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Abstract. We consider the complex and not-yet-studied issue of building the tactical plan of a two-tiered City Logistics system while explicitly accounting for the uncertainty in the forecast demand. We describe and formally define the problem, and then propose a general modeling framework, which takes the form of a two-stage stochastic programming formulation. Four different strategies of adapting the plan to the observed demand are introduced together with the associated recourse formulations. The four strategies are compared, and contrasted to the case where no tactical plan is built, through an extensive Monte Carlo experimentation.

Keywords: City Logistics, advanced urban freight transportation, demand uncertainty, tactical planning, two-stage stochastic programming, Monte Carlo simulation.

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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 impacts, while continuing to support 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 structures and activities (Taniguchi et al., 2001).

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 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 role, tactical plans are required to evaluate strategic plans and guide operations. Regarding the latter, 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 paper is a first step toward filling this gap.

We consider the case of two-tier City Logistics (*2T-CL*) systems (Crainic et al., 2004; Gragnani et al., 2004), which are increasingly being considered and deployed, in particular for medium and large cities, and are particularly challenging from an operational and planning-process point of view due to the 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., 2012a). We focus on the variability associated to demand and 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 quite straightforwardly adapted to single-tiered systems and more complex traffic cases.

Our main objective is to introduce and formalize the problem and gain insight into possible strategies to adjust a tactical plan to the actual demand observed each day when this plan must be operated. The proposed two-stage modeling framework aims to mimic the actual decision process, the first stage selecting the first-tier service network design and the general workloads of the inter-tier transfer facilities, while the actual routing on the second tier is determined by the recourse strategies at the second stage. Four such strategies are introduced and experimentally compared through an extensive Monte Carlo simulation, which also considers the case where the entire plan is built daily.

The main contributions of this paper therefore are to 1) Introduce the issue and formally define the problem of explicitly addressing demand uncertainty in tactical planning for City Logistics systems; 2) Propose a general modeling framework, which takes the form of a two-stage stochastic programming formulation, four different strategies to adapt the plan to the observed demand, and the associated recourse formulations; 3) Experimentally compare the recourse strategies and discuss management implications and algorithmic perspectives.

The paper is organized as follows. Section 2 briefly recalls the general 2T-CL setting, discusses associated planning and uncertainty issues, and concludes with a statement of the problem studied. Section 3 introduces the general modeling framework and the first-stage formulation. Section 4 presents the setting, notation, and modeling of the second-stage decisions and describes the recourse strategies and formulations. Section 5 describes the setting of the experiments we conducted, the results obtained, and the corresponding analyzes. We conclude in Section 6.

2 Uncertainty and Tactical Planning for 2T-CL

This section is dedicated to identifying issues and challenges associated with accounting for demand uncertainty in planning the operations of a 2T-CL system for the next medium-term planning horizon and, thus, specifying the problem setup of this paper.

We start by briefly recalling the general setting of two-tier City Logistics systems, introduced by Crainic et al. (2004) and illustrated in Figure 1. 2T-CL systems are made up of two layers of facilities, different vehicle fleets moving loads among facilities and from them to the appropriate customers. Loads arrive by various modes at primary facilities, generally located on the outskirts of the city and called *external zones* in the following (large squares in Figure 1). Loads are then sorted and consolidated into rather large *urban vehicles*, which bring them to satellite facilities (triangles in Figure 1) "close" to the City-Logistics controlled zone, hereafter named *city center*. At *satellites*, loads are transferred to smaller vehicles, the *city freighters*, performing the actual delivery routes within the city-center. (Notice that "satellites" may be located within external-zone facilities to service near by customers; in order not to overcrowd the presentation, we do not address this case in this paper.) Satellites are assumed to 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 time instances, with very short waiting times permitted, loads being directly moved from urban vehicles to city freighters without intermediate storage. From an information and decision point of view, the 2T-CL process starts with the demand for loads to be distributed within the urban zone. The consolidation at the primary facilities 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.

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 courier 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 process 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, 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

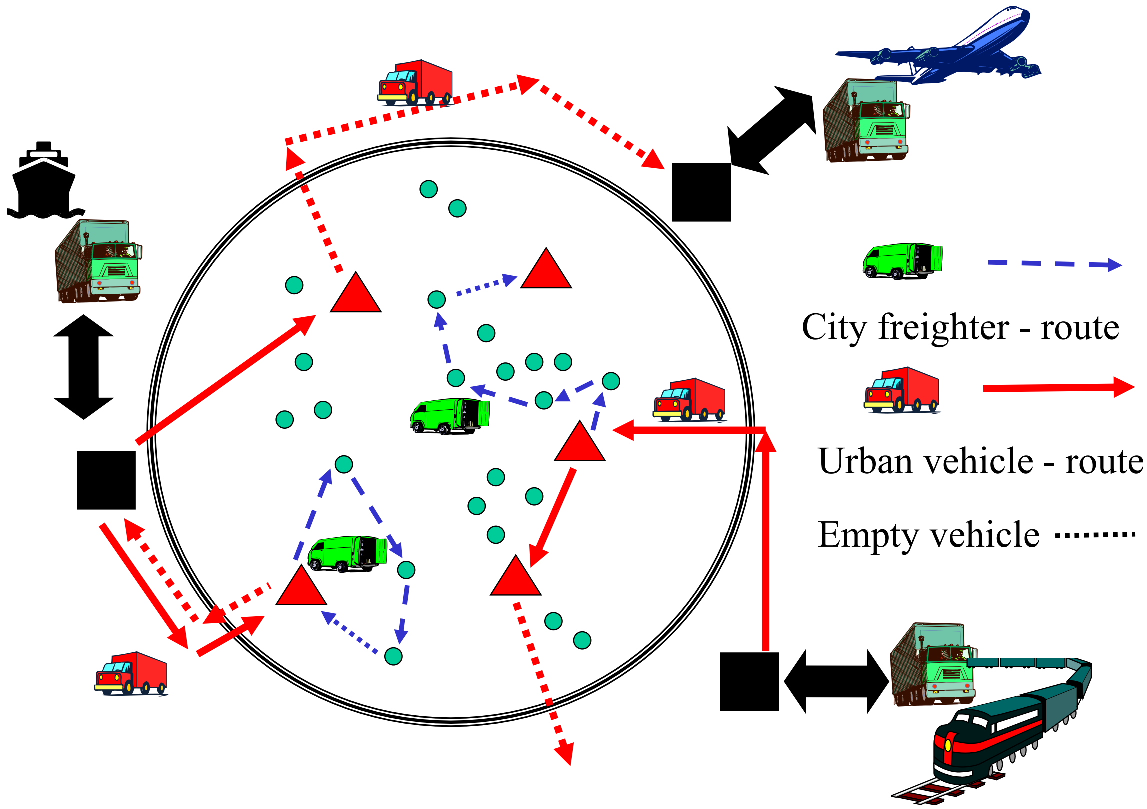

Figure 1: A Two-tiered City Logistics System Illustration

repositioning, power allocation and circulation, etc.).

Tactical planning models for City Logistics concern the departure times, routes, and loads of vehicles, the routing of demand and, when appropriate, the utilization of the satellites and the distribution of work among them. Tactical planning models assist the deployment of resources and the planning of operations and guide the real-time 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 for City Logistics 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 2T-CL 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). Their contribution focuses on the *day-before* tactical planning problem, where a plan is built every day for the entire system given the particular demand for that day. The application of the methodology to broader planning issues was mentioned but not detailed. Our present work constructs upon this methodological foundation, the day-before model corresponding to the "no advanced planning" situation.

Tactical planning is based on a demand forecast for the planning horizon considered. Moreover, demand uncertainty is inherent to any complex system and planning process. City Logistics is no exception. Various sources and type of uncertainty may be defined (see, e.g., Klibi et al., 2010). In this work, we focus on the uncertainty related to the variation of predicted volume of 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 choice of an appropriate methodological approach is directly related to the magnitude of the demand variability and the confidence one puts in the demand forecasts. A series of problems and formulations follows from the combination of particular answers to these questions. 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) 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 may then be addressed through ad-hoc extra capacity, e.g., external vehicles or carriers or delayed delivery with penalty cost. At the other extreme, one 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 vehicle dispatch 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.

The various problem settings in between these extremes differ in the latitude left to the adjustment of the plan once the actual demand is observed. This corresponds to the second main methodological issue one must address in integrating uncertainty into tactical planning, that is, what part of operations should be fixed within the plan and what should be left to be decided on the day of operations. Put into stochastic-programming terms, "what decision goes into each stage?"

All transportation services of most consolidation-based systems are generally determined by the plan, which also gives broad guidelines for routing the freight for each origin-destination pair of terminals while the actual itineraries are to be 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; Sungur et al., 2010; 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. Yet, these two components do not face the same variability with respect to their "customers". Thus, for example, the actual locations where deliveries have to be made within a clustered group of offices or streets might vary daily, yet the total volume to be delivered to customers within that group of offices or streets would be fairly stable. One therefore expects large volumes from external zones to urban regions clustered "around" satellites to be rather regular and stable, while actual delivery routes 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 satellite workloads, in terms of numbers of vehicles of both tiers accommodated at each time period and the customers to be serviced, and estimate the 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.

3 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, 2011; King and Wallace, 2012). The 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, to given realizations of demand. We start with the general notation, which generally follows Crainic et al. (2009a), then introduce the first-stage formulation and the information it yields - the plan. The definitions and formulations of the recourse strategies are presented in the next section.

3.1 General notation

Let $\mathcal{E} = \{e\}$ be the set of external zones (the primary facilities and other points of origin for loads traveling directly to satellites), and $\mathcal{Z} = \{z\}$ the set of satellites. The nature of each satellite location determines when it can be used, its topology, available space, and connections to the street network yielding its capacity measured in the number of urban vehicles $u_z^{\mathcal{T}}$ 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, to be the same for all satellites and is denoted δ.

Let $\mathcal{T} = \{\tau\}$ and $\mathcal{V} = \{\nu\}$ represent the set of urban-vehicle and city-freighter types, respectively, with corresponding capacities u_τ and u_ν. Thick and narrow dashed arrows in Figure 1 represent urban-vehicle and city-freighter movements, respectively, 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 $\delta(\nu)$ the loading time (assuming a continuous operation) of a city freighter of type ν. Without loss of generality, we assume these times 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.

Finally, let $\mathcal{C} = \{c\}$ represent the set of customers to be serviced by (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 of 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 customer demands.

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 model development follows 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 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.

3.2 Two-stage formulation

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 planned 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 system and model components 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

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

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

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

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

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

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

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

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 section.

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.

The first stage of the model does not address city-freighter routing. It actually determines the customer-demand itineraries up to the (satellite, period) rendez-vous points (and the type of city freighter) using an approximation of the routing cost from the satellite to the customer location. This corresponds to the urban-vehicle service network design model of Crainic et al. (2009a) and Crainic and Sgalambro (2009). A feasible solution for the formulation of the first stage - an priori plan - then 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 $\mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \bigcup_{\nu \in \mathcal{V}} \bigcup_{zt \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$.

It is this information that guides and constrains the second-stage strategies.

4 Recourse Strategies and Formulations

The recourse strategies we consider target the routing of "regular" and "additional" city freighters required to move the demand observed for a particular day, but differ in the degree of freedom relative to the first-stage customer-to-rendez-vous point assignments, as well as in whether or not slight adjustments to the service network selected in the first stage are permitted. We initiate the presentation with general considerations on the additional city-freighter capacity one might require when adapting the plan to demand realizations, introducing also the notation relevant to all strategies presented later in the section.

4.1 The second stage

To instantiate the plan for each day of the season, the recourse strategy of the second stage must determine the actual routing and complete or build the itineraries for the observed particular realizations of customer demands $d(\omega)$. When all volumes are lower or equal to the forecast values, the $\mathcal{R}(\boldsymbol{\rho}^1)$ 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 $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. Notice that, even in this case, considering a recourse strategy could lead to a more efficient distribution operation by, e.g., avoiding unnecessary vehicle movements.

Additional capacity might be required in all other cases, at a (generally) much higher cost than regular operations. Because the strategies considered aim not to modify (at least, not in any way significant) the first stage plan and the deployment of major resources,i.e., the urban-vehicle services and satellite utilization, the additional capacity has to be provided by vehicles that are allowed to move in all the zones of the city, which excludes urban vehicles. Several operational strategies may be envisioned for these "extra" city freighters, each requiring particular numbers of vehicles and resulting in specific costs. The choice of a strategy strongly depends on the application context: city topography, regulations and labor relations, particular combination or public and private involvement, and so on. (See Crainic et al., 2012a, for a more in-depth discussion of fleet operation strategies.) We assume a straightforward *single-fleet* strategy in this paper, where the same city freighters may service customers either from satellites, in most cases, or from the external zones where the loads of the "extra" demand-customers are located. Let $\mathcal{E}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, \mathcal{D}(\omega))$ represent the set of such external zones.

A simple modification adds slack variables to the urban-vehicle service network design model as arcs from external zones to customer-demand nodes. Then, given an approximation of the cost of direct distribution from the appropriate external zone to each customer, the modified formulation determines the demands that shall be serviced directly from the external zones and the corresponding $\mathcal{E}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, \mathcal{D}(\omega))$ set. Let $\mathcal{C}_e^{\nu}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, $\nu \in \mathcal{V}$, identify the sets of customer demands to be serviced from the external zone $e \in \mathcal{E}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, \mathcal{D}(\omega))$ by the extra city-freighter movements. A city freighter could then travel to a satellite, load and distribute the corresponding freight, then travel to an external zone where extra loads exist, pick them up and deliver them, then, either the day is finished and the vehicle returns to the garage, or it travels to either another external zone with extra demands and repeats the previous process or to a satellite arriving on time to synchronize with first-tier urban vehicles. We identify as *direct delivery*, the strategy moving such "extra" loads on city freighters directly from external zones to customers.

Formally, 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 city-freighter *work segments*, where each $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ visits a sequence $\sigma(w) = \{(z_l, t_l)\,[,(e_l, t_l)]\ |\ (z_l, t_l) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ e_l \in \mathcal{E}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, \mathcal{D}(\omega)),\ l = 1, \ldots, |\sigma(w)|\}$ of facilities, satellites, external zones (eventually), and associated customers, according to a schedule compatible with the planned rendez-vous points $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and the given travel and service times. Let $\mathcal{W}^{+}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \subset \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ \nu(w) \in \mathcal{V}$, represent the set of work segments including at least one external zone in $\sigma(w)$.

At each facility on its route, the city freighter takes loads to deliver to a set of customers $\mathcal{C}_l(w)$, where $\mathcal{C}_l(w) \subseteq \mathcal{C}^{\nu}_{z_l t_l}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ when the facility is a satellite z_l, and $\mathcal{C}_l(w) \subseteq \mathcal{C}^{\nu}_{e_l}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, when the facility is an external zone e_l. We define the route *leg* l, the work-segment component that starts at satellite z_l or external zone e_l, services the customers in $\mathcal{C}_l(w)$, and then proceeds to the next facility in $\sigma(w)$, or to a depot $g(w)$ when the facility is last in the list (when required, the notation l^{+} identifies a leg starting from an external zone). 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 three-leg work segment, where zt and $z't^{++}$ represent feasible rendez-vous points in $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, et^{+} stands for an external zone with extra demand, gt^{-} and gt^{+++} illustrate the initial and final pairs of (depot, period), while $\mathcal{C}_1(w) = \{i, k, j, \ldots, h\}$, $\mathcal{C}_2(w) = \{i', k', j', \ldots, h'\}$, and $\mathcal{C}_3(w) = \{i'', k'', j'', \ldots, h''\}$ are the three sets of customers serviced by the three legs, respectively. Dashed lines stand for undisplayed customers, dotted lines indicate empty travel, and full lines represent actual delivery tours.

Let $t_l(w),\ l = 1, \ldots, |\sigma(w)|$, be the departure time of the city freighter from the facility defining leg l, with $t_0(w)$ indicating when the city freighter leaves the depot to reach the first facility in time for the planned activities, and $t_{|\sigma(w)|+1}(w) = t(g(w))$ giving the period the vehicle arrives at the depot at the end of the work segment. 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 facility in the work-segment sequence (or the depot, when $l = |\sigma(w)|$). The

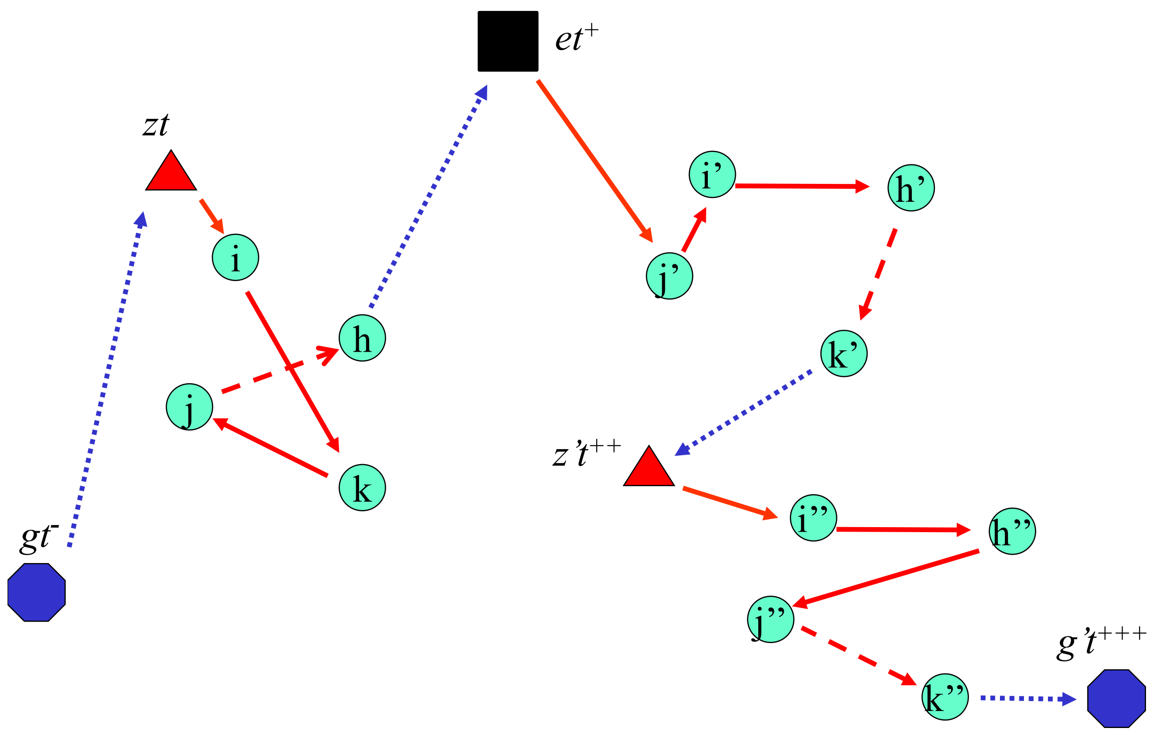

Figure 2: A City-Freighter Three-Leg Work Segment Illustration

dynamics of the work segments are determined by the time windows of the customers and the requirements of the satellite rendez-vous activities (as well as the congestion conditions generally prevailing at the corresponding period). Thus, the arrival time of the city freighter at the facility of leg $l \in \mathcal{L}(w)$ equals $t_{l-1}(w) + \delta_{l-1}(w)$ and, when two consecutive facilities are satellites, $t_l(w) = t_{l-1}(w) + \delta_{l-1}(w) + \delta(\nu)$.

Let the *starting time* of the work segment w equal the arrival time at the first facility in its sequence, $t(w) = t_1(w)$, and note $\delta(w)$ its total duration (without the first movement out of the depot). The costs of operating city-freighter legs and work segments are denoted $k_l(w)$ and $k(w)$, respectively, where $k(w) = \sum_{l \in \mathcal{L}(w)} k_l(w)$. Similarly to $k(r)$, these costs capture the monetary expenses of operating the city freighters, including loading and unloading freight, as well as any "nuisance" factors related to its presence in the city at the particular time of the service. It is assumed, of course, that the cost of the extra vehicles, i.e., the cost of city freighters moving toward external zones and operating l^+ legs, is higher than that of regular operations. 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 patterns of demand itineraries may then be defined given this routing strategy. 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 observed demand will move on a *regular* itinerary $m \in \mathcal{M}(d(\omega)) \subset \mathcal{M}(d)$ composed of this partial itinerary $m(\boldsymbol{\zeta}^1, d)$ and a leg of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, of a city freighter of appropriate type, leaving from the satellite z at period t. Some observed customer demands could be moved instead by one of the additional vehicles operating a l^+ leg out of an external zone and belonging to one of the work segments in $\mathcal{W}^+$. Such an itinerary is called *direct*, and the associated set of itineraries is noted $\mathcal{M}^+(d(\omega))$, with $\bar{\mathcal{M}}(d(\omega)) = \mathcal{M}(d(\omega)) \cup \mathcal{M}^+(d(\omega))$. As stated by Crainic et al. (2009a), the costs associated to itineraries are accounted for through the service (first stage) and routing costs.

4.2 Routing recourse strategies

The first strategies aim to modify the plan as little as possible and, thus, the sets of selected services, $\mathcal{R}(\boldsymbol{\rho}^1)$, and active rendez-vous points, $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, are not modified. Two strategies are described. The first, called simply *Route*, proceeds according to the first-stage determined customer-to-satellite rendez-vous assignments, $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, while the *Route & Assign* strategy relaxes this feature.

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). We call these bounds $F^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) = \lceil \sum_{d \in \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} \widehat{vol(d)}/u_\nu \rceil$, and group them 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 enforced in the Route 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 $Q^{\mathrm{R}}\left(\mathcal{R}(\boldsymbol{\rho}^1), F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right)$.

The customer-demand itineraries defined in the previous section apply straightforwardly to this case. We then define two sets of decision variables to select city-freighter work segments and customer-demand itineraries, respectively:

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

The second-stage routing model then becomes:

$$Q^{\mathrm{R}}\left(\mathcal{R}(\boldsymbol{\rho}^1), F(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{C}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} k(w)\varphi^2(d(\omega), w) \quad (8)$$

$$\sum_{m \in \bar{\mathcal{M}}(d(\omega))} \zeta^2(d(\omega), m) = 1 \qquad d(\omega) \in \mathcal{D}(\omega) \tag{9}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \mathcal{M}(d(\omega), r)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_\tau \qquad r \in \mathcal{R}(\boldsymbol{\rho}^1), \tau(r) \in \mathcal{T}, \tag{10}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \bar{\mathcal{M}}(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_\nu \varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w),\ w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ v \in \mathcal{V}, \tag{11}$$

$$\sum_{w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t)} \varphi^2(d(\omega), w) \leq F^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \qquad (z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \nu \in \mathcal{V}, \tag{12}$$

$$\varphi^2(d(\omega), w) \in \{0, 1\}, \qquad w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ \nu \in \mathcal{V}, \tag{13}$$

$$\zeta^2(d(\omega), m) \in \{0, 1\} \qquad m \in \bar{\mathcal{M}}(d(\omega)),\ d(\omega) \in \mathcal{D}(\omega). \tag{14}$$

The objective function minimizes the generalized cost of operating all city freighter routes, with and without legs starting at external zones, and performing the associated loading and unloading activities. Equations (9) enforce the single-itinerary requirement for customer delivery. Relations (10) ensure the capacity of the services selected in the first stage are respected, where $\mathcal{M}(d(\omega), r)$ stands for the set of itineraries for customer demand $d(\omega) \in \mathcal{D}(\omega)$ using urban-vehicle service $r \in \mathcal{R}(\boldsymbol{\rho}^1)$. Constraints (11) enforce the capacity of city freighters operating any leg l, the set $\bar{\mathcal{M}}(d(\omega), l)$ containing the corresponding itineraries. 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 (12), with $\mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1, z, t)$ giving the set of work segments loading at a rendez-vous point $(z, t) \in \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. The integrality of the decision variables is enforced through constraints (13) and (14).

The second routing 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 (12) 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 name of the recourse strategy, the corresponding term in the global objective function (1) taking the form $Q^{\mathrm{RA}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right)$.

The operational setting is similar to that of the Route strategy, as are most notations and definitions. 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 a leg part of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, of a city freighter of appropriate type, starting from the appropriate satellite at the period specified by the rendez-vous point. With this modification, the Route & Assign recourse formulation becomes

$$Q^{\mathrm{RA}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1) \bigcup \mathcal{W}^+} k(w)\varphi^2(d(\omega), w) \qquad (15)$$

subject to constraints (9) - (11) and (13) - (14).

4.3 Service dispatch and routing strategies

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, $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, 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. The routing of city freighters is, of course, also part of the recourse decisions, and we define two strategies based on this idea. The first enforces the first-stage customer-to-satellite assignments, $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, and is called *Dispatch & Route*, while the second, called *Dispatch & Route & Assign*, relaxes this rule.

Figures 3 and 4 illustrate this idea. The former 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, an external zone with extra loads, 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 $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ serviced by vehicles starting their routes 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 call an *opportunity time window*

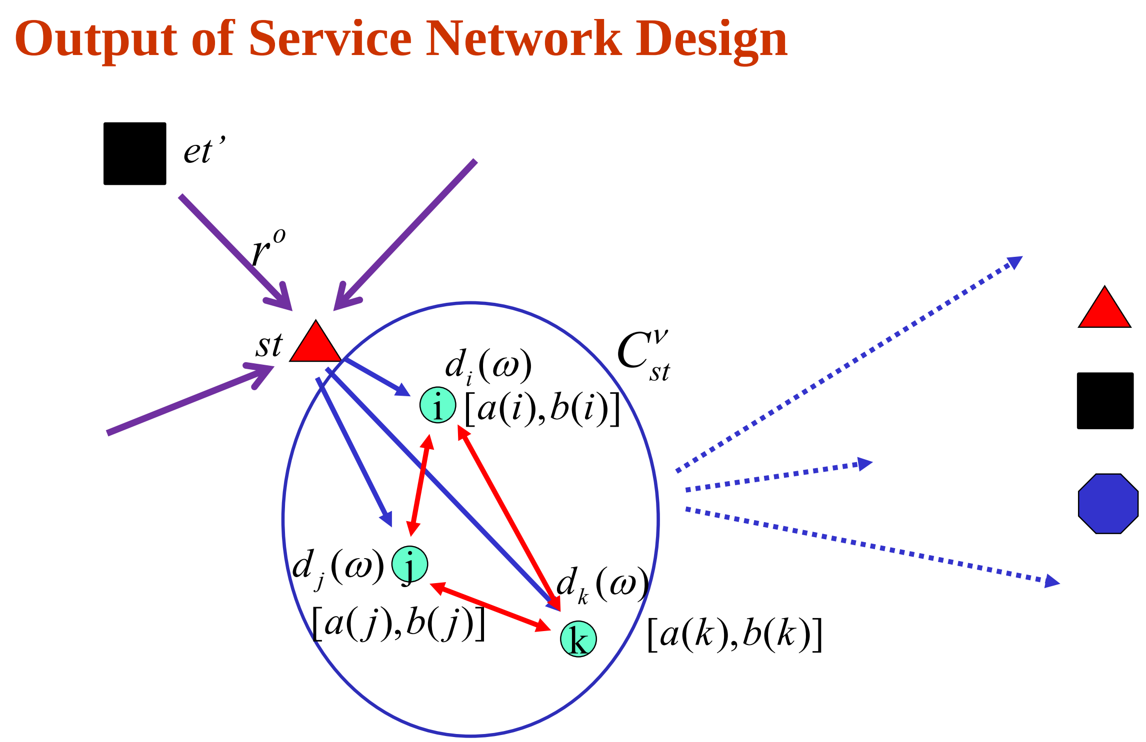

Figure 3: Output of Stage 1 - Zoom on a Rendez-vous Point

$[a(r^o), b(r^o)]$. As illustrated in Figure 4, 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 the 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 work segments $\mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, including $\mathcal{W}^+(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, are defined as for the previous two recourse strategies (Section 4.2). The regular customer-demand itineraries are restricted to the services in $\mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ and the satellite assignments $\mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ 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 a leg l of the work segment $w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$, of a city freighter of the appropriate type, which starts at satellite z at period t. Demand may alternatively be moved by a direct itinerary in $\mathcal{M}^+(d(\omega))$ corresponding to a city freighter operating a leg l^+ out of an external zone.

Compared to the previous two strategies, a new set of decision variables must then

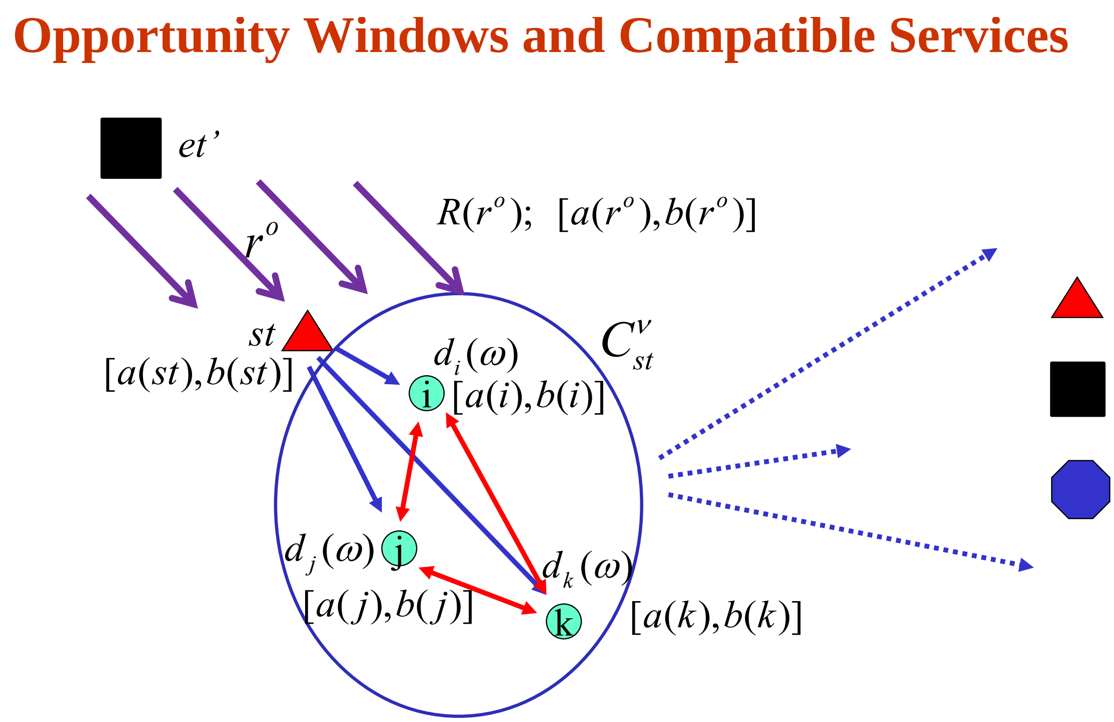

Figure 4: Service Opportunity Window - Zoom on a Rendez-vous Point

be added to account for the service departure-time selection:

$\rho^2(d(\omega), r) =$ 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 $w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$ is selected, 0, otherwise;

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

The second stage formulation of the first strategy 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:

$$Q^{\mathrm{SR}}\left(\mathcal{R}(\boldsymbol{\rho}^1), \mathcal{C}^{\nu}_{zt}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \mathcal{D}(\omega)\right) = \text{Minimize} \sum_{r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} k(r)\rho^2(d(\omega), r) + \sum_{w \in \mathcal{W}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)} k(w)\varphi^2(d(\omega), w) \tag{16}$$

$$\text{Subject to} \quad \sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \bar{\mathcal{M}}(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_{\tau}\rho^2(d(\omega), r) \quad r \in \mathcal{R}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1), \tag{17}$$

$$\sum_{r \in \mathcal{R}(r^o)} \rho^2(d(\omega), r) = 1 \quad r^o \in \mathcal{R}(\boldsymbol{\rho}^1), \tag{18}$$

$$\sum_{d(\omega) \in \mathcal{D}(\omega)} \sum_{m \in \bar{\mathcal{M}}(d(\omega), l)} vol(d(\omega))\zeta^2(d(\omega), m) \leq u_{\nu}\varphi^2(d(\omega), w) \quad l \in \mathcal{L}(w),\ w \in \mathcal{W}(\nu, \boldsymbol{\rho}^1, \boldsymbol{\zeta}^1),\ v \in \mathcal{V}, \tag{19}$$

$$\sum_{m \in \bar{\mathcal{M}}(d(\omega),l)} \zeta^2(d(\omega),m) = 1 \quad d(\omega) \in \mathcal{D}(\omega), \tag{20}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{r \in \mathcal{R}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1,z,t^-)} \rho^2(d(\omega),r) \leq u_z^{\mathcal{T}} \quad (z,t) \in \mathcal{ZT}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1), \tag{21}$$

$$\sum_{t^-=t-\delta(\tau)+1}^{t} \sum_{h \in \mathcal{W}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1,z,t^-)} \varphi^2(d(\omega),w) \leq u_z^{\mathcal{V}} \quad z,t) \in \mathcal{ZT}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1), \tag{22}$$

$$\rho^2(d(\omega),r) \in \{0,1\} \quad r \in \mathcal{R}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1), \tag{23}$$

$$\varphi^2(d(\omega),w) \in \{0,1\}, \quad w \in \mathcal{W}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1),\ \nu \in \mathcal{V}, \tag{24}$$

$$\zeta^2(d(\omega),m) \in \{0,1\} \quad m \in \bar{\mathcal{M}}(d(\omega),l),\ d(\omega) \in \mathcal{D}(\omega). \tag{25}$$

The objective function (16) computes the total cost of operating the selected urban-vehicle services and the normal and additional city-freighter work assignments. Relations (17) enforce the urban-vehicle capacity restrictions, while constraints (18) state that exactly one departure must be selected for each opportunity window (these constraints could be eliminated or relaxed for increased flexibility).

Constraints (19) enforce the capacity of city freighters on all legs, both regular and starting from an extra zone. Equations (20) indicate that each demand must be satisfied by a single itinerary. Constraints (21) and (22) 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 the 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 $\mathcal{W}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1,z,t^-)$, respectively, for each rendez-vous point $(z,t) \in \mathcal{ZT}(\boldsymbol{\rho}^1,\boldsymbol{\zeta}^1)$.

The *Dispatch & Route & Assign* recourse strategy relaxes the first-stage customer-to-rendez-vous point assignments. The corresponding formulation, Q^{SRA}, takes exactly the same form as (16) - (25), the only difference being in the definition of the $\bar{\mathcal{M}}(d(\omega),l)$ itineraries, no longer restricted to the first-stage rendez vous assignments.

5 Experimental Results and Analyses

The goal of the experimental campaign is to evaluate the proposed recourse strategies through a Monte Carlo simulation, performed by comparing them, as well as a "no-advance-planning" strategy, in terms of system performance measures – transportation costs, number of demands serviced by direct delivery, vehicle loading, and utilization of the fleets and satellite facilities –, as well as managerial challenges and trade-offs. The section first introduces the experimental setting, then proceeds to the presentation of the results obtained and their analysis.

5.1 Experimental setting

The case considered for experimentation included a single product and vehicle type at each level, fixed travel times, and no-split deliveries. We generated test instances with an actual geographical basis (a large European city) and real distances, but dimensions that allow to address efficiently the problems at hand with off-the-shelf software. All test instances cover 6 periods (of 25 minutes each for a total duration of 2.5 hours), and display the same values for a number of parameters: capacity of external zones = 100 urban vehicles; satellite capacity = 5 urban vehicles and 10 city freighters; capacity of urban vehicles and city freighters equal to 30 and 15 units, respectively. The various costs associated to vehicles are also the same for all instances, the cost of a vehicle route being computed as a "fixed" vehicle cost (city-freighter cost equals one third of the urban-vehicle cost) plus a "variable" cost related to the length of the route. The cost of direct services is some 1.67 times that of urban vehicles.

Instances differ in the number of external zones, 1 or 2, satellites, 2 or 3, and customer zones, 15 or 25. They also differ in the distribution of the customer demands relative to their volumes and in how the predictive $\widehat{vol(d)}$ value is computed. Two triangular distributions were used for the former, both having the maximum demand volume equal to the capacity of a city freighter. The first distribution has 30% of the demands displaying low volumes, 40% medium-size volumes, and 30% high volumes; the figures for the second distribution are 30%, 50%, and 20% respectively. Low, medium, and high demands were computed as 20%, 50%, and 80% of the maximum demand, respectively. Finally, two values were used for $\widehat{vol(d)}$, 80% and 100% of the average volume used to generate demands and for the no-planning, deterministic, strategy. Thirty scenarios were then generated for each of the thirty-two instances. CPLEX version 12.3 was used as both LP and MIP solver. Experiments were run (sequentially) on several workstations with Dual-Core AMD Opteron(tm) Processor 2218 and 2G DDR2 RAM memory operating under SunOS 5.10.

We used the same solution approach for the four recourse strategies. The a priori plan was first generated by solving the (first tier) urban-vehicle scheduled service network design problem with the appropriate $\widehat{vol(d)}$ value for all customer demands. This problem corresponds to the restricted tactical planning formulation of Crainic et al. (2009a) and model (1) - (7) with the expectation over the recourse actions replaced by an approximation of the routing cost from each satellite to each customer. We used the implementation of Crainic and Sgalambro (2009).

The recourse solutions were then computed for each scenario using a two-step procedure. The first step identifies customers to be serviced directly, if any, and prepares the routing network by building itineraries on the service network defined by the services in $\mathcal{R}(\boldsymbol{\rho}^1)$, the slack arcs providing possible direct services (added when at least one observed volume demand is higher than the corresponding $\widehat{vol(d)}$ value), and the selected rendez-vous points $\mathcal{ZT}(\boldsymbol{\rho}^1, \boldsymbol{\zeta}^1)$. We then perform the customization required by each recourse strategy. We thus solve a minimum cost multicommodity network flow problem for the routing strategies, restricting or not customers to their first stage rendez-vous point allocations as indicated in Section 4.2. For the service dispatch and routing strategies, we first determine the sliding time windows, as described in Section 4.3, and then solve the restricted tactical planning formulation as described above.

When the output of the first step includes customers to be serviced directly, dummy rendez-vous points, corresponding to the external zones of those customers, with wide time windows are added to the rendez-vous points, and associated customers, determined during the first step. We then solve the resulting SS-MDMT-VRPTW (Crainic et al., 2009a) with the meta-heuristic detailed in (Crainic et al., 2012b), which first decomposes the problem by rendez-vous point and solves the resulting series of VRPTW and, then, calls upon a minimum cost flow problem to determine the vehicle work segments.

As previously mentioned, we also defined a no-advance-plan strategy for comparison purposes. This strategy assumes total flexibility in the assignment and deployment of resources and, thus, it builds the plan of operations for each day once the actual demand is revealed. This corresponds to the complete tactical planning model of Crainic et al. (2009a) and we followed the heuristic proposed in that paper, solving first the restricted model (as for the first stage described above) and then the city-freighter routing formulation (using the same heuristic as for the second stage). Obviously, no direct services are required in this case.

5.2 Results and analyses

We group the experimental results by type of performance measure and give aggregated figures over the range of problem instances (detailed results may be obtained from the authors). In the tables of this section, the routing recourse strategies are identified **R** and **RA** for the Route and Route & Assign cases, respectively. Similarly, the service dispatch and routing strategies are identified **SR** for Dispatch & Route, and **SRA** when the first stage customer-to-satellite assignments are relaxed in the Dispatch & route& Assign strategy. The no-plan strategy is identified as **NO**.

The first group of measures regards the costs of the system. The average measures are displayed in Table 1. We identify by *1s* and *2s* the first and second stages, respectively, by *1l* and *2l* the first (urban vehicle) and second (city freighter) tiers of the City Logistics system, respectively, and by *DD* the direct-delivery mode. Table 1 then displays for each strategy the average city-freighter utilization costs for the first and second stages, the standard deviation for the latter, and the average cost of direct delivery movements with the average and standard deviation of the corresponding numbers of customers involved. Notice that the no-advance-plan strategy does not rely on direct services as the service network on both tiers is optimized for each scenario and, therefore, the corresponding **# DD** figure gives the average difference between the cost of the customized first-tier service and the cost of the same service optimized for the average demand $\widehat{vol(d)}$.

Recourse	1s2l	2s2l	2s2l_s	DD	#DD	#DD_s
R	20941.0	22900.4	10%	13988.4	2.8	1.1
RA	20938.9	22087.1	11%	6475	1.3	0.8
NO	18311.7	18506.2	13%	1928.2	0	0
SR	20947.5	23041.5	10%	13988.4	2.8	1.1
SRA	20899.9	22538.8	11%	6194.3	1.2	0.8

Table 1: Aggregated cost measures

As indicated by the figures of Table 1, the difference between the plan and no-plan cases is low. Of course, adjusting the service to each period demand results in the lowest-cost operation with no additional vehicles required to perform direct customer servicing. It is thus clear that when material and human resources can be mustered with almost no advance notice and their deployment can be modified at will with no cost, tailoring the service and schedule for each period is best from a cost point of view. This is not possible in most cases, however, in particular regarding the management of human resources. The "cost of planning" appears then to be around 15% off the lower bound provided by the no-plan strategy. Comparing recourse strategies, it is interesting to notice that there is no significant difference from a total cost point of view. This is not surprising as very similar numbers of vehicles are required in all cases.

Strategies start to differentiate when the need for additional vehicles is considered, in particular with respect to the value of flexibility. Increasing managerial flexibility, by allowing to modify the customer-to-rendez-vous point assignments, reduces slightly the city-freighter routing costs but reduces significantly the number of customers that need to be serviced directly, as well as the corresponding variability. A somewhat more in-depth analysis of the cost and extra vehicle figures relative to various system characteristics, yields that the recourse to direct servicing increases with the number of customers but decreases with the number of external zones, while the impact of the number of satellites and the width of the time windows appears negligible, given an a priori first tier service network. The analysis also seems to indicate that setting the predictive $\widehat{vol(d)}$ value at 100% of the forecast (average) demand yields better overall results that a 80% value. The cost of the plan - the first stage urban vehicle service network - is higher but it is compensated by lower second stage routing and direct services costs.

The second analysis focuses on the utilization of the vehicles and their presence in the city. While also linked to cost performance, these measures provide an indication of the impact of freight transportation on the city in terms of numbers of vehicles on the streets and the duration of their presence. The figures related to this analysis are displayed in Tables 2 and 3. The former displays the average length of the routes vehicles perform, where the last column gives the average distance of the empty movements performed by city freighters, including the trips to the external zones to pick up loads for customers serviced by direct delivery. Table 3 gives aggregate measures (averages) for the number of urban vehicles and city freighters used, the number of work segments performed by city freighters, the number of customers serviced directly, and the urban vehicle and city freighter loads.

Recourse	2s1l	2s2l	2s2l_s	Empty CF
R	64.8	318.6	37.6	156.4
RA	64.8	298.4	36.2	147.0
NO	80.4	233.4	29.3	118.6
SR	64.8	321.8	38.8	157.2
SRA	65.2	303.3	36.7	149.6

Table 2: Aggregated route-length measures

Recourse	#UV	#CF	#CFWS	#DD	UV load	CF load
R	4.5	10.2	11.4	2.8	77.00%	79.30%
RA	4.5	10.2	11.1	1.3	88.40%	81.10%
NO	4.6	9.2	9.5	0	85.60%	82.60%
SR	4.5	10.2	11.5	2.8	77.00%	78.80%
SRA	4.5	10.4	11.3	1.2	88.40%	79.40%

Table 3: Aggregated vehicle-performance measures

The general trends in comparing the five strategies are similar to those of the cost analysis. Increased flexibility in adapting the plan to revealed demand yields enhanced performances in terms of reduced city-freighter empty movements and route lengths, as well as higher utilization of the vehicle capacity for both urban vehicles and city freighters. A larger number of customers seems to induce a somewhat higher number of empty movements, while the trend is reversed for the numbers of external zones and satellites.

This observation parallels that relative to the number and cost of direct deliveries. It also emphasizes the interest to design a system that "covers" adequately a given size and dispersion of customer population through a network of proximity facilities.

Two additional observations are worth noticing related to these results. The first one concerns the utilization of the vehicle capacities. This rate is very high, particularly when compared to what is reported from actual practice. This emphasizes the interest of consolidation. The second concerns the average number of work segments performed by the city freighters. The figure is low, of the order of 1.1, indicating that most city freighters perform one work segment only when leaving the garage. This observation emphasizes the difficulty associated to operating a system with very tight synchronization requirements. As measured in somewhat more depth in Crainic et al. (2012b) and Nguyen Khanh et al. (2012), the time vehicles are allowed to wait at satellites before the load transfer operations begin dramatically impacts the capability of the system to chain several work segments within vehicle routes. The same studies have also shown that providing a few waiting stations may significantly enhance this capability. This observation is important for the design of multi-tier City Logistics systems because, while many satellites cannot accommodate waiting (e.g., transfers between light rail and truck modes performed at ad-hoc tram stops), one can often identify parking facilities where vehicles can stop for short periods.

We complete this analysis with a few comments relative to the utilization of the satellite facilities. We examined the volatility of the facility utilization in terms of number of vehicle visits and customer assignments. Table 4 displays the variances of these measures, over all scenarios and time periods, for the five strategies. Columns #UV and #CF display the standard deviation for the numbers of urban vehicles and city freighter, respectively, while the last column displays the same measure for the number of customers assigned to the satellite.

Recourse	#UV	#CF	#Cust
R	0.0	0.1	0.1
RA	0.0	0.1	0.2
NO	0.3	0.7	1.1
SR	0.2	0.4	0.8
SRA	0.3	0.6	1.1

Table 4: Variability of satellite utilization

A high volatility measure points to satellites being used differently during the day or in different scenarios. Some might not be used all day, or the number of vehicles and customers serviced might change during the day. In the field, such variability might require the managerial capability to rapidly re-deploy resources, including personnel. Thus, not surprisingly, the variability increases with the flexibility in management. It increases when the first-stage assignments of customers to rendez-vous points are relaxed, the higher variability being associated to the no-advance-plan strategy, according to which one decides every day how to deploy resources. It is thus higher for the strategies that yield the highest benefits in terms of cost, fleet utilization, and impact on the city. The analysis thus further underlines the need to valuate not only the design of City Logistics systems, but also the flexibility and agility of the management processes and policies in order to find the best trade off between the benefits to the city, its citizens and economy, on the one hand, and the working conditions of the personnel making the system function, on the other hand. The models presented in this paper may make a significant contribution to such studies.

6 Conclusions and Perspectives

We introduced the tactical planning problem for City Logistics systems when demand uncertainty is explicitly considered, and gave a first formal description. At the best of our knowledge, no previous contribution in the literature addresses uncertainty issues in tactical planning for City Logistics.

Tactical planning is central both in the overall planning process, as tactical plans are required to evaluate strategic plans and guide operations, and 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. The challenge in introducing explicit consideration of uncertainty into tactical planning for City Logistics therefore is not only into building an appropriate mathematical formulation of the problem, but also into understanding the impact on the management and performance of the CL system. The paper is a first answer to this double challenge.

We proposed a two-stage stochastic-programming model for general two-tier CL system setting, where the first stage selects the first-tier service network design and the general workloads of the inter-tier transfer facilities, while the second stage determines the actual vehicle routing on the second tier as well as some limited adjustments of the first-stage service design decisions.

Four different recourse strategies, and formulations, were proposed to adapt the plan to the observed demand. These strategies, as well as the no-advanced-planning strategy building the plan for each "day" once the actual demand is observed, were experimentally compared through an extensive Monte Carlo simulation. The performance of the 2T-CL system under the five strategies were contrasted through performance measures relative to the costs of operating the system, including the additional vehicle capacity and movements required when the plan was not providing sufficient transportation means, the utilization of the various types of vehicles, including the expected loading factors, the intensity of the vehicle presence within the city, including the amount of empty movements, as well as the utilization of the inter-tier satellite facilities.

The comparisons were discussed both based on the numerical figures obtained through simulation and from the point of view of managerial insights into the implication for managing CL physical and human resources. The analysis emphasized the interest of flexibility in managing resources and operations for the overall performance of the system, and discussed the associated trade-offs that must be reached for each particular application. The results also underlined the benefit of consolidation in terms of vehicle utilization (high) and presence in the city (low), as well as the need to carefully design the layout of the system in terms of inter-fleet synchronization capabilities, which may impact quite directly the sizes of the fleets required to service a given amount of demand.

Several research avenues are now open. To mention but a few among the most interesting and challenging, 1) high-performance solution methods for the deterministic and stochastic tactical planning problems for City Logistics; 2) integrating into the tactical plan and the routing strategies the uncertainty related to travel and service times; and 3) integrating passenger and freight transportation issues into a comprehensive methodology for the planning of urban transportation systems. We are advancing on a number of these issues and plan to report soon.

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References

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

J.R. Birge and F. Louveaux. *Introduction to Stochastic Programming*. Springer, New York, 2011.

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

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

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

T.G. Crainic and A. Sgalambro. Service Network Design Models for Two-tier City Logistics. Publication CIRRELT-2009-60, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada, 2009.

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

T.G. Crainic, N. Ricciardi, and G. Storchi. Models for Evaluating and Planning City Logistics Transportation Systems. *Transportation Science*, 43(4):432–454, 2009a.

T.G. Crainic, N. Ricciardi, and G. Storchi. Models for Evaluating and Planning City Logistics Transportation Systems. Publication CIRRELT-2009-11, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada, 2009b.

T.G. Crainic, X. Fu, M. Gendreau, W. Rei, and S.W. Wallace. Progressive Hedging-based Meta-heuristics for Stochastic Network Design. *Networks*, 58(2):114–124, 2011.

T.G. Crainic, F. Errico, W. Rei, and N. Ricciardi. Integrating c2e and c2c Traffic into City Logistics Planning. In E. Taniguchi and R. G. Thompson, editors, *Seventh International Conference on City Logistics, June 7-11, 2011, Mallorca, Spain*, volume 39 of *Procedia - Social and Behavioral Sciences*, pages 47–60. Elsevier, 2012a.

T.G. Crainic, M. Gendreau, and Y. Gajpal. Multi-Zone Multi-Trip Vehicle Routing Problem with Time Windows. Publication CIRRELT-2012-36, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada, 2012b.

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

P. Kall and S.W. Wallace. *Stochastic Programming.* John Wiley & Sons, Chichester, N.Y., 1994.

A.J. King and S.W.. Wallace. *Modeling with Stochastic Programming.* Springer, New York, 2012.

W. Klibi, A. Martel, and A. Guitouni. The Design of Robust Value-Creating Supply Chain Networks: A Critical Review. *European Journal of Operational Research*, 203: 283–293, 2010.

A.-G. Lium, T.G. Crainic, and S.W. Wallace. A Study of Demand Stochasticity in Service Network Design. *Transportation Science*, 43(2):144–157, 2009.

P. Nguyen Khanh, T.G. Crainic, and M. Toulouse. A Tabu Search for Time-dependent Multi-Zone Multi-Trip Vehicle Routing Problem with Time Windows. Publication CIRRELT-2012-44, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal, Montréal, QC, Canada, 2012.

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

W.B.. Powell. Dynamic Models of Transportation Operations. In Graves, S. and de Kok, A.G., editors, *Supply Chain Management*, volume 11 of *Handbooks in Operations Research and Management Science*, pages 677–756. North-Holland, Amsterdam, 2003.

W.B.. Powell, B. Bouzaïene-Ayari, and H. P. Simaõ. Dynamic Models for Freight Transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, pages 285–365. North-Holland, Amsterdam, 2007.

I. Sungur, Y. Ren, F. Ordóñez, M. Dessouky, and H. Zhong. A Model and Algorithm for the Courier Delivery Probelm with Uncertainty. *Transportation Science*, 44(2): 193–205, 2010.

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