringing the load of each customer demand k in time to its appointed satellite;
- A set of active *rendez-vous* points (satellite, period), $(z,t) \in \mathscr{R}(y^1,\zeta^1)$, where urban vehicles and city freighters meet and freight is transferred; Customer-to-satellite assignments are associated to each rendez-vous point.

The notation (y^1,ζ^1) used in this section emphasizes that the second stage optimization problem is constrained by the decisions of the first stage. The *Dispatch & Route* recourse strategy assumes y^1,ζ^1 fixed, focusing on possibly changing the departure times of the selected services, as well as on optimizing the second-tier routing to service inbound and outbound customer demands.

Let $[a(zt),\ b(zt)]$ be the time window of satellite z at rendez-vous point (z,t), such that customers serviced by vehicles starting/finishing their routes within the interval will be serviced (delivery or pick up) on time. Let $[a(\sigma),b(\sigma)]$ be the *opportunity time window* around the departure time of service $\sigma \in \Sigma(y^1)$, derived from the satellite time windows and the travel times between satellites and CDCs. Let $\Sigma(y^1,\sigma)$

be the set of possible departures in the opportunity window of service $\sigma \in \Sigma(y^1)$ among which one selects to instantiate the plan to the observed demand.

The movements of freight by city freighters at the second tier of the system is restricted to the service network and satellite utilization specified in the *a priori* plan. Given the possibility of extra city freighters visiting CDCs to move excess demand, the definition of a work segment is enlarged to encompass CDCs as the first or last stop on its route. The notation of the city-freighter work assignments and work segments then becomes $\mathscr{H}(y^1, \zeta^1)$ and $\mathscr{W}(y^1, \zeta^1, h)$, respectively. Similarly, the demand itineraries restricted to the first-stage service design, and the possibility of CDC-related work segments, are indicated by $i \in \mathscr{I}(y^1, \zeta^1, k(\omega)) \subset \mathscr{I}(k)$.

The decision variables defined for the second stage then are:

$y^2(k(\omega), \sigma^2) =$ 1, if urban-vehicle service $\sigma \in \Sigma(y^1)$ is selected, 0, otherwise;
$\varphi^2(k(\omega), h) =$ 1, if work assignment $h \in \mathscr{H}(y^1, \zeta^1)$ is selected, 0, otherwise;
$\zeta^2(k(\omega), i) =$ 1, if itinerary $i \in \mathscr{I}(y^1, \zeta^1, k(\omega))$ of demand $k(\omega) \in \mathscr{K}(\omega)$ is selected, 0, otherwise.

The two-stage SSND formulation minimizing the expected generalized cost of the system over the planning horizon may then be written as

$$\text{Minimize} \quad \sum_{\sigma \in \Sigma} c(\sigma) y(\sigma) + \sum_{k \in \mathscr{K}} \sum_{i \in \mathscr{I}^{\mathrm{R}}(k)} \tilde{c}(k,i) \widehat{d(k)} \xi(i) + \mathrm{E}_{\mathsf{K}} \left[Q^{RP}(y^1, \zeta^1, \mathscr{K}(\omega)) \right] \tag{25}$$

$$\text{Subject to} \quad \sum_{i \in \mathscr{I}^{\mathrm{R}}(k)} \xi(i) = 1, \; k \in \mathscr{K}, \tag{26}$$

$$\sum_{k \in \mathscr{K}(\sigma l)} \sum_{i \in \mathscr{I}^{\mathrm{R}}(k) | \sigma(i) = \sigma} \widehat{d(k)} \xi(i) \le u_{\tau(\sigma)} y(\sigma), \; l \in \mathscr{L}(\sigma), \sigma \in \Sigma, \tag{27}$$

$$\sum_{\sigma \in \Sigma(z,t)} y(\sigma) \le u_z^{\mathrm{T}}, \; z \in \mathscr{Z}, \; t = 1, \dots, T, \tag{28}$$

$$\sum_{\sigma \in \Sigma(z,t)} y(\sigma) \le u_{z\tau}^{\mathrm{T}}, \; z \in \mathscr{Z}, \; \tau \in \mathscr{T}_m, \; m \in \mathscr{M}, \; t = 1, \dots, T, \tag{29}$$

$$\sum_{v \in \mathscr{V}} \left[\sum_{k \in \mathscr{K}} \sum_{i \in \mathscr{I}^{\mathrm{R}}(k,v,t)} \widehat{d(k)} \xi(i) \right] / u_v \le u_z^{\mathrm{V}} \quad z \in \mathscr{Z}, \; t = 1, \dots, T, \tag{30}$$

$$\sum_{v \in \mathscr{V}} \left[\sum_{k \in \mathscr{K}} \sum_{i \in \mathscr{I}^{\mathrm{R}}(k,v,t)} \widehat{d(k)} \xi(i) \right] \le u_z^{\mathrm{K}}, \; z \in \mathscr{Z}, \; t = 1, \dots, T, \tag{31}$$

$$\sum_{\sigma \in \Sigma(f,t,\tau)} y(\sigma) \le n_{f\tau}, \; f \in \mathscr{F}, \; \tau \in \mathscr{T}_m, \; m \in \mathscr{M}, \; t = 1, \dots, T, \tag{32}$$

$$y(\sigma) \in \{0,1\}, \; \sigma \in \Sigma, \tag{33}$$

$$\xi(i) \in \{0,1\} \quad i \in \mathscr{I}^{\mathrm{R}}(k), \; k \in \mathscr{K}, \tag{34}$$

with

$$Q^{RP}(y^1,\zeta^1,\mathscr{K}(\omega)) = \tag{35}$$

$$\text{Minimize} \sum_{\sigma\in\varSigma(y^1)} c(\sigma) \sum_{\sigma^2\in\varSigma(y^1,\sigma)} y^2(k(\omega),\sigma^2) + \sum_{h\in\mathscr{H}(y^1,\zeta^1)} c(h)\varphi^2(k(\omega),h)$$

$$\text{Subject to} \sum_{i\in\mathscr{I}(y^1,\zeta^1,k(\omega))} \zeta^2(k(\omega),i) = 1,\ k(\omega)\in\mathscr{K}(\omega), \tag{36}$$

$$\sum_{\sigma^2\in\varSigma(y^1,\sigma)} y^2(k(\omega),\sigma^2) = 1,\ \sigma\in\varSigma(y^1), \tag{37}$$

$$\sum_{k(\omega)\in\mathscr{K}(\omega)} \sum_{i\in\mathscr{I}(y^1,\zeta^1,k(\omega),\sigma)} d(k,\omega)\zeta^2(k(\omega),i) \le u_\tau y^2(k(\omega),\sigma^2), \tag{38}$$

$$\sigma^2\in\varSigma(y^1,\sigma), \sigma\in\varSigma(y^1),$$

$$\sum_{k(\omega)\in\mathscr{K}(w(h)t)} \sum_{i\in\mathscr{I}(y^1,\zeta^1,k(\omega))|h(i)=h} d(k,\omega)\zeta^2(k(\omega),i) \le u_\nu\varphi^2(k(\omega),h) \tag{39}$$

$$w\in\mathscr{W}(y^1,\zeta^1,h),\ h\in\mathscr{H}(y^1,\zeta^1),\ t=1,\dots,T,$$

$$\sum_{\sigma\in\varSigma(y^1)} \sum_{\sigma^2\in\varSigma(y^1,\sigma,z,t)} y^2(k(\omega),\sigma^2) \le u_z^{\mathrm{T}}, \tag{40}$$

$$(z,t)\in\mathscr{R}(y^1,\zeta^1),\ z\in\mathscr{Z},\ t=1,\dots,T,$$

$$\sum_{\sigma\in\varSigma(y^1)|\tau(\sigma)=\tau} \sum_{\sigma^2\in\varSigma(y^1,\sigma,z,t)} y^2(k(\omega),\sigma^2) \le u_{z\tau}^{\mathrm{T}}, \tag{41}$$

$$(z,t)\in\mathscr{R}(y^1,\zeta^1),\ z\in\mathscr{Z},\ \tau\in\mathscr{T}_m,\ m\in\mathscr{M},\ t=1,\dots,T,$$

$$\sum_{h\in\mathscr{H}(y^1,\zeta^1)} \varphi^2(k(\omega),h) \le u_z^{\mathrm{V}},\ (z,t)\in\mathscr{R}(y^1,\zeta^1),\ z\in\mathscr{Z},\ t=1,\dots,T, \tag{42}$$

$$\sum_{i\in\mathscr{I}(y^1,\zeta^1,k(\omega))} d(k)\xi(i) \le u_z^{\mathrm{K}},\ z\in\mathscr{Z},\ t=1,\dots,T, \tag{43}$$

$$\sum_{h\in\mathscr{H}(y^1,\zeta^1)} \varphi^2(k(\omega),h) \le n_\nu^+,\ \nu\in\mathscr{V}_m,\ m\in\mathscr{M}, \tag{44}$$

$$y^2(k(\omega),\sigma^2)\in\{0,1\},\ \sigma\in\varSigma(y^1), \tag{45}$$

$$\varphi^2(k(\omega),h)\in\{0,1\},\ h\in\mathscr{H}(y^1,\zeta^1), \tag{46}$$

$$\zeta^2(k(\omega),i)\in\{0,1\},\ i\in\mathscr{I}(y^1,\zeta^1,k(\omega)),\ k(\omega)\in\mathscr{K}(\omega). \tag{47}$$

The first-stage objective function (25) minimizes the total generalized cost computed as the cost of selecting and operating urban-vehicle services to move the point-forecast demand between external zones and satellites, plus the approximated cost of assigning customers to satellites and moving demand between them, plus the expected cost of the recourse over the planning period, i.e., the cost of operating the system according to the *a priori* plan $x(y^1, \zeta^1)$ adjusted, *instantiated*, for the realized demand $\mathscr{K}(\omega)$ by applying the recourse policy RP with cost $Q^{RP}(x(y^1, \zeta^1), \mathscr{K}(\omega))$.

The first-stage constraints (26) - (34) correspond to constraints (2), (3), (5) - (9), (11), and (13), where the numbers of second-tier city freighters in constraints (30) are derived from the total volume of demand leaving the satellite at period t on city freighters of all types, where $\mathscr{I}^{\mathrm{R}}(k, \nu, t)$ stands for the corresponding itineraries of demand k. (Constraints (4), (10), (12) are not needed in the first-stage formulation.)

The objective function of the second-stage formulation (35) computes the total cost of operating the selected urban-vehicle services, with possibly new departure times, and the normal and extra city-freighter work assignments. Equations (36) indicate that each demand must be satisfied by a single itinerary, while constraints (37) state that exactly one departure must be selected for each opportunity window. Constraints (38) enforce the urban-vehicle capacity restrictions, where $\mathscr{I}(y^1, \zeta^1, k(\omega), \sigma)$ stands for the set of itineraries of customer demand k being moved on service σ. Constraints (39) enforce the capacity of city freighters on all work segments of both regular and extra city-freighter work assignments. Constraints (40) and (41) enforce the satellite capacity restrictions in terms of urban vehicles, total and by mode, respectively. The satellite capacity in terms of city freighters and freight volume are enforced by constraints (42) and (43), respectively. Constraints (44) limit the number city freighters (work assignments) of each type used to the available fleet augmented with the cardinality of the extra fleet. Finally, constraints (45) - (47) define the feasible region of the second-stage formulation.

4.3 Designing the City Logistics Network - Strategic Planning

The previous SSND formulations yield “best” (optimal, when solved exactly) tactical plans and two-tier scheduled service networks in terms of the generalized cost of the system given the forecast demand, the 2T-CL system layout, composition, and attributes, as well as current regulations and operation policies. The models may be used not only for drawing tactical plans, however, but also as an analysis and evaluation tool for a broad range of longer-term issues (Section 2.2). Scenarios related to the structure, environment or policies of a (two-tier) City Logistics system may be evaluated using the model framework described in this chapter appropriate for the case. To illustrate, the complete formulations (Sections 3 and 4.2) are appropriate to evaluate the impact on system performance of vehicle fleet deployment including number and dimension of fleets at both tiers, assignment to CDCs or satellites, vehicle characteristics, etc. On the other hand, models approximating the second-tier routing (Sections 4.1 and 4.2 with approximated routing cost) appear more appropriate to evaluate longer-term scenarios implying a certain level of imprecision in the demand data, such as different system layouts in terms of number, location, and capacity of facilities.

The SSND models may also be used to study different cooperation rules when several service providers (public and private carriers, terminals, etc.) share infrastructure and jointly perform the City Logistics activities under joint planning and operations-management mechanism (e.g., an arm-length information-sharing and decision platform). Such rules may specify, e.g., how costs or vehicle utilization, or both have to be distributed among the participants to reflect their contractual commitment (in terms of type and size of the fleet, territory covered, financial and risk share, etc.). Not much research has been dedicated yet on how to extend SSND models to account for these issues. To illustrate a first step in this direction, consider a group $\mathscr{C}$ of first-tier collaborating carriers, each with a weight ()“share”) $\alpha_c, c \in \mathscr{C}$, representing the target for its level of activity or cost it incurs. Let $[\alpha_c^-, \alpha_c^+]$ represent the interval of variation acceptable for the next planning cycle, and $c(\sigma, c)$ the cost of service $\sigma \in \Sigma$ performed by carrier $c \in \mathscr{C}$. Defining $y(\sigma, c) = 1$, if the urban-vehicle service $\sigma \in \Sigma$ is selected to be operated by carrier $c \in \mathscr{C}$, and 0, otherwise, the total service-selection cost in the SSND objective function becomes

$$\sum_{\sigma \in \Sigma} \sum_{c \in \mathscr{C}} c(\sigma, c) y(\sigma, c), \tag{48}$$

the share of that cost borne by each carrier in the coalition being controlled by

$$\alpha_c^- \sum_{\sigma \in \Sigma} \sum_{c \in \mathscr{C}} c(\sigma, c) y(\sigma, c) \leq \sum_{\sigma \in \Sigma} c(\sigma, c) y(\sigma, c) \leq \alpha_c^+ \sum_{\sigma \in \Sigma} \sum_{c \in \mathscr{C}} c(\sigma, c) y(\sigma, c) \tag{49}$$

Similar constraints may be added on the operations performed to limit the resource utilization (measured, e.g., in time, km, or weight-km) by the respective carriers. Penalties may also be added to the objective function to add flexibility to the solution methods. This constitutes an interesting research avenue.

The SSND models may also be generalized for a direct utilization as decision-support tools for strategic decisions such as the location/selection of facilities, CDCs and satellites, the design of freight-dedicated corridors throughout the city (particularly between external zones and CDCs and between the latter and the satellites) or the introduction of new/upgraded infrastructure and services. Continuing the previous discussion, he long-term nature of strategic decisions suggest that second-tier routing should be approximated in such “strategic” SSND models, which would include design decision variables on the selection of the contemplated facilities or infrastructure structures, as well as the corresponding commodity-flow variables and the capacity and linking constraints. Budget constraints come naturally to mind as well.

To illustrate, consider the 2T-CL case where one aims to select satellites given selection costs and budget. These costs could represent the renting or utilization of facilities for the next planning period, which corresponds to a tactical planning decision, or actual longer-term strategic acquisition or securing costs. Let $c(z), z \in \mathscr{Z}$, the selection cost of satellite $z \in \mathscr{Z}$ and B the total budget available for satellite selection and utilization. The medium-term SSND formulation of Section 4.1 may then be extended with the additional decision variables $\zeta(z) = 1$, is satellite $z \in \mathscr{Z}$ is selected, and 0, otherwise, and the corresponding total selection cost $\sum_{z \in \mathscr{Z}} c(z)\zeta(z)$ added to the objective function (14). The right hand side of constraints (20) - (22) is multiplied by the satellite-selection variable (e.g., $u^{\mathrm{T}}_{z\tau}\zeta(z)$ for the latter constraint) to transform them from capacity to linking constraints. The flow-related linking constraints (50) and budget constraints (51) must also be added.

$$x(b,\sigma,z,k) \leq \zeta(z)\zeta(z),\ k \in \mathscr{K},\ \sigma \in \Sigma,\ z \in \mathscr{Z}(k) \tag{50}$$

$$\sum_{z \in \mathscr{Z}} c(z)\zeta(z) \leq B \tag{51}$$

5 Bibliographical Notes

We aim with this section to give a brief historical survey of and appropriate credit for the developments related to network design and the planning of City Logistics, two-tier systems in particular. General descriptive papers and surveys regarding City Logistics and related operations research developments may be found in, e.g., Taniguchi et al. (2001); Benjelloun and Crainic (2009); Gonzalez-Feliu et al. (2014); Taniguchi (2014); Cattaruzza et al. (2017); Crainic (2008); Bektaş et al. (2017); Savelsbergh and Van Woensel (2016), while Holguín-Veras et al. (2020a,b) review CL initiatives from the point of view of urban freight management.

Most contributions in the literature addressing the design of City Logistics systems focus on the location of facilities only and proposed location-routing models (mentioned bellow). A few different approaches were proposed. Taniguchi et al. (1999) combines a facility-selection-dimensioning model and a nonlinear traffic-equilibrium formulation to reflect the user (truck drivers) choices; Crainic et al. (2004) introduced a general two-tier city logistics system concept (see also Gragnani et al., 2004), together with a location-allocation methodology for the strategic decision issue of determining the satellite structure of the system. The authors consider inbound demand and single motor-carrier modes and fleets for each of the two tiers of the system; Baldi et al. (2012) address the same problem setting with stochastic costs for the paths from CDC to satellite to customer zone; Gianessi et al. (2016, see also Gianessi (2014)) propose a location-routing formulation integrating decisions related to the design of a ring structure connecting the CDCs, inbound and outbound demands, and routing of inter-CDC flows onto the ring structure to avoid excessive travel through the city and on the highways around; Guerrero-Lorente et al. (2020) propose a location-routing model for a Cl postal network with approximated routing costs; Hu et al. (2020) present a bi-objective location-allocation model to study an underground 2T-CL system for in Beijing, China.

Crainic et al. (2009) proposed the first modeling framework for the short to medium-term planning of inbound-demand, single-mode 2T-CL systems with the possibility of different vehicle types and specific product-to-vehicle assignment rules. The authors also introduced to the City Logistics literature the time-dependency of demand and the corresponding issue of scheduling and synchronizing first-tier urban-vehicle services and second-tier city-freighter multi-tour work assignments. They proposed a path-based formulation for the day-before planning problem, when planning is performed shortly ("the day before") before operations when the demand is known. The SSND modeling framework of Section 3 starts from this work.

Crainic et al. (2009) also introduced formulations for the first-tier scheduled service network design and the second-tier synchronized, scheduled, non-substituable origin-destination (OD) demand, multi-depot, multi-tour, heterogeneous vehicle routing problem with time windows (*SSOD-MDMTH-VRPTW*) problems (see, e.g., Nguyen et al., 2013; Crainic et al., 2016c; Nguyen et al., 2017; Bettinelli et al., 2019, for developments on the latter problem). The paper discusses solution-method avenues for all formulations, introducing a meta-heuristic structure for the full model based on decomposing it along tiers, without actually solving the problem.

Two additional observations were made in Crainic et al. (2009). First, that one could view the service selection on the first tier as a particular case of a vehicle routing problem, yielding a two-tier, or, in VRP terminology, a two-echelon SSOD-MDMTH-VRPTW. Several publications followed focusing on two-echelon vehicle routing (e.g., Perboli et al., 2011; Hemmelmayr et al., 2012; Contardo et al., 2012; Mancini et al., 2014; Masson et al., 2017; Grangier et al., 2015; Breunig et al., 2016, 2019; Dellaert et al., 2019) and location-routing problems with facilities being selected on a single tier (e.g., Guyon et al., 2012; Gianessi et al., 2016; Winkenbach et al., 2016; Boccia et al., 2017) or, more rarely, on both tiers (e.g., Boccia et al., 2010, 2011). It is noteworthy that most of these contributions do not include the full range of attributes defined above; thus, OD demand, multiple demand types, time-dependency, multiple tours, and synchronization are quite often missing..

The second observation of Crainic et al. (2009) is that for longer-term planning, e.g., mid-term tactical planning and the evaluation of long-term strategic alternatives, the second-tier routing problem could be approximated and added to the first-tier formulation through appropriately-defined service costs on links connecting satellites and customer-zone. Crainic and Sgalambro (2014) adopted this idea and focused on the modeling of the first-tier service network design within the day-before planning problem, studying the impact of a number of system parameters on the final design. This line of work was significantly extended by Fontaine et al. (2017) while addressing a richer problem setting than in previous literature.

Fontaine et al. (2017) address a 2T-CL setting which integrates inbound and outbound demands (see Crainic et al., 2012, for an initial discussion on the impact of integrating several types of demand into City Logistics planning), decisions on the assignment of customers to consolidation distribution centers and satellites, multiple satellite capacity measures in terms of freight volume and numbers of first and second-tier vehicles, several heterogeneous limited-size fleets of particular transportation modes. The intermodal transportation aspect brings together traditional, road-based, carriers and massive-flow carriers and vehicles captive of their routes or infrastructure, e.g., buses, trolleybuses, tramways, subways, and regular rail bringing flows from CDCs to satellites located within downtown train stations (Trentini and Mahléné, 2010; Freemark, 2011; Riemann, 2019; Lindholm and Behrends, 2012; Masson et al., 2017). As several vehicle types have more than one cargo-holding space, as illustrated by the multiple cargo bays of several proposed cargo tramways and the (vertical or horizontal) separators that may be used within trucks, the authors also introduced multi-compartment vehicles. Fontaine et al. (2017) propose an arc-based SSND formulation for the tactical planning of such extended systems, where the customer service cost through pickup or delivery routing is approximated on corresponding customer-satellite arcs. They also proposed an efficient Benders decomposition algorithm (Crainic et al., 2016a), which includes specialized valid inequalities and an innovative partial decomposition strategy based on the use of aggregation techniques for deterministic problems. The numerical results show the efficiency of the proposed algorithm compared to a well-known commercial solver, as well as the benefits of considering several transportation modes and demand types. The model of Section 3 includes a number of elements of this work.

One finds very few contributions addressing the uncertainty inherent to the City Logistics system. To the best of our knowledge, travel and service time uncertainty has not been addressed in the context of optimization for city logistics planning, although the issue is mentioned by several authors. A limited number of contributions addressed time-dependent travel times (e.g., Liu et al., 2020) but focused on routing issues only and no uncertainty was considered. Contributions were made with respect to developing appropriate data for these problems (e.g. Ehmke et al., 2012; Maggioni et al., 2014), but were not included into tactical planning models.

With respect to demand uncertainty, Crainic et al. (2016b) propose a two-stage stochastic-programming formulation for a 2T-CL tactical planning model aimed at the system setting defined in Crainic et al. (2009). The first stage corresponds to the selection of the first-tier services and the determination of the partial demand itineraries up to the selected satellites, as well as the satellite utilization in terms of customer assignments. The second stage models the selection of ad-hoc additional city freighters and the routing-based strategy to adjust the plan once demand is realized. The authors used the meta-heuristic of Crainic et al. (2009) as the basis of a Monte-Carlo evaluation procedure of several recourse strategies with increasing degrees of flexibility in routing and customer assignments. Not surprisingly, increased flexibility in resource allocation and system management displayed the best performances. This is an encouraging first step in what constitutes a major research issue.

Another rich research challenge corresponds to address the case multiple organizations, public and private carriers and other service providers operating in (parts of) cities under some form of cooperation/coalition and resource sharing agreements (e.g., Morana et al., 2014). A few policy and simulation-based studies may be found in the literature, but we know of only one paper at this time representing some of these rules within a tactical planning model (Crainic et al., 2020, used in the discussion of Section 4.3). The authors introduced penalty costs and constraints limiting the utilization of certain resources according to the shares of participating carriers into a simplified version of the Fontaine et al. (2017) SSND formulation. Experimental results show the impact of such conditions, not only on the computational burden, but also on the distribution of resources and the performance of the system.

6 Conclusions and Perspectives

The transportation and logistics industry is continuously evolving with the evolution of society, politics, and technology. City Logistics constitutes one of the paths of this evolution, echoing and interacting with similar developments in new business and organizational models such as Physical Internet and synchromodality. Operation Research and analytics accompany and sometimes precede this evolution by providing methods and decision-support instruments for the analysis, planning and management of transportation and logistics systems, from potentiality to deployment and operations or abandon. The impact is a two-way street, however. as changes in social and industrial behavior and in technology challenge the field and spur modeling and algorithmic development.

This chapter presented the main outcomes of this interaction from the point of view of network design. The formulations target tactical and strategic planning-level issues and reflect the novel characteristics proper to City Logistics, in particular, several layers (tiers) of facilities and operations, multimodality, multiple heterogeneous fleets, collaboration of private and public service providers, time-dependency of demand and operations, interaction of somewhat regular transport services and local pickup and delivery activities, and synchronization of fleet operations on the two tiers at the intermediary facilities, to name but a few.

Many challenges are still facing the field and new ones are emerging, yielding a rich set of exciting research avenues for Operations Research and Transportation Science. We conclude the chapter briefly discussing a number of those, focusing on modeling and algorithmic challenges from a network-design perspective.

Modeling issues are many and of the utmost interest. We already mentioned in previous sections a number of important and challenging research directions not only for City Logistics but also for (service) network design in general: 1) the integration into SSND formulations inbound, outbound, and local demand into a seamless and comprehensive operation, which requires integrating and synchronizing SSND and time- and OD-dependent multi-tour heterogeneous pickup and delivery routing; 2) the development of SSND methodology for various cases of collaborating and capacity-sharing stakeholder consortia, operating a unified system of private and public resources under various profit-cost-risk-resource utilization sharing rules; 3) the explicit representation and integration of the uncertainty regarding the demand as well as travel and service times at facilities and customer locations.

It is noteworthy that methodological and application challenges emerge, on the one hand, from the particular political, social, and entrepreneurial characteristics of each city and country, which impact directly how technology is accepted and used, how information and traffic flows are ruled, and how people and institutions are allowed to behave. They also follow, on the other hand, from new technology and changing social behavior (see, e.g., Oliveira et al., 2020; Snoeck et al., 2020; Taniguchi et al., 2020). The former includes a very broad range of issues, from the Internet of Things, the Smart City concepts, and the movement towards a numeric and automated transportation and logistics 4.0 industry, to the drones, delivery robots, lockers, and crowd-based logistics which are increasingly part of local delivery. The latter group of issues is equally broad, from the continuously stronger trend of on-line shopping combined to customer requirements for very fast and very cheap delivery, to the increasing variety of time and cost-defined customer-service classes, to revenue management strategies.* How each of these issues is represented individually and when several are jointly present in the problem setting makes for particularly challenging issues. The challenge is increased considering that one needs coherent representations at operational and tactical-strategic levels, and that one aims for objective function and constraint formulations that are amenable to efficient solving.

Worthy of notice is the modeling and algorithmic challenge of combining and synchronizing network design and vehicle routing in an unique formulation. On the one hand, this raises the issue of the adequate modeling of routing into tactic and strategic formulations, and the related efficient and representative approximations of costs and times. On the other hand, one observes that there is not as yet any solution method, neither exact nor meta-heuristic, able to provide consistently high-quality solutions to integrated SSND formulations with synchronization. Moreover, the algorithmic challenge increases significantly with the dimensions of the system in numbers of facilities, customers, fleets, time periods. It is further compounded when uncertainty is explicitly considered.

Research is thus required on high-performance solution methods for deterministic and stochastic network design with explicit or approximated routing models for City Logistics. We mention some very promising avenues, which could, probably should, be combined into efficient solution frameworks: 1) decomposition methods of path and arc-based formulations with novel projections of the synchronization relations on tier-specific subproblems; 2) dynamic generation of first-tier services and second-tier pickup and delivery routes; it is noteworthy that one may address a service route as a vehicle route with particular characteristics and restrictions, opening the way for a unified solution methodology; 3) the dynamic generation of the time-space network delivered very good performances on particular SSND problem settings and is being extended for routing; extending it further to rich SSND with pickup and delivery routing problem settings is particularly fascinating and promising; 4) parallel exact methods and collaborative-search matheuristics for efficiently addressing deterministic and stochastic formulations of realistic dimensions.

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