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Modeling Demand Uncertainty in Two-Tiered City Logistics Planning

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Abstract. We consider the complex and not-yet-studied issued of building the tactical plan of a two-tiered City Logistics system while explicitly accounting for the uncertainty in forecast demand. We describe and formally define the problem, and propose a general modeling framework, which takes the form of a two-stage stochastic programming formulation. Three different strategies of adapting the plan to the observed demand are introduced together with the associated recourse formulations. Algorithmic challenges are discussed and a promising solution methodology is proposed.

Keywords. City Logistics, advanced urban freight transportation, demand uncertainty, planning, service network design, vehicle routing.

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1 Introduction

For cities, the transportation of goods constitutes both a major enabling factor for most economic and social activities and a major disturbing factor to urban life (OECD, 2003). Several concepts have been introduced and projects have been undertaken in recent years to reduce the negative impact of freight-vehicle movements on city-living conditions, particularly in terms of congestion/mobility and environmental impact, while not penalizing its social and economic activities. The fundamental idea that underlies most initiatives is to consider shipments, firms, and vehicles (as well as the other stakeholders in a city's transportation system) not individually but rather as components of an *integrated logistics system*. Such a view emphasizes the need for an optimized *consolidation* of loads of different shippers and carriers within the same vehicles and for the *coordination* of the resulting freight transportation activities within the city. The term *City Logistics* has been coined to describe such systems and the optimization of their structure and activities.

Similarly to any complex transportation system, City Logistics systems require planning at strategic, tactic, and operational levels (Benjelloun and Crainic, 2008). We focus on tactical planning issues because of its central role in the overall planning process, as well as in providing the means to operate efficiently with respect to the overall goals and constraints of the system. With respect to the former statement, tactical plans are required to evaluate strategic plans and guide operations. As for the latter aspect, tactical planning selects the services and schedules to run, assigns resources, and defines broad policies on how to route the freight and operate the system to satisfy demand and attain the economic and service-quality objectives of the system.

Planning means a certain level of look-ahead capability and the inclusion of forecast events into today's decision process. The variation in demand over the horizon of the tactical plan, from a season to a year, constitutes a particularly important element to consider, as it may significantly impact not only the level of service one will offer but also the structure of the resulting design of the service network (Lium et al., 2009). At the best knowledge of the authors, no contribution in the literature addresses uncertainty issues in tactical planning for City Logistics. This report is a first step toward filling this gap.

We consider the case of two-tiered City Logistics (*2T-CL*) systems (Crainic et al., 2004; Gragnani et al., 2004), which are generally designed for large cities and are particularly challenging from an operational and planning-process point of view due to their additional complexity of interacting layers of facilities and vehicle fleets. To keep the length and complexity of the discussion within reasonable limits, we address the standard case of inbound traffic only (Crainic et al., 2010). We focus on the variability associated to demand and on how to address it within the process of building the tactical plan for the regular operations of 2T-CL systems, under various hypotheses relative to what is fixed and what may be adjusted at operation time. The models proposed for each case may be rather straightforwardly adapted to single-tiered systems and more complex traffic cases.

The main contributions of the work are: First, we introduce the issue and formally define the problem of explicitly addressing demand uncertainty in tactical planning for City Logistics systems. Second, we propose a general modeling framework, which takes the form of a two-stage stochastic programming formulation. Third, we study three different strategies to adapt the plan to the observed demand and propose associated recourse formulations. Finally, we discus algorithmic challenges and propose a promising solution methodology.

Section 2 briefly recalls the general two-tiered City Logistics system concepts, setting, and operations. planning issues, and literature. Section 3 discusses planning and uncertainty issues. Planning issues for 2T-CL systems are first recalled, together with a brief literature review. Sources of uncertainty and how these could be considered in planning the operations of 2T-CL systems are discussed in the second part of the section, concluding with a statement of the problem studied. Section 4 introduces the general modeling framework and the first-stage formulation. Sections 5, 6, and 7 detail the three recourse strategies we propose. Algorithmic issues are discussed in Section 8 and we conclude in Section 9.

2 Two-Tiered City Logistics

The section recalls the general setting of two-tiered City Logistics systems, introduced by Crainic et al. (2004), and illustrated in Figure 1 We also introduce the basic definitions and notation, which generally are those of proposed by Crainic et al. (2009a). Table 1 in the Annex summarizes the notation.

Two-tiered City Logistics systems are made up of two layers of facilities and of vehicle fleets moving loads among facilities and from them to the appropriate customers. In such systems, loads are first sorted and consolidated at primary facilities, the consolidated loads being loaded into rather large vehicles, which bring them to a smaller facility "close" to the City-Logistics controlled zone, hereafter named *city center*. This makes up the first tier of the system. Loads are then transfered to smaller vehicles, appropriate for city-center activities, which then deliver them to the final customers, thus making up the second tier of the system.

Primary facilities may be intermodal platforms or City Distribution Centers (CDCs). They are generally large in terms of load and vehicle-handling capacity and are located on the outskirts of the city. Freight may also arrive on ships or trains, however, and sorting and consolidation operations may be performed in facilities located within the port, rail yard, or rail station situated close to or within the city. We refer to all these primary facilities and sites as *external zones*, denoted by the set $\mathcal{E} = \{e\}$ and illustrated by large squares in Figure 1.

Let $\mathcal{C} = \{c\}$ represent the customers that may be served (are registered with) the system. On any given day, loads of products $p \in \mathcal{P}$ are destined to a subset of customers in $\mathcal{C}$. Let $\mathcal{D} = \{d\}$ represent the set of *customer demands* corresponding either to such a subset or to an aggregation of customers located within a particular zone with the city center. A customer demand d is characterized by a volume $vol(d)$ of product $p(d)$ available 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 the customer (i.e., unload the freight) is denoted $\delta(d)$. The small disks in Figure 1 illustrate a number of customer demands.

The second tier of the system is constituted of satellite facilities, *satellites* for short, where loads coming from external zones are transferred to and consolidated into vehicles adapted for the city center and that perform the actual delivery routes. In the advanced system we address, satellites operate according to a vehicle synchronization and cross-dock transshipment operational model, i.e., vehicles operating within the first and second tiers of the system meet at satellites at appointed periods, with very short waiting times permitted, loads being directly moved from a first-tier - an *urban vehicle* - to a second-tier - a *city freighter* - vehicle without intermediate storage. Let $\mathcal{Z} = \{z\}$ stand for the set of satellites illustrated as triangles in Figure 1. The nature of each satellite location

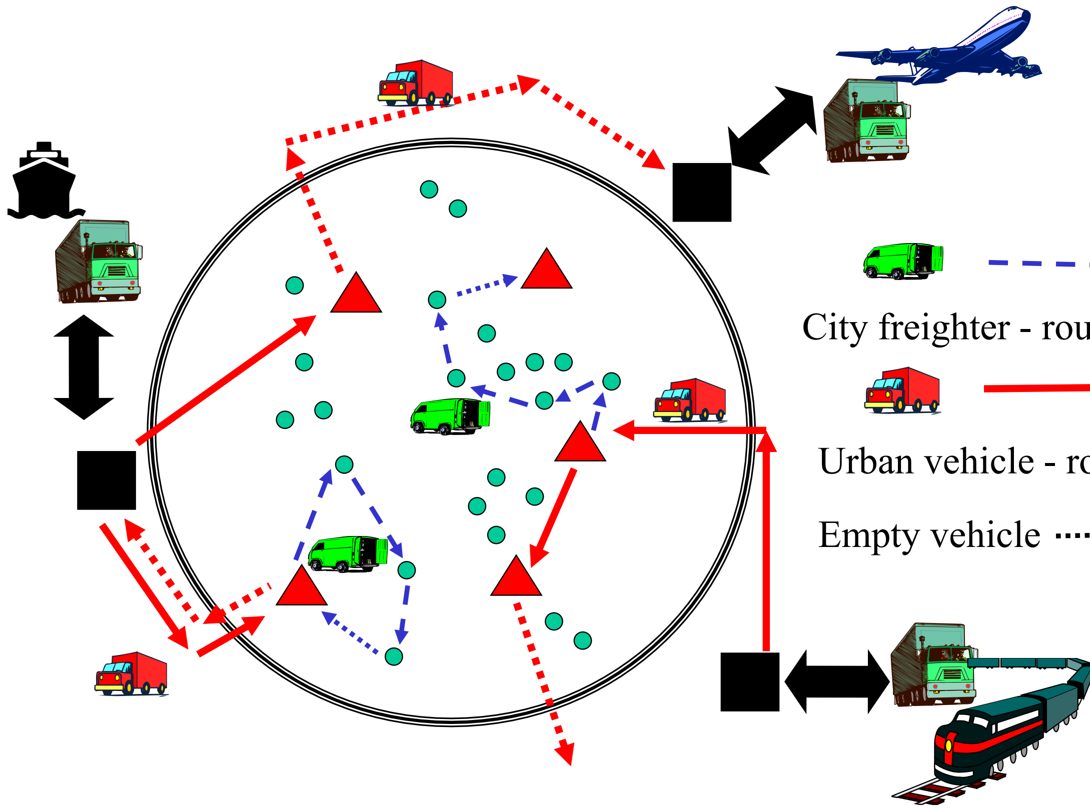

Figure 1: A Two-tiered City Logistics System Illustration

determines when it can be used, its topology, available space, and connections to the street network yielding its capacity measured in the number of urban vehicles $u_z^{\mathcal{T}}$ and city freighters $u_z^{\mathcal{V}}$ it can accommodate simultaneously. The (small) time vehicles are allowed to wait at satellites is assumed, for simplicity of presentation, the same for all satellites and is denoted δ.

Urban vehicles move freight Within the first tier, from external zones 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. Urban vehicles may visit more than one satellite during a trip, and their routes and departure times have to be optimized and coordinated with satellite access and city-freighter availability. Let $\mathcal{T} = \{\tau\}$ represent the set of urban-vehicle types, with corresponding fleet sizes n_τ and capacities u_τ. Thick arrows in Figure 1 represent urban-vehicle movements, empty for dotted arrows.

City freighters are vehicles of relatively small capacity that can travel along any street in the city center to perform the distribution of freight from satellites to customers. Let $\mathcal{V} = \{\nu\}$ represent the set of city-freighter types, with corresponding fleet sizes n_ν and capacities u_ν. Narrow dashed arrows in Figure 1 represent city-freighter movements, empty for dotted arrows. Because not all products may be loaded together, the vehicle-type definitions encompass the identification of the products they may carry, and include as many "copies" of an actual vehicle as there are mutually exclusive products that may use it (products that are not incompatible may use all the copies). One then has $\mathcal{T}(p) \subseteq \mathcal{T}$ and $\mathcal{V}(p) \subseteq \mathcal{V}$, the sets of urban vehicles and city freighters, respectively, that may be used to transport product p.

Let $\delta(\tau)$ represent the time required to unload an urban vehicle of type τ and $\delta(\nu)$ stand for the loading time (assuming a continuous operation) of a city freighter of type ν. Without loss of generality, we assume these durations to be independent of particular satellites. Also let $\delta_{ij}(t)$ stand for the time-dependent travel times, between all couples i, j of (origin, destination) points in the system, reflecting the settings of each particular application, in particular the estimated congestion conditions at departure time t. Travel times are not necessarily symmetric and the triangle-inequality conditions cannot be assumed.

From a physical point of view, the system then operates according to the following sequence: freight arrives at an external zone where it is consolidated into urban vehicles, unless it is already into a fully-loaded urban vehicle; each urban vehicle receives a departure time and route, travels to one or several satellites, unloads, and either leaves the system or travels to an external zone where it waits for the next departure; at satellites, freight is transferred to city freighters; each city freighter performs a route serving the designated customers, and then travels to a satellite, or a so-called *depot*, for its next cycle of operations. City freighters travel to a depot when the last customer on the route is served and no immediate operation is planned at a satellite. Depots, represented by set $\mathcal{G}$, may be the actual city-freighter garages or other existing facilities, e.g., parking lots or municipal bus garages.

From an information and decision point of view, the process starts with the demand for loads to be distributed within the urban zone. The consolidation of the corresponding freight yields the actual demand for the urban-vehicle transportation and the satellite cross-dock transfer activities that, in turn, generate the input to the city-freighter circulation. The objective is to have urban vehicles and city freighters on the city streets and at satellites on a "needs-to-be-there" basis only, while providing timely delivery of loads to customers and economically and environmentally efficient operations.

3 Planning and Uncertainty Issues

This section is dedicated to exploring a number of general concepts related to planning and uncertainty, focusing on tactical planing and on how demand uncertainty may be accounted for in the associated processes and formulations. The exploration is viewed through the City Logistics lens and starts with a review of the main issues in planing City Logistics systems and associated contributions present in the literature. It then moves to the particular case of uncertainty and tactical planning, where the City Logistics case is contrasted to that of other freight transportation carriers operating consolidation systems. The goal is to identify issues and challenges associated with accounting for uncertainty in planning City Logistics system and thus define and position our work.

3.1 Planning City Logistics Systems

Planning occurs when one desires to identify, sequence and, eventually, provide with resources a set of events, activities, and decisions. It contributes to the efficiency and performance of complex systems with many interacting components, goals, activities, and resources. The resulting plan may concern either all the activities over a given length of time - the *campaign* for the *planning horizon* - and be thus applied once only, or may address operations over a "short" time span and be repeatedly applied over the planning horizon. The deployment over a number of years of additional capacity for a production-distribution system belongs to the former case, while the design of the weekly schedule for the next season of a consolidation-based carrier, for passengers or freight, illustrates the latter. The length of the planning horizon, the level of operational and temporal detail one aims to address, the level of management and decision-making involved, and the amount of resources required to implement the plan identify the planning activity as strategic (long-term), tactical (medium term), or operational (short term or real time). It is noteworthy that these categories are not exclusive blocks, but rather indicative of a continuum of planning processes. actual definitions being particular to each industrial sector or, even, firm. Equally noteworthy, processes at different levels interact, higher levels of decision making providing policies and guidelines to activities lower in the above-described planning hierarchy, while these, in turn, provide the measures and instruments needed to build and evaluate higher-level policies and directions. City Logistics systems belong to such settings and require planning at strategic, tactic, and operational levels (Benjelloun and Crainic, 2008; Crainic et al., 2009a).

The strategic level is concerned with the design of the system and its evaluation. Strategic CL design issues concern locating facilities at all levels, selecting dedicated corridors for various types of traffic movements, determining the composition and dimension of the vehicle fleets, etc. Few contributions have yet been proposed, most of them addressing the issue of locating CDC facilities in single-tier systems (e.g., Taniguchi et al., 1999). Crainic et al. (2004) proposed a model to determine satellites locations for two-tiered systems, while the cost of customer service from satellites, the second-tier routing, is approximated. According to the best knowledge of the authors, Boccia et al. (2011) and Boccia et al. (2010) are the first contributions to jointly address the location of both CDC and satellite facilities and the routing of the first and second-tier vehicles. The former contribution introduces and discusses the problem class, proposes several formulations for the basic version of the problem, and compares them on small-sized instances; A tabu search meta-heuristics is proposed in Boccia et al. (2010). All previous contributions do not address uncertainty issues.

Evaluation refers to estimating the probable behavior and performance of proposed systems and operating policies under a broad range of scenarios. It also addresses the continuous analysis of deployed systems and the planning of their evolution, both as stand-alone systems and in relation to the general transportation system of the city and the larger region that encompasses it. In particular, the choice of a specific City Logistics business model and operational structure should be based on cost-benefit analyzes performed using such strategic planning models. Few formal models have been proposed specifically for City Logistics (Taniguchi and van der Heijden, 2000; Taniguchi et al., 2001a; Taniguchi and Thompson, 2002), but simulation-based models and methods start to be introduced (Barceló et al., 2007). Benjelloun and Crainic (2008) discuss the challenges associated to extending the urban transportation systems planning methodology to City Logistics, but the individual models and methods that would make it up are still to be developed for the most part.

At the other extreme of the planning-level scale, operational plans address issues related to work schedules of vehicle drivers and terminal personnel, maintenance of vehicles and facilities. It is also at the operational level that one performs the control and dynamic adjustment of vehicle and terminal operations. Although we are not aware of any specific contribution to the first topic, a few papers deal with the second, focusing generally on the operations of a single fleet within a limited part of the city (e.g., Taniguchi et al., 2001b; Thompson, 2004).

Tactical planning usually bridges the gap between long-term strategic decisions and the management of operations. Synthetically, strategic planning designs the system, tactical designs the service and allocates resources to operate within the given system aiming for the objectives set for it, while the operational level implements and adjusts the tactical plan to actually satisfy the customer demand. From a temporal point of view, strategic plans are typically built over multi-year horizons, tactical plans are valid for a limited number of months making up the"next" season, while operational activities focus on days or even minutes.

City Logistics systems belong to the important class of consolidation-based transportation systems that include rail and less-than-truckload carriers, high-sea navigation lines, intermodal systems, express currier and postal services, and so on. Tactical planning for such systems aims to build a transportation (or load) plan to provide for efficient operations and resource utilization, while satisfying the demand for transportation within the quality criteria (e.g., delivery time) publicized or agreed upon with the respective customers (Crainic, 2000, 2003; Crainic and Kim, 2007). The scope of the plan is to select the services to operate (routes, types of vehicles, speed and priority, and so on) and their schedules, determine the policies and rules conducting the classification and consolidation of freight and vehicles at terminals for long-haul movements, fix the itineraries used to move the freight between each particular origin-destination pair (for each product and customer, eventually). General resource-management policies are also within the scope of tactical planning, in particular those related to the management of the fleet (empty-vehicle repositioning, power allocation and circulation, etc.).

Tactical planning models for City Logistics concern the departure times, routes, and loads of vehicles at all levels, the routing of demand and, when appropriate, the utilization of the second-tier consolidation facilities and the distribution of work among them. Tactical planning models assist the deployment of resources and the planning of operations and guide the real-time activities of the system. They are also important components of models and procedures to evaluate City Logistics systems, from initial proposals to deployment scenarios and operation policies. Yet, very few contributions to tactical planning methodology may be found in the literature. Crainic et al. (2009a) present an in-depth discussion of the issues and challenges in the context of inbound traffic within a two-tiered City Logistics system. The authors also introduce a comprehensive methodological framework, proposing formulations and an algorithmic scheme (see Crainic et al., 2009b, for an application of the methodology to the single-tier case). Our present work constructs upon this methodological foundation.

3.2 Uncertainty and tactical planning

Demand uncertainty is inherent in any complex system and planning processes and City Logistics is no exception. Various sources and type of uncertainty may be defined (see, e.g., Klibi et al., 2010). In this work with focus on the uncertainty related to the variation of predicted demand over the next planning period, variation that is observed and has to be dealt with when the plan is applied day after day during actual operations.

The first main issue concerns the choice of an appropriate methodological approach, choice related to the relative importance and confidence one puts in the demand forecasts and the magnitude of the variability of demand. A series of problems and formulations follow from the combination of particular answers to these issues.

At one extreme of this sequence one finds the case of total confidence in forecasts of (very) low variability. A deterministic model (e.g., Crainic et al., 2009a, and 4) may then be used to plan and schedule all or part of the activities, as well as the allocation of the corresponding resources. "Accidental" variations in observed demand are then addressed through ad-hoc extra capacity, e.g., external vehicles or carriers or delayed delivery with penalty cost (using a model similar to the one is Section 5).

The other extreme of the problem setting series finds a very high variability of demand combined to a low or no confidence in the possibility to adequately forecast it. This case is characteristic of the no-tactical-plan, quasi real-time planning situation observed in many fleet management situations (e.g., Powell, 2003; Powell et al., 2007). For City Logistics, this case may still yield a planning problem, however. Indeed, given the advanced information systems normally linking the customers, carriers. and managers of City Logistics systems, it is reasonable to expect the system to be aware of most orders passed by customers as well as of the planned day of arrival and distribution time window. This case then corresponds to the day-before planning problem class Crainic et al. (2009a) with, eventually, considerations of late arrival-induced variations.

In between these extremes, the various problem settings differ in the latitude left to the adjustment of the plan once the actual demand is observed. This corresponds to the second main issue concerned with what part of operations should be fixed within a plan and what should be left to be decided on the day of operations. Put into stochastic-programming terms, "what decision goes in each stage?"

For most consolidation-based systems, all transportation services are generally covered by the plan, e.g., the trains (and the blocks that make them up), the trucks, the high-sea vessels, etc. The plan also gives broad guidelines for routing the freight for each origin-destination pair of terminals but the actual itineraries are generally defined for each shipment. Stochastic models addressing demand variability for consolidation carriers thus usually take the form of two-stage formulations, where the "design" decisions selecting the service network appear in the first stage, while routing is decided in the second (Lium et al., 2009; Crainic et al., 2011).

Such a strategy for City Logistics would include in the tactical plan the first-tier service design, the second-tier routing and scheduling of city freighters (their work assignments), and the customer-demand itineraries. Then, once actual demand is observed, any extra demand would be delivered using the residual capacity of the first and second-tier vehicles and satellites, if any, as well as extra city freighters as needed.

We believe this strategy to be much too rigid, a case of "over planning" assuming a very low variability of demand and not allowing any significant operational flexibility. Moreover, it does not really fit the case of City Logistics systems, which are somewhat different from the more traditional consolidation-based carriers. Indeed, "all" transportation services in two-tiered City Logistics systems means services on the first and the second tiers provided by urban vehicles and city freighters, respectively. These two components do not face the same variability with respect to their “customers” however. Thus, for example, the actual location where a delivery is to be made within a clustered group of offices or streets might vary daily, yet the total volume to be delivered to the set of customers within those offices or streets would be fairly stable. This illustrates the characteristic that large volumes from external zones to urban regions clustered “around” satellites should be rather regular and stable, while actual delivery routes should vary at each day.

Consider also that, in contrast to most consolidation-type carriers, City Logistics systems are not required to publish and follow a rigid schedule. Planning is in fact performed to achieve an efficient allocation and utilization of resources, satellites and vehicles, as well as a low-impact scheduling of services relative to the expected traffic conditions of the city. It is then sufficient at the planning stage to select services - departures and satellites visited -, identify the workloads of satellites, in terms of numbers of vehicles of both tiers accommodated at each time period and the customers to be served, and determine the approximate numbers of vehicles required. The plan is then instantiated for each day once the actual demand is known by determining the actual routing of the city freighters and, possibly, adding extra vehicles as needed and slightly modifying the service network. This is the class of situations we address as described in the next section.

4 Modeling Framework

This section is dedicated to the methodology we propose to build the tactical plan‘while accounting for uncertainty in demand. We follow the stochastic programming two-stage formulation with recourse approach (Kall and Wallace, 1994; Birge and Louveaux, 1997). The *a priori* plan is built prior to the beginning of the season in order to fix the structure of the work plan that will be then executed regularly each day. The goal is to optimize the cost of the system, in terms of resource allocation and operations as well as environmental impact, while also providing the flexibility needed to efficiently and economically adjust operations to actual demand. The recourse then models the strategies and associated costs of adapting this plan to the day-to-day operations, that is, given realizations of demand. The presentation proceeds "pedagogically" and first introduces the first-stage formulation in this section, together with the information it yields - the plan - for the second stage. The formulations of possible recourse strategies are then presented in the next sections.

In the modeling framework we propose, the plan concerns the selection of the first-tier services and schedules together with the associated demand itineraries from external zones to satellites. This also allocates customers to (satellite, period) rendez-vous points, thus giving strong indications on the satellite workloads and the dimensions of the fleets of city freighters required. City-freighter routing decisions are left for the second stage and, thus, only an approximation of the corresponding costs and operations are integrated in the first-stage decisions. The recourse then addresses the city-freighter routing, determines the extra capacity required, if any, and, eventually, slightly modifies the service network. The notation and model development follow Crainic et al. (2009a).

The plan is built for a contiguous time available for daily operations, denoted work-day length (of a few hours to a half day in most cases), which is divided into $t = 1, ..., T$ periods. (When more than one work day exists within an actual day, a plan is built for each of them.) Similarly to Crainic et al. (2009a), the *period length* is defined such that 1) at most one departure of a service from its external zone may take place during a period, and, 2) the unloading times for urban vehicles are integer multiples of the period length.

Let $\widehat{vol(d)}$ be the point forecast of the volume of customer demand $d \in \mathcal{D}$ used in the first stage of the formulation. Usually, $\widehat{vol(d)}$ corresponds to the "best" estimate used in deterministic service network design, 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 plan to provide for a resource allocation and scheduling able to address this demand or, in other words, to provide at least this level of service in all cases.

Let $\Omega = \{\omega\}$ be the sample space of the random event and ω a random element in Ω. We then denote $\mathcal{D}(\omega) = \{d(\omega)\}$ the set of customer-demand realizations for $\omega \in \Omega$, with $\mathsf{D} = \{\mathcal{D}(\omega) | \omega \in \Omega\}$. The demand volume, $vol(d)$, varies randomly and, thus, $vol(d(\omega))$ stands for the volume associated with $d(\omega)$. (The notation of all attributes associated to customer-demand realizations is qualified by adding the ω symbol.)

Consider the set of urban-vehicle *services* $\mathcal{R} = \{r\}$. Service r operates a vehicle of type $\tau(r) \in \mathcal{T}$, originates at external zone $e(r) \in \mathcal{E}$, travels to one or several satellites, and returns to an external zone $\bar{e}(r)$, possibly different from $e(r)$. The ordered set of visited satellites is denoted $\sigma(r) = \{z_i \in \mathcal{Z},\ i = 1, \ldots, |\sigma(r)|$, such that if r visits satellite i before satellite j then $i < j\}$. The cost associated to service $r \in \mathcal{R}$ is denoted $k(r)$. The cost captures the monetary expenses of operating the route, including loading and unloading freight, as well as any “nuisance” factors related to the presence of the urban vehicle in the city at the particular time of the service.

Together with the access and egress corridors, $\sigma(r)$ defines a route through the city. Let $t(r)$ be the period the service leaves its origin $e(r)$ to perform this route. The urban vehicle then arrives at the first satellite on its route, $s_1 \in \sigma(r)$, at period $t_1(r) = t(r) + \delta_{e(r)z_1(r)}(t(r))$, 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 the 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 $t_0(r) = t(r)$, $t_i(r) = t_{i-1}(r)+\delta(\tau)+\delta_{z_{i-1}(r)z_i(r)}(t(r))$, for $i > 0$, representing the period the service visits satellite $z_i \in \sigma(r)$, and the service finishes its route at the external zone $\bar{e}(r)$ at period $t_{|\sigma(r)|+1}$.

Freight is moved from external zones to customers via *itineraries*, each made up of an urban-vehicle movement, a transshipment operation at a satellite, and the final distribution by a city-freighter route. The latter is represented at tactical planning level by $\tilde{k}(d, z, t)$, an approximated cost of delivering demand $d \in \mathcal{D}$ by the appropriate type of city freighter, from satellite z starting in period t. Similarly to the $k(r)$ definition, $\tilde{k}(d, z, t)$ includes the cost of loading and unloading 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. Let $\mathcal{M}(d) = \{m\}$ stand for the set of itineraries that may be used to satisfy customer demand $d \in \mathcal{D}$. The itinerary $m \in \mathcal{M}(d)$ then leaves its external zone $e(d) \in \mathcal{E}$ on urban-vehicle service $r(m) \in \mathcal{R}$ at $t_e(m) = t(r(m)) > t(d)$, and arrives at satellite $z(m) \in \sigma(r(m))$ in period $t_z^{\text{in}}(m) = t_{z(m)}(r(m))$, where it is transferred to a city freighter for delivery at the final customer $c(d)$ according to its time window.

Two sets of decision variables are defined to select urban-vehicle services and demand itineraries, where the superscript 1 identifies the first stage of the formulation:

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

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

The two-stage formulation that minimizes the expected cost of the system over the planning horizon may then be written as

$$\text{Minimize} \quad \sum_{r\in\mathcal{R}} k(r)\rho^1(r) + \sum_{d\in\mathcal{D}}\sum_{m\in\mathcal{M}(d)} \tilde{k}(d,z,t)\widehat{vol(d)}\zeta^1(m) + \mathrm{E}_{\mathsf{D}}\left[Q(x(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1),\mathcal{D}(\omega))\right] \tag{1}$$

$$\text{Subject to} \quad \sum_{d\in\mathcal{D}}\sum_{m\in\mathcal{M}(d,r)} \widehat{vol(d)}\zeta^1(m) \le u_\tau \rho^1(r) \qquad r\in\mathcal{R}, \tag{2}$$

$$\sum_{m\in\mathcal{M}(d)} \zeta^1(m) = 1 \qquad d\in\mathcal{D}, \tag{3}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t}\ \sum_{r\in\mathcal{R}(z,t^-)} \rho^1(r) \le u_z^{\mathcal{T}} \qquad z\in\mathcal{Z},\ t=1,\ldots,T, \tag{4}$$

$$\sum_{\nu\in\mathcal{V}}\left[\sum_{d\in\mathcal{D}}\sum_{m\in\mathcal{M}(d,z,t)} \widehat{vol(d)}\zeta^1(m)\right]/u_\nu \le u_z^{\mathcal{V}} \qquad z\in\mathcal{Z},\ t=1,\ldots,T, \tag{5}$$

$$\rho^1(r)\in\{0,1\} \qquad r\in\mathcal{R}, \tag{6}$$

$$\zeta^1(m)\in\{0,1\} \qquad m\in\mathcal{M}(d),\ d\in\mathcal{D}. \tag{7}$$

where the objective function (1) minimizes the cost of selecting and operating services to move the forecast demand from external zones to satellites, plus the approximated cost of using the satellites and delivering this demand, 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 $x(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1)$ adjusted, *instantiated*, for the realized demand $\mathcal{D}(\omega)$ by applying a given recourse policy RP with cost $Q^{RP}(x(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1),\mathcal{D}(\omega))$. We use the notation $x(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1))$ to emphasize that the second stage optimization problem is constrained by the decisions of the fixed stage, $\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1$, which fix part of system $x(.,.)$. The particular elements that are fixed vary according to the recourse strategy as described in the next three sections.

Constraints (2) enforce the capacity restrictions of urban vehicles, while constraints 3 make sure each customer demand is delivered through a unique itinerary. Constraints (4) and (5) enforce the satellite capacity at all periods in terms of urban vehicles and city freighters, respectively, the latter being an approximation derived from the total volume of demand that has to leave the satellite at the given period on city freighters of all types.

A feasible solution for the formulation of the first stage - an priori plan - specifies

- A set of urban-vehicle services $\mathcal{R}(\boldsymbol{\rho}^1)$ to be operated;

- A set of partial itineraries $\mathcal{M}(\boldsymbol{\zeta}^1) = \{m(\boldsymbol{\zeta}^1, d),\ d \in \mathcal{D}\}$ bringing the load of each customer demand $d \in \mathcal{D}$ to its appointed satellite and time period to be distributed by a city freighter of a particular type; Notice that, the hypothesis that loads cannot be split implies a single partial itinerary is selected for each demand;

- A set of active *rendez-vous* points (satellite, period), $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \bigcup_{\nu \in \mathcal{V}} \mathcal{ZT}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1))$, where urban vehicles and city freighters meet and freight is transferred for final delivery; The sets $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, for $\nu \in \mathcal{V}$, give the corresponding customer-to-satellite assignment, with $\mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \bigcup_{\nu \in \mathcal{V}} \bigcup_{zt \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$.

To instantiate the plan for each day of the season, the recourse strategy of the second stage must determine the actual routing for the observed demands and provide additional capacity when needed, within the limits imposed by this feasible solution. The next sections present such recourse strategies.

5 Routing recourse

The first strategy aims to modify the plan as little as possible and, thus, the sets of selected services, $\mathcal{R}(\boldsymbol{\rho}^1)$, active rendez-vous points, $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, and the associated customer-to-satellite assignments, $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, are not modified.

Recall that the $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ sets give an estimation of the size of the fleet of city freighters required given the forecast demand, as well as an upper bound on the number of city freighters of each type ν planned to leave each rendez-vous point (z, t), $F^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \lceil \sum_{d \in \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} \widehat{vol(d)} / u_{\nu} \rceil$, grouped in the vector $F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. These upper bounds provide for a feasible vehicle circulation from the point of view of satellite capacity and are therefore also enforced in the proposed *routing* recourse strategy. Additional city freighters, not using the planed satellites, are then required to service any extra demand, if any. The recourse term in the global objective function (1) corresponding to this first strategy may then be written as

$$Q^{\mathrm{R}} \left(\mathcal{R}(\boldsymbol{\rho}^1), F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega) \right) \tag{8}$$

The main task of the second stage is to determine the actual routing of flows once the particular realization of demand $d(\omega)$ has been observed. We therefore identify it as the *routing* recourse. When all volumes are lower or equal to the forecast values, the services and itineraries determined in the first stage are feasible and one has just to solve the *synchronized, scheduled, multi-depot, multiple-tour, heterogeneous vehicle routing problem with time windows* (*SS-MDMT-VRPTW*) introduced by Crainic et al. (2009a), restricted to the (satellite, period) rendez-vous points that belong to $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$.

Following Crainic et al. (2009a) but accounting for the first-stage decisions, let $\mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \bigcup_{\nu} \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ \nu(w) \in \mathcal{V}$, be the set of feasible *work segments* for city freighters, where each $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ visits a sequence of satellites $\sigma(w) = \{(z_l, t_l) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ l = 1, \ldots, |\sigma(w)|\}$, and associated customers, according to a schedule compatible with the required travel and service times as well as the admissible rendez-vous points $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. (The city-freighter arrives empty out of a depot, but this movement is not included in the work segment.) At each satellite z_l on its route, the city freighter takes loads to deliver to a set of customers $\mathcal{C}_l(w)$ $(= \mathcal{C}^{\nu}_{z_l t_l}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1))$. We define the route *leg* l, the work-segment component that starts at satellite z_l, serves the customers in $\mathcal{C}_l(w)$, and then proceeds to satellite z_{l+1} (or a depot $g(w)$ when satellite z_l is last in $\sigma(w)$). The set $\mathcal{L}(w)$ contains all route legs of work segment w sorted in the same order as $\sigma(w)$. Figure 2 illustrates a feasible two-leg work segment, where zt and gt represent feasible rendez-vous points $(z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and pairs of (depot, period) (g, t), respectively, $z_1 = z$, $z_2 = z'$, $\mathcal{C}_1(w) = \{i, k, j, \ldots, f\}$ and $\mathcal{C}_2(w) = \{a, b, c, \ldots, d\}$. The dashed lines stand for undisplayed customers, whereas the dotted lines indicate the empty arrival from a depot (not included in the segment), the empty movement from the last customer demand in

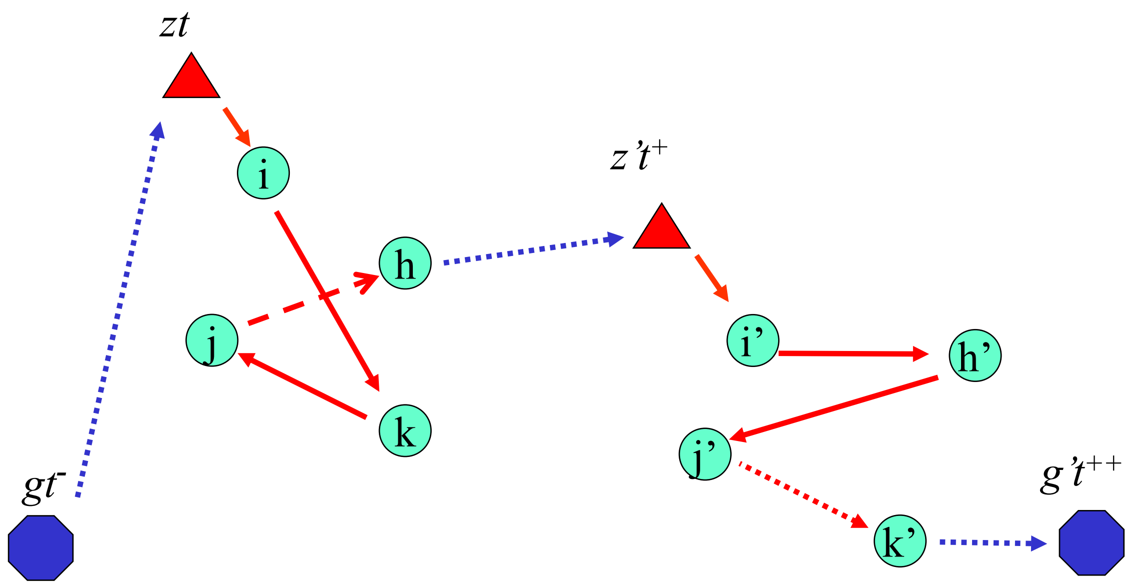

Figure 2: A City-Freighter Two-Leg Work Segment Illustration (Crainic et al., 2009a)

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 $\delta_l(w)$, $l \in \mathcal{L}(w)$, 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. Let the *starting time* of the work segment equal the arrival time at the first satellite in the sequence, $t(w) = t_1(w)$. The arrival times at the other satellites in the sequence are then given by $t_l(w) = t_{l-1}(w) + \delta(\nu) + \delta_l(w)$, $l = 2, \ldots, |\sigma(w)| + 1$, with $t_{|\sigma(w)|+1}(w) = t(g(w))$ the 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 $\delta(w)$. The costs of operating city-freighter legs and work segments are denoted $k_l(w)$ and $k(w)$, respectively, where $k(w) = \sum_{l \in \mathcal{L}(w)} k_l(w)$. A "fixed" cost is also included in $k(w)$ to represent the cost of travel from and to the depot and capture the economies of scale related to long (but legal) work segments.

The actual demand may, however, exceed the capacity offered by the planned services $\mathcal{R}(\boldsymbol{\rho}^1)$ and city freighter fleet $F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. Extra capacity must then be used. It is assumed that the extra capacity involves a much higher cost than regular operations. When services and satellite workloads are not altered, extra capacity has to be provided by additional vehicles that can move in all the zones of the city. This excludes urban vehicles. We therefore assume that city freighters are used to provide the needed extra capacity.

Several operational strategies may be envisioned, each requiring particular numbers of vehicles and resulting in specific costs. The choice of a strategy or strategies strongly depends on the application context: city topography, city regulations and labor relations, the particular combination or public and private involvement, and so on. To illustrate, we describe three such strategies, identifying for each case the definition of associated work segment set $\mathcal{W}^+ = \bigcup_{\nu \in \mathcal{V}} \mathcal{W}^+(\nu)$ (see Crainic et al., 2010, for a more in-depth discussion of fleet integration strategies):

Partitioned fleet. According to this strategy, a certain number of city freighters would be associated to each external zone, some customers being served by tours starting and terminating at their corresponding external zones. A feasible work segment then corresponds to a feasible solution to a time-dependent multi-tour VRPTW starting at a given external zone, each tour departure defining a leg.

It is worth noting that this is arguably the most expensive strategy (with the exception of sending a vehicle for each demand), with the largest number of vehicles moving within the city. Actually, when the need for extra capacity is not too high, a more environmental-friendly solution is to have loads delivered by an express courier carrier for a higher degree of consolidation and a lower number of vehicles in the city.

Single fleet. In this case, a city freighter work segment would follow the sequence, from the garage to an external zone for loading, travel to deliver the corresponding customers then, either the day and leg are finished and the vehicle returns to the garage, or it travels to another external zone to complete the current leg and start a new sequence of operations (after, possibly, waiting for the appropriate departure time). A feasible work segment for a given city-freighter type then then takes the form of a feasible solution to a time-dependent (single or multi-depot) pick up and delivery routing problem with time windows, where customer loads picked up at an external zone must all be delivered before another pick up may take place.

Pickup&Deliver. The previous definition enforces the delivery of the loads picked up at an external zone before the vehicle travels to the next external zone in its work segment. This is very restrictive, particularly when distances between external zones and customers are significant and the number of actual customer demands for each external zone and period is not very high. This alternative definition allows the vehicle to pick up loads at an external zone, travel to one or more other external zones to pick up more loads, deliver, return to an external zone, and so on. Feasible work segments are then feasible solutions to time-dependent (single or multi-depot) pick up and delivery routing problems with time windows, where either a LIFO loading/unloading policy is enforced, or loads may be re-arranged within the vehicles at "intermediary" external zones. Similarly to the previous strategy, a leg corresponds to an inter external zones set of operations.

Similarly to the other costs defined in this paper, the cost $k(w)$ associated to work segment $w \in \mathcal{W}^+$ includes the cost of loading and unloading freight at external zones and customers, 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 operation. It is assumed, of course, that the cost of the extra vehicles is higher than that of the regular operations.

We may now define the customer-demand itineraries and decision variables for the routing recourse. The first-stage decisions provide a partial itinerary $m(\boldsymbol{\zeta}^1, d) \in \mathcal{M}(\boldsymbol{\zeta}^1)$ for each demand specifying a first-tier service $r \in \mathcal{R}(\boldsymbol{\rho}^1)$, a city freighter type, and a rendez-vous point $zt \in \mathcal{ZT}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1))$. Most demand will there move on an itinerary $m \in \mathcal{M}(d(\omega)) \subset \mathcal{M}(d)$ composed of this partial itinerary $m(\boldsymbol{\zeta}^1, d)$ and part of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ of a city freighter of appropriate type. When total demand exceeds the planned capacity, however, some customer demands will be moved instead by one of the additional vehicles operating one of the work segments in $\mathcal{W}^+$. The associated set of itineraries is denoted $\mathcal{M}^+(d(\omega))$. As defined by Crainic et al. (2009a), the costs associated to itineraries are accounted for through the service (first stage) and routing costs.

Two sets of decision variables are defined for the recourse formulation to select city-freighter work segments and customer-demand itineraries, respectively

- $\varphi^2(d(\omega), w) = 1$, if work segment $w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \cup \mathcal{W}^+$ is selected, 0, otherwise;
- $\zeta^2(d(\omega), m) = 1$, if itinerary $m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))$ of demand $d(\omega) \in \mathcal{D}(\omega)$ is selected, 0, otherwise.

The second stage routing model then becomes:

$$Q^{\mathrm{R}}\left(\mathcal{R}(\boldsymbol{\rho}^1), F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \bigcup \mathcal{W}^+} k(w)\varphi^2(d(\omega), w) \tag{9}$$

$$\sum_{m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))} \zeta^2(d(\omega), m) = 1 \quad d(\omega) \in \mathcal{D}(\omega) \tag{10}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}(d(\omega), r)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_\tau \quad r \in \mathcal{R}(\boldsymbol{\rho}^1), \tau(r) \in \mathcal{T}, \tag{11}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_\nu \varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w),\ w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ v \in \mathcal{V}, \tag{12}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}^+(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_\nu \varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w), w \in \mathcal{W}^+(\nu),\ v \in \mathcal{V}, \tag{13}$$

$$\sum_{w \in \mathcal{W}(\nu,\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1,z,t)} \varphi^2(d(\omega), w) \leq F^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \quad (z,t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \nu \in \mathcal{V}, \tag{14}$$

$$\varphi^2(d(\omega), w) \in \{0,1\}, \quad w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \cup \mathcal{W}^+,\ \nu \in \mathcal{V}, \tag{15}$$

$$\zeta^2(d(\omega), m) \in \{0,1 \quad m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega)),\ d(\omega) \in \mathcal{D}(\omega), \tag{16}$$

where $\mathcal{M}(d(\omega), r)$, $\mathcal{M}(d(\omega), l)$, and $\mathcal{M}^+(d(\omega), l)$ stand for the sets of itineraries for customer demand $d(\omega) \in \mathcal{D}(\omega)$ using urban-vehicle service $r \in \mathcal{R}(\boldsymbol{\rho}^1)$, and leg $l \in \mathcal{L}(w)$ of work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ or $w \in \mathcal{W}^+(\nu)$ (for city-freighter type $v \in \mathcal{V}$), respectively, while $\mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t)$ is the set of work segments loading at a rendez-point $(z,t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$.

The objective function minimizes the generalized cost of operating normal and additional city freighter routes and performing the associated loading and unloading activities. Equations (10) enforce the single-itinerary requirement for customer delivery. Relations (11) ensure the capacity of the services selected in the first stage are respected. Constraints (12) and (13) enforce the capacity of city freighters operating the regular delivery circuits and the additional routes, respectively. The limits on the number of departures of each city-freighter type at each rendez-vous point determined during the first stage are controlled by constraints (14), while the integrality of the decision variables is enforced through (15) and (16).

6 Assignment and Routing Recourse

The second recourse strategy introduces more flexibility in addressing variations in demand, while still not significantly modifying the resource allocation and plan determined at the first stage. The main idea is to fix the principal components of the plan, the sets of selected services and departure times, $\mathcal{R}(\boldsymbol{\rho}^1)$, and active rendez-vous points, $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, while allowing a full optimization of the corresponding routing problem.

With respect to the previous recourse, the customer assignments to particular rendez-vous points is no longer enforced. Consequently, the $F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ restrictions on the number of city freighters planned to leave each rendez-vous point, Constraints (14) are discarded as well. This results in additional flexibility being introduced by selecting not only city-freighter normal and additional routes appropriate for the observed demand, but complete demand itineraries as well. This motivates the *assignment and routing* name for the recourse, the corresponding term in the global objective function (1) taking the form

$$Q^{\mathrm{A}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) \tag{17}$$

The operational setting is similar to that of the routing-recourse section. The routing strategies and notation, as well as the definition of $\mathcal{M}^+(d(\omega))$, the set of itineraries using the additional city freighters operating the work segments in $\mathcal{W}^+$, are the same and are not repeated. Differences occur with respect to the "regular" demand itineraries, however, these being no longer forced to pass through the particular (satellite, period) rendez-vous point determined in the a priori plan for each specific demand. It is only globally that itineraries are restricted to the set of rendez-points $\mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ given by the plan, enforced through the set of selected urban-vehicle services. Itineraries in $\mathcal{M}(d(\omega)) \subset \mathcal{M}(d)$, for demand $d \in \mathcal{D}(\omega)$, are therefore composed of any of the first-tier services $r \in \mathcal{R}(\boldsymbol{\rho}^1)$ selected in the a priori plan and part of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ of a city freighter of appropriate type.

With this modification, the assignment-routing recourse formulation becomes:

$$Q^{\mathrm{R}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \bigcup \mathcal{W}^+} k(w)\varphi^2(d(\omega), w) \tag{18}$$

subject to constraints (10) - (13) and (15) - (16).

7 Service Dispatch and Routing Recourse

A different approach to service flexibility and the modeling of the corresponding recourse, is to fix the "backbone" of the urban vehicle service design, $\mathcal{R}(\boldsymbol{\rho}^1)$, as well as the sets of active rendez-vous points, $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, with their associated customer-to-satellite assignments, $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, while permitting to modify the corresponding urban-vehicle departure times. This may be viewed as a dispatching decision to let the vehicle leave somewhat earlier or later than the planed schedule. Because the routing of city freighters is also part of the recourse decisions, we identify this approach as *dispatch and routing* recourse and note the corresponding term in the global objective function (1) as

$$Q^{\mathrm{D}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) \tag{19}$$

To illustrate this idea, consider Figure 3 that focuses on the output of the first stage as observed at a selected rendez-vous point (z, t). In order not to overload the image, only one external zone e is illustrated, together with a selected service $r^o \in \mathcal{R}(\boldsymbol{\rho}^1)$ leaving e at period t'. Part of the loads brought in by r^o are to be transferred to city freighters of type ν to be delivered to customers $\{i, j, k\} = \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ within their time windows. When more than one service brings loads for customers in $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, as illustrated by the two other very thick arrows pointing toward (z, t), a consolidation operation takes place during the transfer. The actual routing of the city freighters is not yet decided, as illustrated by the complete graph within the ellipsoid representing $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and the dotted arrows pointing toward the possible end of the current leg at another rendez-vous point or a garage. One can deduce, however, a time window $[a(zt),\ b(zt)]$ for the satellite z of the rendez-vous point, such that customers in $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ served by a vehicles starting its route within the interval are still receiving their goods on time. Moreover, one can project this time window on the departure time of the service $r^o \in \mathcal{R}(\boldsymbol{\rho}^1)$ to obtain what we denote as an *opportunity time window* $[a(r^o), b(r^o)]$. A service similar to r^o but leaving within the opportunity window may still bring to z loads for customers in $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ such that the corresponding itineraries are feasible.

Let $\mathcal{R}(r^o)$ be the set of possible departures in the opportunity window of a service $r^o \in \mathcal{R}(\boldsymbol{\rho}^1)$, i.e., $\mathcal{R}(r^o) = \{r \mid e(r) = e(r^o),\ \sigma(r) = \sigma(r^o),\ a(r^o) \leq t(r) \leq b(r^o)\}$. To compute the opportunity interval, $a(r^o) = \min_{d(\omega) \in \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} a(d(\omega))$ minus the travel time of the urban vehicle from the external zone to the satellite, the approximate city freighter travel time to reach the customer from the satellite, and the loading/unloading time at satellite; one computes $b(r^o)$ similarly. Then, $\mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \bigcup_{r^o \in \mathcal{R}(\boldsymbol{\rho}^1)} \mathcal{R}(r^o)$ represents the set of services (service departures, actually) among which one may select to instantiate the plan to the observed demand.

The sets of regular and additional routes, $\mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and $\mathcal{W}^+$, respectively, are defined as for the previous two recourse strategies (Sections 5 and 6). The regular customer-demand itineraries are restricted to the services in $\mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and the satellite assignments

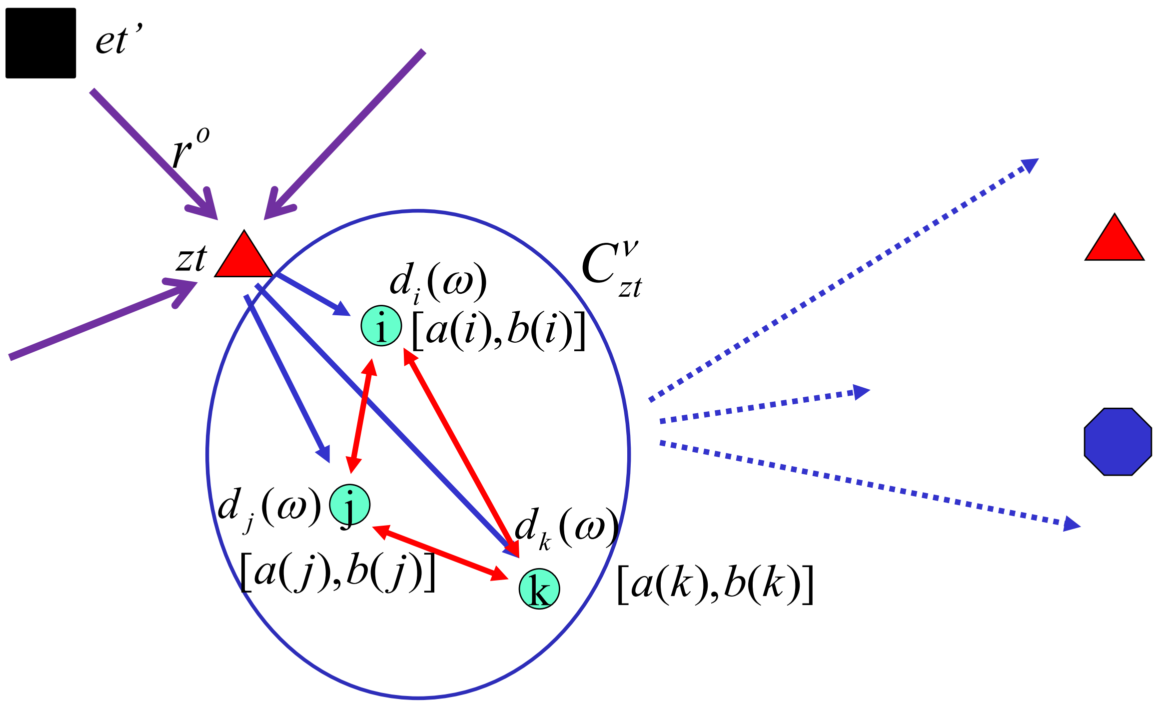

Figure 3: Output of Stage 1 - Zoom on a Rendez-vous Point

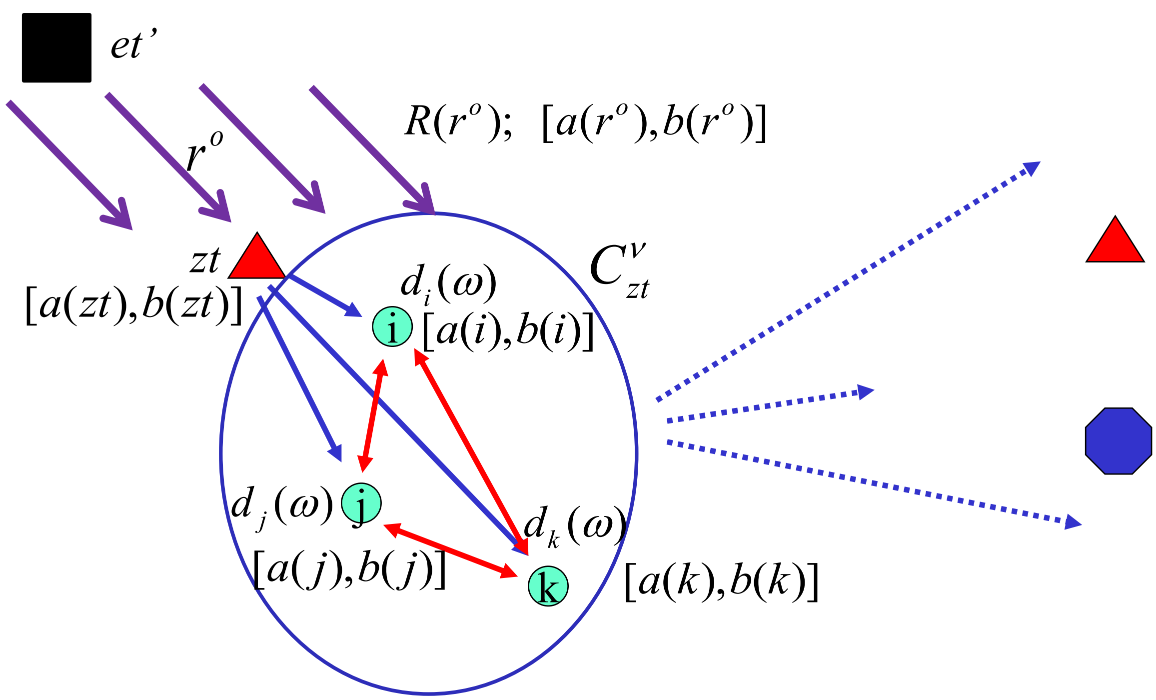

Figure 4: Service Opportunity Window - Zoom on a Rendez-vous Point

$\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ defined in the first stage. An itinerary $m \in \mathcal{M}(d(\omega)) \subset \mathcal{M}(d)$ in then composed of a first-tier service $r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ that brings the load at satellite z of $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ within $[a(zt),\ b(zt)]$, and part of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ of a city freighter of the appropriate type. Demand may alternatively be moved by an itinerary in $\mathcal{M}^+(d(\omega))$ corresponding to the operations of the additional city freighters operating work segments in $\mathcal{W}^+$.

Compared to the previous two strategies, a new set of decision variables must be added to account for the service departure-time selection. One then has

$\rho^2(d(\omega), r) =$ 1, if the urban-vehicle service $r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ is selected, 0, otherwise;

$\varphi^2(d(\omega), w) =$ 1, if the work segment $w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \cup \mathcal{W}^+$ is selected, 0, otherwise;

$\zeta^2(d(\omega), m) =$ 1, if itinerary $m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))$ of demand $d(\omega) \in \mathcal{D}(\omega)$ is used, 0, otherwise.

The second stage formulation takes then the form of the tactical model proposed by Crainic et al. (2009a), restricted to the sets of services, work segments, and itineraries defined above and accounting for the extra vehicles that may be required:

$$Q^{\mathrm{C}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} k(r)\rho^2(d(\omega), r) + \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \cup \mathcal{W}^+} k(w)\varphi^2(d(\omega), w) \tag{20}$$

$$\text{Subject to} \quad \sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))} vol(d(\omega))\zeta^2(d(\omega), m) \le u_\tau \rho^2(d(\omega), r) \quad r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \tag{21}$$

$$\sum_{r \in \mathcal{R}(r^o)} \rho^2(d(\omega), r) = 1 \qquad r^o \in \mathcal{R}(\boldsymbol{\rho}^1), \tag{22}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \le u_\nu \varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w),\ w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ v \in \mathcal{V}, \tag{23}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}^+(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \le u_\nu \varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w), w \in \mathcal{W}^+(\nu),\ v \in \mathcal{V}, \tag{24}$$

$$\sum_{m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))} \zeta^2(d(\omega), m) = 1 \qquad d(\omega) \in \mathcal{D}(\omega), \tag{25}$$

$$\sum_{t^- = t - \delta(\tau) + 1}^{t} \sum_{r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t^-)} \rho^2(d(\omega), r) \le u^{\mathcal{T}}_z \qquad (z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \tag{26}$$

$$\sum_{t^{-}=t-\delta(\tau)+1}^{t} \sum_{h \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t^{-})} \varphi^2(d(\omega), w) \leq u_z^{\mathcal{V}} \quad z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \tag{27}$$

$$\rho^2(d(\omega), r) \in \{0, 1\} \quad r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \tag{28}$$

$$\varphi^2(d(\omega), w) \in \{0, 1\}, \quad w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \cup \mathcal{W}^{+}, \ \nu \in \mathcal{V}, \tag{29}$$

$$\zeta^2(d(\omega), m) \in \{0, 1\} \quad m \in \mathcal{M}(d(\omega)) \cup \mathcal{M}^{+}(d(\omega)), \ d(\omega) \in \mathcal{D}(\omega). \tag{30}$$

The objective function (20) computes the total cost of operating the selected urban-vehicle services and the normal and additional city-freighter work assignments. Relations (21) enforce the urban-vehicle capacity restrictions, while constraints 22 state that exactly one departure must be selected for each opportunity window (these constraints could be eliminated or relaxed for increased flexibility). Constraints (23) and (24) enforce the capacity of city freighters operating the regular delivery circuits and the additional routes, respectively. Equations (25) indicate that each demand must be satisfied by a single itinerary. Constraints (26) and (27) enforce the satellite capacity restrictions in terms of urban vehicles and city freighters, respectively, where the number of vehicles using a satellite at any given period t equals those that arrive at t plus those that arrived before but are still at the satellite at time t, the possible services in $\mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and work segments in $\mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ that may contribute to the satellite congestion being represented by sets $\mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t^{-})$ and $\mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t^{-})$ for each rendez-vous point $(z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$.

The following section discussed possible solution approaches for the stochastic formulations presented in the last sections.

8 Algorithmic Perspectives

The models proposed in this paper pose tremendous challenges when one is trying to design solution strategies to tackle them. Addressing this issue is beyond the scope of this report. In the following, we only briefly review a number of challenges and interesting avenues of research.

As with most stochastic models, a first source of complexity resides in the evaluation of the recourse function. We opt for a classical stochastic programming strategy (see, e.g., Birge and Louveaux, 1997), and approximate the recourse function using a sample of representative scenarios of the random event. Determining how such scenarios are obtained, i.e., which ones should be used as well as how many are necessary to produce a proper approximation, stands as a first important challenge to address when designing any efficient algorithm for the considered problems (Dupačová, J. et al., 2001; Høyland, K. and Wallace, S.W., 2001; Høyland et al., 2003; Kaut and Wallace, 2007).

The particular decomposition strategy for the resulting multi-scenario formulations constitutes another major component of any solution procedure for such problems. In the present case, The approximation problems obtained in the present case are large-scale deterministic binary problems with a block diagonal structure, each scenario accounting for a different block. Given their size and particular structure, these problems are amenable to different decomposition schemes to produce either exact or meta-heuristic algorithms. To name a few of the most relevant strategies, Benders decomposition (Benders, 1962) was used to develop the integer L-Shaped algorithm proposed by Laporte and Louveaux (1993), while scenario decomposition was used in the progressive hedging algorithms proposed by Løkketangen and Woodruff (1996), Haugen et al. (2001), Hvattum and Løkketangen (2009), and Crainic et al. (2011). These strategies could also be used in the present case but, based on the characteristics of the problem, we contemplate a different scheme.

Notice that all stochastic problems proposed in this paper have relatively complete recourse (Birge and Louveaux, 1997) and, thus, all feasible first stage solutions generate a feasible second stage. This characteristic makes it easier to explore the feasible space of possible a priori solutions, as one does not have the added complexity of searching the first stage feasible region for solutions that are also feasible in the second stage. A decomposition scheme based on projection, i.e., projecting first stage solutions onto the second stage, appears therefore as an interesting approach to consider.

It should also be noted that, by using such an approach, the original problem is decomposed according to the first and second stages of the stochastic model. Furthermore, the second stage becomes scenario separable. Given the size and complexity of the approximated problems, a meta-heuristic search strategy appears appropriate in the present case. To this end, it is important to state that, when solving the planning model, one is mainly interested in obtaining the a priori plan, which will then be used for a period of time. Then, given the a priori plan, it may not be necessary to explicitly determine the recourse actions that will be implemented for each scenario considered. One only needs a good approximation of the recourse cost associated with the plan. This entails that it is not necessary to solve the scenario subproblems to optimality, good lower or upper bounds being sufficient.

We therefore propose to develop a meta-heuristic search strategy that explores the first stage feasible region, using a neighborhood-based algorithm, the second stage subproblems being used to approximate the recourse cost only. A number of major algorithmic challenges must be addressed.

Let us start by considering the structure of the first stage problem. Recall that the first stage problem is a time-dependent service network design formulation (Crainic and Kim, 2007), where one selects services (and departures) for urban vehicles and load itineraries to satisfy the forecast demand. Several meta-heuristics have been proposed for this class of problems (e.g., Ghamlouche et al., 2001; Chouman and Crainic, 2010; Hewitt and Nemhauser, 2009) and offer an interesting starting point for defining neighborhoods for this type of problem.

Given that the defined neighborhood will then have to be evaluated to identify an improving move considering the recourse cost, we should note that it might not be efficient to use all scenarios generated to obtain the approximated problems in order to perform this operation within the local search algorithm. One might again need to further restrict the number of scenarios that are used to approximate the recourse function. How this restriction is to be done (choosing amongst available scenarios or apply further sampling), remains an open and important question to address. Considering the second stage scenario subproblems, they are, in the case of the routing recourses, defined as synchronized, scheduled, multidepot, multiple-tour, heterogeneous vehicle routing problems with time windows (Crainic et al., 2009a). Although, this appears as a new type of problem, it belongs to the more general class of vehicle routing problems, which have been widely studied within the operations research community (Toth and Vigo, 2002; Golden et al., 2008). Some of the most efficient heuristics for more classical vehicle routing problems will then be the starting point to obtaining good upper bounds for the second stage subproblems. In the case of the service dispatch and routing recourse, the scenario subproblems appear as reduced tactical models. Therefore, we should note that a second decomposition scheme is needed to solve them (Crainic et al., 2009a). Finally, we would like to briefly evoke the meta-heuristic strategy that is envisioned for the problems. The tabu search strategy appears as a natural choice, given the local search procedure that is proposed. In developing such a procedure, an important issue to focus on is what information should be kept from the local neighborhood searches to help both diversify and intensify the search strategy.

9 Conclusions

Similarly to any complex transportation system, City Logistics systems require planning at strategic, tactic, and operational levels. In this report, we focused on tactical planning issues because of its central role in 1) the overall planning process, as tactical plans are required to evaluate strategic plans and guide operations, and 2) providing the means to operate efficiently with respect to the overall goals and constraints of the system, tactical planning selects the services and schedules to run, assigns resources, and defines broad policies on how to route the freight and operate the system to satisfy demand and attain the economic and service-quality objectives of the system.

Planning means look-ahead capabilities and the inclusion of forecasts into today's decision process. The variation in demand over the horizon of the tactical plan, from a season to a year, constitutes a particularly important element to consider, as it may significantly impact not only the level of service one will offer but also the structure of the resulting design of the service network. Yet, at the best knowledge of the authors, this report constitutes a first contribution addressing uncertainty issues in tactical planning for City Logistics.

We focused on demand uncertainty within the scope of two-tiered City Logistics systems and on how to address it within the process of building the tactical plan for the regular operations of 2T-CL systems, under various hypotheses relative to what is fixed and what may be adjusted at operation time. We formally defined this problem and proposed a general modeling framework taking the form of a two-stage stochastic programming formulation. We then studied three different strategies to adapt the plan to the observed demand and proposed associated recourse formulations. Finally, we discussed algorithmic challenges and proposed a promising solution methodology.

We are now proceeding with a first evaluation of the proposed recourse formulations and the algorithm development work to address problem instances of realistic dimensions. We plan to report on these developments in the near future.

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Annex - Summary of Notation

Table 1 summarizes the general notation of 2T-CL basic components and flows presented in Section 2, while Table 2 summarizes the notation of the modeling framework and the recourse formulations in Sections 4 - 7.

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

Table 1: General 2T-CL Notation

$\mathcal{R} = \{r\}$	Set of urban vehicle services
$\tau(r)$	vehicle type of r
$e(r)$	external zone of r
$\bar{e}(r)$	terminal external zone for r
$k(r)$	cost of service r
$t(r)$	departure period for r
$\sigma(r) \subset \mathcal{Z}$	ordered set of visited satellites for r
$t_i(r)$	period service r visits satellite z_i
$\mathcal{D}(\omega) = \{d(\omega)\}$	Set of customer-demand realizations for $\omega \in \Omega$
$\widehat{vol(d)}$	point forecast of the volume of customer demand d used in the 1st stage
$\tilde{k}(d, z, t)$	approximated cost of delivering demand d from satellite z starting in period t
$\mathcal{M}(d) = \{m\}$	Set of itineraries for customer-demand d
$t_e(m) = \quad t(r(m))$	departure period from external zone $e(d)$ of service $r(m)$ of m
$t_z^{\text{in}}(m)$	arrival period at satellite $z(m)$ of service $r(m)$ of m
$\mathcal{R}(\boldsymbol{\rho}^1)$	Set of urban-vehicle services selected at 1st stage
; $\mathcal{M}(\boldsymbol{\zeta}^1) = \{m(\boldsymbol{\zeta}^1, d)\}$	Set of partial itineraries selected at 1st stage for customer demand d
$\mathcal{ZT}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1))$	Set of active rendez-vous points selected at 1st stage for city-freighter type ν
$\mathcal{C}_{zt}^{\nu}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$	Set of customers assigned at 1st stage to rendez-vous point (z, t)
$F_{zt}^{\nu}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$	Upper bound on the number of city freighters of type ν planned in the 1st stage to leave rendez-vous point (z, t)
$\mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \{w\}$	Set of feasible work segments for city freighters given the 1st stage decisions
$\sigma(w) \subset \mathcal{Z}$	ordered set of visited satellites for w
$k(w)$	cost to operate w
$t(w)$	starting period of w
$t_l(w)$	period work segment w arrives at satellite z_l
$\delta(w)$	duration of w
$\mathcal{L}(w) = \{l\}$	Set of legs of w
$\mathcal{C}_l(w)$	set of customers of leg l of w
$\delta_l(w)$	duration of l
$k_l(w)$	cost of operating l of w
$\mathcal{W}^+$	Set of feasible work segments for additional city freighters
$\mathcal{M}(d(\omega))$	Set of second phase itineraries for d constrained by 1st stage decisions
$\mathcal{M}^+(d(\omega))$	Set of 2nd phase itineraries for d using additional city freighters $\mathcal{W}^+$
$[a(zt),\ b(zt)]$	Time window for the satellite z and customers in $\mathcal{C}_{zt}^{\nu}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$
$[a(r^o), b(r^o)]$	Opportunity time window for service $r^o \in \mathcal{R}(\boldsymbol{\rho}^1)$

Table 2: Notation for the General Framework and Recourse Models