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Tactical Capacity Planning in an Integrated Multi-stakeholder Freight Transportation System

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Abstract. This study focuses on investigating the tactical planning of an integrated multi-stake holder system in which revenue management concepts including shipper categories, demand classification, penalty costs for demand satisfaction outside of prescribed time-windows, and offering services with bundles are addressed. The aim of tactical planning in this system is to design the demand and supply sides of this integrated system simultaneously. To this end, a scheduled service network design formulation on a space-time network is developed to build a transportation plan by selecting profitable requests from non-contract shippers, selecting a subset of individual and bundled transportation scheduled services, and identifying the itineraries of the shipments on the selected service network with the objective of maximizing the profit of the system. Using realistic-size instances, an extensive computational analysis is performed on the split and unsplit shipment-flow versions of the problem. The aim of the analysis is twofold: 1) assess the computational effort required to solve the developed optimization model and 2) investigate the structural characteristics of the obtained tactical plans for different system settings

Keywords: Tactical planning, integrated consolidation-based freight transportation, revenue management, scheduled service network design

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1 Introduction

Worldwide, the transportation and logistics (TL) sector is a massive economic force, employing numerous workers, acting as a key component of the national and international trade, and playing an important role in the health of the economy. The U.S. Department of Transportation reported that the freight transportation system moved nearly 17.9 billion tons of goods valued at more than $18.2 trillion across the United States in 2019 alone. Hence, improving the TL sector and stakeholder efficiency and profitability yields significant social and economic benefits. The industry is rapidly evolving under pressure for higher efficiency and profitability coupled with lower environmental footprint. Technologies, notably operations research methods, support this evolution, as illustrated by the success of intelligent transportation systems, the emergence of platforms where shippers and carriers may meet and initiate negotiations, and form partnerships.

This study addresses an integrated multi-stakeholder system, where on the one side, many *shippers* including producers, wholesalers, and distributors make *shipper-demand requests* for cost and time-efficient transportation for their *product loads* to be moved from their origins to their destinations. On the other side of the system, many *carriers* make *carrier-capacity offers* for transportation and warehousing space, while requesting profitable loads. In the middle, using an *Intelligent Decision Support Platform* (*IDSP*) for "automated" planning and optimizing operations, the aim is to profitably and simultaneously satisfy the needs of both categories of participants. The shipper-demand requests and the carrier-capacity offers are made available to the system at different time periods. Accordingly, the IDSP receives time-dependent requests from both stakeholders and thus optimizes in time and space the selection of shipper requests, carrier capacity offers, shipment-to-carrier assignments, and shipment itineraries through the consolidation of loads of different shippers into the same vehicles and synchronization of activities as illustrated in Figure 1. The figure also illustrates the communications, including data and decision exchanges and monitoring of activities, which occur between all involved stakeholders. Efficiency and profitability benefits are expected to result from sharing resources and an integrated IDSP through the efficient coordination and planning performed by the IDSP.

This integrated multi-stakeholder system is called a *Many-to-One-to-Many* (*M1M*) system that defines a freight transportation decision-making setting in which shippers are the demand side and carriers are the supply side. For the demand side, revenue management concepts are addressed by considering two types of shippers: contract-based and non-contract. The demand of contract-based shippers must be fully satisfied. While for the demand of non-contract shippers, selection decisions are made on satisfying this demand depending on its profitability and also the available capacity of the services. The demand of both contract-based and non-contract shippers is classified into two categories based on the delivery duration, which can be standard or urgent. It is also assumed that the IDSP is allowed to pick up and deliver the shipper-demand requests earlier or later

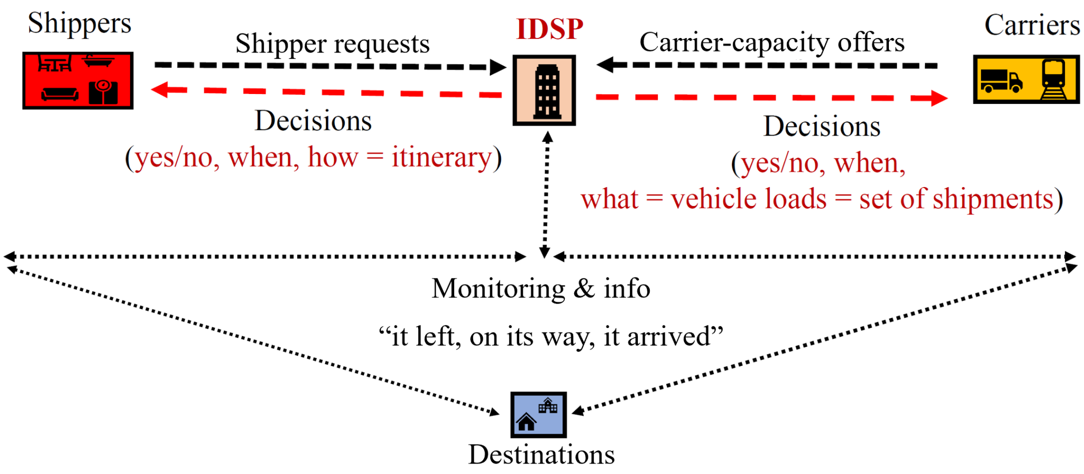


Figure 1: An integrated multi-stakeholder system structure, communications, and decisions

than their preferred time window by paying a penalty cost to the shippers.

For the supply side, it is assumed that carriers can offer services to the IDSP individually or as part of a bundle. The IDSP is then allowed to select any particular service individually or with the bundle, while optimizing the assignment of the shipper-demand requests to the selected services. This assumption actually embeds revenue management considerations to the supply side. Moreover, some carries in addition to transportation services, may offer warehousing space at terminals for the shipments that need to be stored temporarily. Hence, the IDSP needs to make location decisions to select such terminals and use their warehousing space. The IDSP also manages the space of the selected terminals during different time periods to improve the efficiency of the transportation network. The characteristics of the M1M system and its main components are described in detail in Section 2.

Such an advanced system, with massive amount of interactions, needs planning at the strategic, tactical, and operational levels to efficiently manage the activities. In this study, we focus on building an efficient instrument for planning the transportation activities of this system at the tactical level. The aim is to design the demand (i.e., shippers) and supply (i.e., carriers) sides of this integrated system simultaneously and plan for them. For the demand side, the goal is to select the demand requests of non-contract shippers that generate profit for the IDSP and satisfy them together with all the demand requests of contract-based shippers. For the supply side, on the other hand, the goal is to select individual and bundled services offered by carriers in order to fit the demand side with the supply side and move the shipper-demand requests using the capacities of the selected services in the most cost efficient way. Tactical plan also aims to determine the shipments itineraries including transferring and consolidation activities in terminals, together with the routing of shipper-demand requests from their origin to their destination through the resulting service network. The objective is to build a plan that maximizes the profit of the IDSP. This transportation plan is performed within a given *schedule length* (e.g., one week) and is then repeatedly operated over a certain *planning horizon* (e.g., a season) to manage the operations during this period.

There is a broad and extensive literature on tactical planning performed by consolidation-based transportation carriers where the aim is to satisfy the demand of shippers (which are contract-based) by setting up a cost-efficient service network (which is built by selecting individual services) with respect to the forecasted demand. An interested reader may refer to Crainic and Laporte (1997), Crainic (2000), Wieberneit (2008), and Crainic and Hewitt (2021) for general surveys of the literature. However, addressing tactical planning issues for an integrated multi-stakeholder system like M1M has been rarely studied in the literature. Our objective is to contribute to fill up the gaps in knowledge by focusing on tactical planning issues for the M1M system. We also incorporate revenue management concepts into the problem while addressing tactical planning, which usually is tackled at the operational planning level. For the demand side, we introduce shipper differentiation, between contract and non-contract types, as well as differentiation in the type of demand, standard and urgent and include selection decisions on the acceptance of requests from non-contract shippers. We also pay penalty cost to the shippers for the early and late pick-up and delivery of their shipments. Incorporating these assumptions into the problem provides room for more flexible demand routing, more effective consolidation, capturing more of the high priced contribution demands, and thus gaining more profit. For the supply side, we introduce differentiation in the type of service requested, regular and fast. We also assume that each service can be offered either individually or as part of a bundle. The inclusion of bundles has a direct link with the revenue management which enables carriers to offer their services with lower fixed selection costs resulting in higher volume of business for them and profit for the platform. Unlike the traditional tactical plan, where the aim is to just design the supply side and plan for it in the most cost efficient way, the aim in this integrated system is to simultaneously design both the demand and supply sides and plan for them with the objective of maximizing the profit.

Scheduled service network design (SSND) is widely used as the methodology to support tactical planning issues (Crainic and Hewitt 2021). We also propose a SSND formulation to address tactical planning of the M1M system aiming for best system performance yielding a four-win situation: carriers earn additional revenue instead of moving air, shippers see their delivery costs decrease, the IDSP earns on each transaction, and the society benefits from consolidation through less vehicles on the road and less pollution. By addressing tactical planning, we build an evaluation instrument that can be also used for contractual negotiations and strategic planning. We perform an extensive computational analysis on the split and unsplit shipment-flow versions of the problem to evaluate the behavior and structural characteristics of the solutions of the proposed model using realistic-size instances.

The contributions of this paper are: 1) addressing tactical planning issues for an integrated multi-stakeholder system in which revenue management concepts are considered; 2) proposing a new SSND formulation for the problem setting; 3) solving the corresponding formulation for realistic-size instances; 4) analyzing and showing the impact of revenue management, including shipper categories and different demand types, penalty costs, bundle service offers, and different service types on the structure of the scheduled service network as well as on the IDSP's profit through extensive computational experiments and also providing meaningful managerial insights for the decision maker.

The remainder of the paper is organized as follows. The next section provides the description of the main components of the M1M system and the corresponding operations required to be planned. Section 3 reviews the related literature. Problem definition and mathematical formulations are introduced in Section 4. Section 5 presents extensive computational experiments. Concluding statements along with future research directions are provided in Section 6.

2 Problem Setting

This section presents the description of the main components of the integrated M1M system including network (Section 2.1), shipper-demand requests (Section 2.2), and carrier capacity offers (Section 2.3), respectively. This section also discusses tactical planning issues for the M1M system (Section 2.4).

2.1 Physical Network

The problem settings are defined on a transportation network as illustrated in Figure 2. Activities take place between several *zones*, illustrated through the large disks in Figure 2. We assume that all *origins and destinations* within a zone may be serviced by the terminals associated to that zone. The small numbered disks within the large disks in the figure represent possible origins and destinations.

Terminals, squares in the figure, may be either owned, managed, or only used by the IDSP to perform required activities (e.g., warehousing or crossdock transferring). Figure 2 represents two types of terminals: *consolidation terminals* and *transfer terminals*. The former are generally “close” to at least one zone and can be used to perform the complete gamut of services, in particular, 1) *first-mile service* to the zone, receiving picked up shipments from the zone delivered by appropriate carriers and vehicles; 2) *sorting* (*classifying*) inbound shipments, both from other terminals and from the zones preparing them for the next long-haul transport; 3) crossdock *transfer* of shipments between

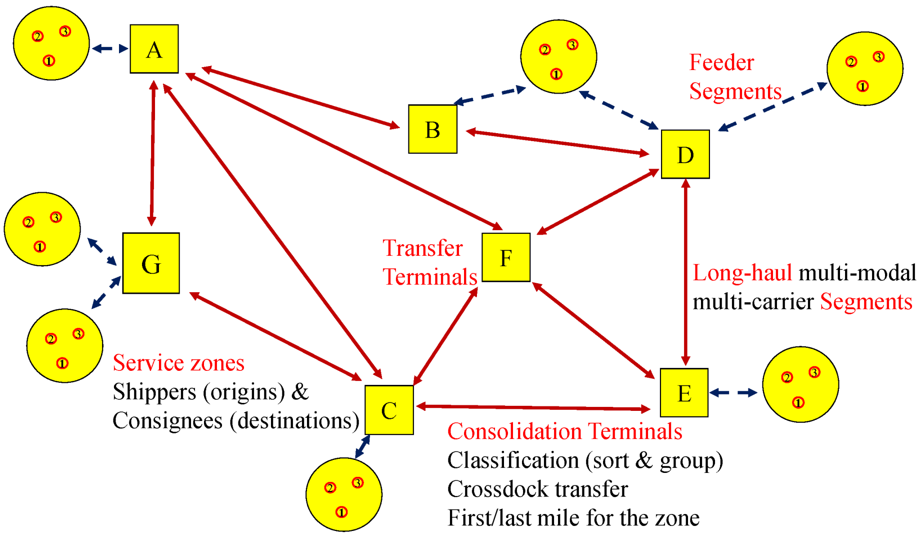


Figure 2: Hyper corridor network

vehicles without classification; 4) *last-mile service* to the zone, preparing shipments for distribution to the respective destinations (e.g., all except F in Figure 2). The transfer terminals perform services of types 2 and 3 only (e.g., F in Figure 2). The transfer and warehousing activities at both types of terminals are limited due to the limited number of available handling equipment and storage space.

The nodes representing terminals, origins, and destinations make up the nodes of the physical network. The arcs of the network represent physical or conceptual modal connections between the nodes of the network. The former represent land-based infrastructure, e.g., roads, railways, rivers, and canals, while the latter stand for maritime and air connections. The network contains two types of arcs. The full lines of Figure 2 represent the *long-haul arcs*. Dashed lines in the figure represent the association between terminals and zones, linking activities within the zones and the main long-haul network, called *feeder arcs*. Arrows at both ends indicate that movement is possible in both directions.

Transportation activities in M1M systems are organized as follows. A shipment, resulting from a shipper request, is picked up from its origin. Then, it is transported to one of the terminals associated with the zone. Loads brought in at terminals may be either transferred (unloaded, crossdock moved, and loaded) to an outgoing vehicle or classified (re-classified, eventually; unloaded, sorted, moved and loaded into the outgoing vehicle). Consolidated freight may thus travel to the final destination, i.e., a terminal associated to the zone of the final destination, or to an intermediary terminal for transfer, with or without re-consolidation. At the destination terminal, vehicles are unloaded, freight is potentially separated and re-consolidated into vehicles for efficient "local" delivery.

2.2 Shipper-demand Requests for Transportation

Shippers are the costumers and hence the demand side of the M1M system. They make shipper-demand requests for their loads. Each *shipper-demand request* is characterized by several attributes, including the volume, the origin, and the destination. We assume that products need similar packing, loading, transport, and warehousing requirements; hence, they can be loaded together. Depending on the characteristics of the shipments, the volume of the shipper-demand requests may be split or unsplit. Such information is provided to the platform before making any decision. In this study, we consider both cases where the volume can be split or unsplit to analyse and evaluate the impact of these characteristics on the optimal solutions. For each shipper-demand request, there is a time window indicating the *release time*, when the shipper makes the shipment available for pickup, and the *due date*, preferred delivery time of the shipment to the destination.

Most of the studies in the literature consider one type of category for the shippers known as *contract-based*. This category generally corresponds to the case where shippers negotiate in advance and often enter into a long-term contract to secure their required capacity for a specified planning horizon (e.g., one season) and thus all demand volume of such shippers must move on time and safely. However, in realistic applications, in addition to contract-based shippers, there might be irregular potential shippers that request transportation services with a short-notice. Such shippers are called *non-contract* and their demand may be fully accepted to be moved or not accepted at all depending on the profit obtained from satisfying this demand and also the available capacity of the services. In this study, we consider both categories of shippers (i.e., contract-based and non-contract) to take revenue management considerations into account and make selection decisions on the non-contract requests. To provide more detailed insights, we additionally assume that the demand of both contract-based and non-contract shippers is classified based on their delivery duration: standard and urgent. As expected from their names, for the same origin and destination, the delivery duration of an urgent shipper-demand request is shorter than that of a standard one.

The economic attributes includes the revenue for the IDSP to take care of the shipment. There is a *unit revenue* for each shipper-demand request. The revenue is mainly dependent on the demand type (i.e., standard and urgent), the characteristics of the product (e.g., weight and volume), and the distance between origin and destination, respectively.

In most applications, it is not realistic to assume that all the demand requests can be satisfied (i.e., picked up and delivered) within their preferred time window. This assumption leaves the carriers no choice but to provide services at any time and cost, resulting in higher costs for the platform and poor consolidation. To represent a more realistic problem setting, we assume that shippers allow to move their shipment earlier or later than their preferred time window with a penalty cost. Such information is provided to the platform by shippers. Such penalties are paid by the IDSP to the shippers whenever their shipments cannot be handled within their preferred time windows.

2.3 Carrier Capacity Offers

Carriers are the supply side of the M1M system. They make carrier-capacity offers for transportation by providing services. A *service* can be available at certain points, terminals or zones, in a given region, which the IDSP can use for a certain time period. Each service is labeled by the origin and destination terminals, capacity, and a route through the physical network making up of the sequence of physical arcs together with a series of terminals included in the sequence where the service makes stops.

Each service is further characterized by a carrier-predefined timetable (which accompanies the offer) indicating the service departure and arrival times for all the terminals visited in the sequence: origin, intermediary terminals, and destination. The time-stamped service arcs are called service legs. Accordingly, each leg has a departure time from its origin and an arrival time at its destination. Each service has a *duration* representing the total travel time from its origin to destination, which is identified by the legs schedule and includes both travel and stop times. Each service with such time attributes is called a *scheduled service*. We assume that all the services offered by carriers are scheduled and classified into two categories based on their travel time (duration): regular and fast. As expected from their name, the duration of a fast service is shorter than that of a regular service with the same origin and destination.

The economic attribute of a carrier capacity offer is its price composed of two parts, which we identify as costs since they have to be paid by the platform if it decides to use the service. Accordingly, there are two cost measures associated with each scheduled service: a fixed cost and a unit transportation cost. The *fixed* cost is for selecting and using the capacity of the service and is also related to the service type (i.e., regular and fast). The *unit transportation* cost, on the other hand, gives the cost per unit of volume and distance that is applied.

We assume that carriers can offer services individually or within a bundle. Service bundles are offered to induce large orders by giving discounts on service selection costs. For example, a carrier that can run services back and forth between some origin-destination pairs may offer them in a bundle with a discount applied on the bundle selection cost. Another variant would be the case where a carrier can run several different services at a same time period. The type and number of services in each bundle is provided by carriers. There is no fixed selection cost for each individual service in a bundle, instead, each bundle is associated with a fixed selection cost. However, a unit transportation cost is associated with each service in a bundle.

Each *carrier-capacity offer* may include an individual service or a bundle of services and the IDSP accepts or rejects those offers optimizing comprehensively the assignment of shipper requests to the carrier offers available and selected at decision time. The set of individual services and bundles are not mutually exclusive. Accordingly, any particular service cannot be selected individually and within a bundle at a same time. Therefore, the IDSP selects each service either with the bundle or as a single capacity offer. Moreover, any particular service may be in several bundles, but, it can be selected at most once.

Some carriers, in addition to transportation services, may also offer warehousing space with limited capacity at some terminals where the shipments could be stored temporarily if the offer is accepted. Similar to transportation services, the economic attributes of offering warehousing space is its price which incur costs for the IDSP. If the IDSP decides to use the warehousing space of a terminal, it has to pay to the carrier a fixed selection cost to have access the capacity as well as the variable cost per unit of volume for the shipments that are held.

2.4 Tactical Planning of M1M System

The IDSP is developed to plan and optimize the operations and transportation activities of the M1M system. In this case, tactical planning is performed to establish, in advance, a transportation plan (which includes accepted shipper requests, selected scheduled services and bundles, as well as the assignment of consolidated shipments to these services) that is to be repeatedly used to help streamline the operations of the M1M system and improve its overall profitability. Consequently, the transportation plan is operated within a predefined time period called *schedule length* (e.g., a week). It is then repeatedly performed over a certain medium-term planning horizon (e.g., a season) to help manage the operations during this period.

Remark that, at the tactical level, the estimated demand requests of all origin and destinations within the zones (the large disks in Figure 2) are aggregated and assigned to the closest terminals associated to them. Accordingly, all the information related to the network, shipper-demand requests, and carrier capacity offers described in Sections 2.1, 2.2, and 2.3 is aggregated and presented based on terminals and long-haul arcs for planning the M1M system at the tactical level. For example, we approximate the volume, origin, destination, time-window, and unit revenue of the estimated aggregated demand requests from both contract-based and non-contract shippers based on the terminals.

Tactical planning in the M1M system aims to simultaneously design the demand and supply side of this integrated system and plan for them with the objective of maximizing the profitability of the platform. For the demand side, the goal is to select the demand requests from the non-contract shippers that generate profits for the platform and satisfy them together with all the demand requests from contract based shippers. Recall that the design of the demand side of the system is based on the forecast regular demand requests of contract-based shippers and the potential regular ad-hoc demand requests of non-contract shippers from the terminals.

For the supply side, on the other hand, the goal is to select the individual and bundle of services offered by carriers in order to fit the demand side with the supply side and thus satisfy the shipper-demand requests by making use of the capacity of these selected services in the most cost efficient way. Tactical planning also aims to determine the itineraries used for moving the shipper-demand requests from their origin to their destination throughout the resulting service network. The *demand itinerary* is characterized by the origin and destination of the shipper-demand request along with the pick-up and delivery times, the assignment and sequence of services selected for moving the request to the destination, storing, transferring and consolidating of shipment in the terminals, and routing the shipment through the resulting network.

As all problem elements have time-related characteristics, the problem is *time-dependent* and *time-space networks* are the modelling instruments of choice in this case. We develop a schedule service network design model as the methodology of choice for building the tactical plan for the M1M system within a time-space network where the events and decisions are represented at particular time moments.

3 Literature Review

In this section, we review relevant literature to the M1M system. In particular, we focus on the following themes: service network design for consolidation-based carries, revenue management in freight transportation, third-forth party logistics systems, tactical planning studies in city logistics, and physical internet. The first two touch on the main optimization methods that have been proposed to support the planning processes involved in the considered freight transportation system. The last three themes center on the specific challenges involved in managing logistics systems that entail multiple stakeholders that share resources.

Service network design problems have been extensively studied in the literature to address tactical planning issues for consolidation-based carries (Crainic 2000 and Crainic and Hewitt 2021). The reader may refer to reviews on this field for long-haul transportation by Crainic (2003), for rail by Cordeau et al. (1998) and Chouman and Crainic (2021), for maritime by Christiansen et al. (2007), and for intermodal transportation by Crainic and Kim (2007) and SteadieSeifi et al. (2014). The aim of the classical SSND in the literature is to build a transportation plan by selecting the services and their schedules to satisfy the demand in the most-cost efficient way.

In the context of freight transportation, revenue management concepts have been rarely considered in the literature for planning a system at the tactical or operational levels. Crevier et al. (2012), Bilegan et al. (2015), Wang et al. (2015), and Wang et al. (2016) are the very few studies that address revenue management aspects while planning the carrier services at the operational level. At the tactical level, recently, Bilegan et al. (2021) integrate revenue management in SSND for intermodal barge transportation by addressing several costumer categories along with several tariffs and operations with the objective of maximizing the net revenue of the carrier. In this paper, to address tactical planning issues for the M1M system, we also use the SSND model with the integration of revenue management concepts. In addition to customer categories and demand classification, we include penalty cost for early and late pick-up and delivery of shipments. We also assume that carriers can offer services in bundles which is a novel notion in the context of SSND problems. Moreover, the objective of this problem, unlike the classical SSND in the literature, is to simultaneously design both the demand and supply sides by selecting the profitable demand of non-contract shippers and building a service network that satisfies the demand of contract and non-contract shippers while maximizing the IDSP's profit. The service network is built by selecting individual and bundle of services offered by carriers.

One of the main differences between the M1M system and the classical SSND literature is that the platform does not own resources including transportation services and warehousing spaces. The IDSP exploits carriers and third-forth party logistics (3-4PLs) service providers to handle all transportation activities in the system. Systems involving 3-4PLs has received considerable research attention in the recent past from logistics scholars as increasingly many companies across industry sectors use 3-4PLs for the management of all or part of their logistics operations (Marasco 2008). According to Jayaram and Tan (2010) and Giri and Sarker (2017), using 3-4PLs for coordinating logistics activities results in significant advantage in saving cost and time. The reader may refer to Lieb and Bentz (2004), Maloni and Carter (2006), Marasco (2008), and Aguezzoul (2014) for reviews on 3-4PL systems. Similar to the studies related to 3-4PL in the literature, we also make a selection decision on setting the contract of using transportation resources. However, to the best of our knowledge, there is no study in the literature that uses 3-4PLs for addressing tactical planning issues as we do in this paper.

Most of the problems focusing on City logistics belong to the consolidation-based transportation system studies and their aim is to reduce the externalities and nuisances, and more generally, the environmental footprint associated to the transportation of freight within urban areas, while sustaining the social and economic development of the organizations and cities involved (Crainic et al. 2021). Similar to the M1M system, city logistics is also an integrated system including shippers and carriers, where movements are coordinated and loads of different shippers are consolidated into the same vehicles (Benjelloun and Crainic 2008). Hence, the system involves complex interactions and needs advanced planning methods, in particular for tactical planning. General descriptive papers and surveys regarding city logistics may be found in, e.g., Hesse (2002), Benjelloun and Crainic (2008), Gonzalez-Feliu et al. (2014), Taniguchi (2014), Savelsbergh and Van Woensel (2016), Holguín-Veras et al. (2020a,b), and Crainic et al. (2021). The main difference between the problem setting considered in city logistics literature and the M1M system is the incorporation of revenue management concepts in the M1M system and selection decisions for both the demand and supply sides rather than just the supply side. Moreover, contrary to most of City logistics studies in which the objective is to minimize the selection and operation cost of services, the objective of M1M system is to maximize the profit of the IDSP.

Physical internet (PI) and synchromodal transport/synchromodality are another related line of research. Both address new fundamental solutions to operations of production and freight transportation to reduce environmental and economic sustainability (Ambra et al. 2019). Inspired by digital internet, PI suggests to route the physical goods via different links from their origins to destinations. Montreuil (2011), Pan et al. (2017), and Ambra et al. (2019) provide an overview of the current PI research. Synchromodality, on the other hand, is a form of multimodality and combines the best possible transport modes for moving the shipment with the aim of improving the freight transportation. The reader may refer to Mes and Iacob (2016), Tavasszy et al. (2017), Dong et al. (2018), and Ambra et al. (2019) for review on synchromodality. In the M1M system, similar to PI and synchromodality, the aim is to achieve more economic and social efficiency and also increase the profitability of stakeholders involved in the system (i.e., shippers and carries). To this end, we consider cases where the shippers demand volume can be split and unsplit and analyse the impact of these characteristics on the optimal solutions, in particular on the number of services required for satisfying demand as well as amount of their used capacity. The decision structure in PI and synchromodality is related to the concept of an IDSP. Hence, the studied tactical plan in this paper can be used in PI and synchromodality.

To sum up, compared to the literature, this study contributes to advance the design and planning of an integrated transportation and logistics system with different stakeholders at the tactical level. Specifically, these advancements are in the design of the demand and supply sides of the system with multi-stakeholder demands consolidate in time and space within shared service capacity of multi-stakeholder supply, and the inclusion of revenue management concepts, including different types of shippers and requests, penalty costs, and offering services in bundles. Both propose new fundamental solutions to the challenging logistics problems involved in planning the ever increasing production and freight transportation operations needed to support the economical sustainability and the growth of modern societies while reducing the environmental impact of such operations.

4 Notation and Mathematical Formulations

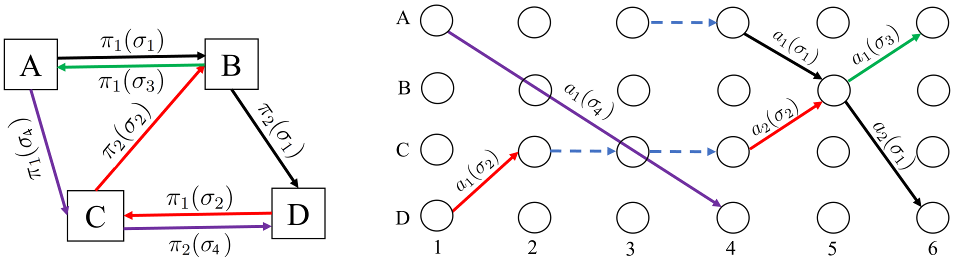
Based on the problem definition introduced in Section 2, in this section we first define the notation and the parameters used (Section 4.1) and then present the mathematical formulation developed for the problem (Section 4.2).

4.1 Notation

Let us consider $\mathcal{G}^{\mathtt{P}} = (\mathcal{N}^{\mathtt{P}}, \mathcal{A}^{\mathtt{P}})$ as the physical network in which $\mathcal{N}^{\mathtt{P}}$ represents the set of physical terminals and $\mathcal{A}^{\mathtt{P}}$ the set of physical arcs of the network. We formulate our service network design problem on a space-time network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where the schedule length denoted by T is partitioned into intervals of equal length. The set of time points is then defined as $\mathcal{T} = \{1, \ldots, T\}$. Accordingly, the time-expanded network has time-stamped nodes $(n, t) \in \mathcal{N}$ for $n \in \mathcal{N}^{\mathtt{P}}$ and $t \in \mathcal{T}$, and time-stamped arcs $((n, t), (\hat{n}, \hat{t})) \in \mathcal{A}$ for $(n, \hat{n}) \in \mathcal{A}^{\mathtt{P}}$ and $(t, \hat{t}) \in \mathcal{T} \times \mathcal{T}$ wherein $t \leq \hat{t} \leq T$.

We define $\mathcal{K}$ as the set of all shipper-demand requests. Each shipper-demand request $k \in \mathcal{K}$ is characterized by its volume w_k, origin $o(k)$, destination $d(k)$, and a time-window $(\alpha(k), \beta(k))$ representing the desired time period for picking up and dropping off the request from its origin and at its destination, respectively. Let's define $\psi^k_{(o(k),t)}$ as the penalty cost for picking up shipper-demand request $k \in \mathcal{K}$ from its origin $o(k)$ at period $t \in \mathcal{T}$. Similarly, let's denote $\psi^k_{(d(k),t)}$ as the penalty for delivering shipper-demand request $k \in \mathcal{K}$ at its destination $d(k)$ at period $t \in \mathcal{T}$. When the shipper-demand request $k \in \mathcal{K}$ is within its predefined time-window, we set the costs to zero (i.e., $\psi^k_{(o(k),t)} = 0$, when $t \in \alpha(k)$ and $\psi^k_{(d(k),t)} = 0$, when $t \in \beta(k)$). There is a unit revenue ρ_k associated to shipper-demand request $k \in \mathcal{K}$. The set of shipper-demand requests includes both contract-based and non-contract shippers, i.e., $\mathcal{K} = \mathcal{K}^{\mathtt{C}} \cup \mathcal{K}^{\mathtt{NC}}$.

Let's $\mathcal{C}$ represent a set of carriers and $\Sigma(c)$ the set of transportation services offered by carrier $c \in \mathcal{C}$ with $\Sigma = \cup_{c \in \mathcal{C}} \Sigma(c)$, the set of all services offered to the platform. Each service $\sigma \in \Sigma$ has a physical route between its origin, $o(\sigma)$, and destination, $d(\sigma)$, in the physical network. The *route* of the service is made up of the *sequence of physical arcs* $\Pi(\sigma) = \{\pi_i(\sigma) \in \mathcal{A}^{\mathtt{P}} \mid i = 1, \ldots, |\Pi(\sigma)|\}$ together with the sequence of terminals $\Theta(\sigma)$ in this sequence where the service stops. In the time-space network, each service is further characterized by a schedule indicating the service departure and arrival times where it originates, stops, and terminates. The time-stamped service arcs are called *service legs.* Accordingly, let us define $\mathcal{L}(\sigma) = \{a_l(\sigma) | l = 1, \ldots, |\mathcal{L}(\sigma)|\}$ as the set of service legs in which each service leg $a_l(\sigma) \in \mathcal{L}(\sigma)$ has a departure time from its origin, $\alpha(a_l(\sigma))$, and an arrival time at its destination, $\beta(a_l(\sigma))$. Each service $\sigma \in \Sigma$ is further characterized by a value vector u_σ which includes the leg specific capacities, i.e., $u_\sigma = \left(u_{a_l(\sigma)}\right)_{a_l(\sigma) \in \mathcal{L}(\sigma)} \in \mathbb{R}^n$, where $u_{a_l(\sigma)}$ represents the maximum amount of shipper-demand volume that leg a_l could serve in its corresponding service σ. Each service has a *travel time* $\tau(a_l(\sigma))$ for each leg (i.e., between each pair of consecutive stops). There is a fixed cost f_σ for selecting and using the capacity of each service and a unit transportation cost $c^k_{a_l(\sigma)}$ for moving one unit of shipper-demand request $k \in \mathcal{K}$ on service leg $a_l(\sigma) \in \mathcal{L}(\sigma)$. Figure 3(a) presents the physical routes of four services between their origin and destination on the physical network ($\mathcal{G}^{\texttt{P}}$). The first two and the forth services (i.e., σ_1, σ_2, σ_4) have two arcs and the third one (i.e., σ_3) has one arc. The time-space representation of these services on the time-space network ($\mathcal{G}$) is illustrated in Figure 3(b). The time-space network indicates the departure and arrival times where each service originates, stops and terminates, respectively. The first and second services have two legs and the third and forth ones have one leg. As represented in the figure, the first and second services have a short and long stay in the intermediary terminals, respectively.



(a) Physical network $\mathcal{G}^{\texttt{P}}$.

(b) Space-time network $\mathcal{G}$, with $|T| = 6$.

Figure 3: Physical routes and space-time representation of three services on the physical and space-time networks, respectively.

Let $\mathcal{B}(c)$ be a set of service bundles offered by carrier $c \in \mathcal{C}$ with $\mathcal{B} = \cup_{c \in \mathcal{C}} \mathcal{B}(c)$ defining the set of all offered service bundles. Let us also define $\Sigma(b)$ as the set of services included in bundle $b \in \mathcal{B}(c)$. There is no fixed cost for each individual service in a bundle. Instead, each bundle $b \in \mathcal{B}$ has a fixed selection cost f_b, a size n_b representing the number of services in it, and a unit transportation cost ($c^k_{a_l(\sigma)}$) associated with each service in the bundle, for all $\sigma \in \Sigma(b)$.

Let us define $u^{\texttt{MH}}_{(n,t)}$ as the maximum amount of shipments that can be handled (unload, tranship, and load) in terminal $n \in \mathcal{N}^{\texttt{P}}$ at time period $t \in \mathcal{T}$. As some terminals may also offer warehousing space, let's define $u^{\texttt{W}}_n$ and f_n as the warehousing capacity and the fixed cost for using the warehousing space of terminal $n \in \mathcal{N}^{\texttt{P}}$, respectively. The measurement used for the volume of the shipper-demand requests is the same as the measurement used for material handling ($u^{\texttt{MH}}_{(n,t)}$) and warehousing capacities ($u^{\texttt{W}}_n$).

In the time-dependent setting, the set of arcs include the set of execution arcs and the set of holding arcs, i.e., $\mathcal{A} = \mathcal{A}^{\texttt{E}} \cup \mathcal{A}^{\texttt{H}}$. The first represents the execution of a service moving between two different terminals at two different time periods. Hence, each execution arc corresponds to a service leg as illustrated by full lines in Figure 3(b).

Accordingly, the capacity of service legs ($u_{a_l(\sigma)}$) can be also defined on these execution arcs, i.e., $u_{a_l(\sigma)} = u_a$, for $a_l(\sigma) = a \in \mathcal{A}^{\mathtt{E}}$. Similarly, the unit transportation cost for moving one unit of shipper-demand requests on service legs ($c^k_{a_l(\sigma)}$) can be also defined on the execution arcs, i.e., $c^k_{a_l(\sigma)} = c^k_a$, for $a_l(\sigma) = a \in \mathcal{A}^{\mathtt{E}}$. Let us define $\mathcal{A}^{\mathtt{E}(+)}(n,t)$ and $\mathcal{A}^{\mathtt{E}(-)}(n,t)$ as the set of execution arcs out of and into node $(n,t) \in \mathcal{N}$, respectively. Note that when several services have equivalent legs with an origin, destination, and time-window according to the schedule, they result in a series of corresponding arcs in parallel on the time-space network. The repetition of the same service in different bundles also results in parallel arcs on the time-space network. Holding arcs between two consecutive time periods at the same terminal indicate an idle time of a vehicle or an operation time of a demand at a terminal. The dashed lines in Figure 3(b) represent such holding arcs. There is a unit holding cost at terminals defined as $\bar{c}^k_a$ for one unit of shipper-demand request $k \in \mathcal{K}$ on holding arc $a \in \mathcal{A}^{\mathtt{H}}$.

In the next section, we introduce the SSND formulation of the problem.

4.2 Mathematical Formulation

We consider three cases for the volume of shipper-demand requests: 1) the demand volume cannot be split; 2) The demand volume must be picked up from its origin and delivered at its destination as a whole without being split. But, it can be split while it is moved and transported by several services; 3) The demand volume can be split when it is picked up, moved, and delivered. We propose a generic model that can handle the split and unsplit versions of the problem as explained at the end of this section.

We first define the decision variables of the mathematical formulation for the unsplit version as follows:

- $z_k = 1$, if shipper-demand request $k \in \mathcal{K}$ is accepted, 0 otherwise;
- $r^k_{(o(k),t)} = 1$, if shipper-demand request $k \in \mathcal{K}$ is picked up from its origin $o(k)$ at time $t \in \mathcal{T}$, 0 otherwise.
- $x^k_a = 1$, if shipper-demand request $k \in \mathcal{K}$ is traveling on arc $a \in \mathcal{A}^{\mathtt{E}}$, 0 otherwise, where $x^k_{a_l(\sigma)} = x^k_a$, for $a = a_l(\sigma)$, $a_l(\sigma) \in \mathcal{L}(\sigma)$, $\sigma \in \Sigma$.
- $\xi^k_a = 1$, if shipper-demand request $k \in \mathcal{K}$ is held on holding arc $a \in \mathcal{A}^{\mathtt{H}}$, 0 otherwise.
- $r^k_{(d(k),t)} = 1$, if shipper-demand request $k \in \mathcal{K}$ is delivered at its destination $d(k)$ at time $t \in \mathcal{T}$, 0 otherwise. This is an auxiliary variable dependent on $r^k_{(o(k),t)}$, x^k_a, and ξ^k_a which corresponds to the delivery time of shipper-demand request $k \in \mathcal{K}$.

- $y_\sigma = 1$, if service $\sigma \in \Sigma$ is selected, 0 otherwise.
- $\gamma_b = 1$, if bundle $b \in \mathcal{B}$ is selected, 0 otherwise.
- $\lambda_n = 1$, if the warehousing space of terminal $n \in \mathcal{N}^{\mathtt{P}}$ is used, 0 otherwise.

The SSND model for the unsplit version is formulated as follows:

$$\begin{aligned}\max \quad & \sum_{k\in\mathcal{K}} w_k \Big[\rho_k z_k - \sum_{t\in\mathcal{T}} \psi^k_{(o(k),t)} r^k_{(o(k),t)} - \sum_{t\in\mathcal{T}} \psi^k_{(d(k),t)} r^k_{(d(k),t)} - \sum_{a\in\mathcal{A}^{\mathtt{E}}} c^k_a x^k_a - \sum_{a\in\mathcal{A}^{\mathtt{H}}} \bar{c}^k_a \xi^k_a\Big] - \sum_{\sigma\in\Sigma} f_\sigma y_\sigma \\ & - \sum_{b\in\mathcal{B}} f_b \gamma_b - \sum_{n\in\mathcal{N}^{\mathtt{P}}} f_n \lambda_n \end{aligned} \tag{1}$$

$$\text{s.t.} \quad z_k = \sum_{t\in\mathcal{T}} r^k_{(o(k),t)} \qquad k \in \mathcal{K} \tag{2}$$

$$z_k = \sum_{t\in\mathcal{T}} r^k_{(d(k),t)} \qquad k \in \mathcal{K} \tag{3}$$

$$\begin{aligned} & r^k_{(o(k),t)} + \sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(o(k),t)} x^k_a + \xi^k_{((o(k),t-1),(o(k),t))} = \\ & \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(o(k),t)} x^k_a + \xi^k_{((o(k),t),(o(k),t+1))} \qquad k \in \mathcal{K}, (o(k),t) \in \mathcal{N} \end{aligned} \tag{4}$$

$$\begin{aligned} & r^k_{(d(k),t)} + \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(d(k),t)} x^k_a + \xi^k_{((d(k),t),(d(k),t+1))} = \\ & \sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(d(k),t)} x^k_a + \xi^k_{((d(k),t-1),(d(k),t))} \qquad k \in \mathcal{K}, (d(k),t) \in \mathcal{N} \end{aligned} \tag{5}$$

$$\begin{aligned} & \sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(n,t)} x^k_a + \xi^k_{((n,t-1),(n,t))} = \\ & \sum_{a\in\mathcal{A}^{\mathtt{E}(+)}(n,t)} x^k_a + \xi^k_{((n,t),(n,t+1))} \qquad k \in \mathcal{K}, (n,t) \in \mathcal{N} : n \neq o(k), n \neq d(k) \end{aligned} \tag{6}$$

$$\sum_{b\in\mathcal{B}:\sigma\in\Sigma(b)} \gamma_b \leq 1 - y_\sigma \qquad \sigma \in \Sigma \tag{7}$$

$$\sum_{k\in\mathcal{K}} w_k x^k_{a_l(\sigma)} \leq u_{a_l(\sigma)}(y_{a_l(\sigma)} + \sum_{b\in\mathcal{B}:\sigma\in\Sigma(b)} \gamma_b) \qquad a \in \mathcal{A}^E \tag{8}$$

$$\sum_{k\in\mathcal{K}} w_k [\sum_{a\in\mathcal{A}^{\mathtt{E}(-)}(n,t)} x^k_a] \leq u^{\mathtt{MH}}_{(n,t)} \qquad (n,t) \in \mathcal{N} \tag{9}$$

$$\sum_{k\in\mathcal{K}} w_k \xi^k_{((n,t-1),(n,t))} \leq u^{\mathtt{W}}_n \lambda_n \qquad (n,t) \in \mathcal{N} \tag{10}$$

$$z_k = 1 \qquad k \in \mathcal{K}^{\mathtt{C}} \tag{11}$$

$$z_k \in \{0,1\} \qquad k \in \mathcal{K}^{\mathtt{NC}} \tag{12}$$

$$r^k_{(o(k),t)} \in \{0,1\} \qquad k \in \mathcal{K}, (o(k),t) \in \mathcal{N} \tag{13}$$

$$r^k_{(d(k),t)} \in \{0,1\} \qquad k \in \mathcal{K}, (d(k),t) \in \mathcal{N} \tag{14}$$

$$x^k_a \in \{0,1\} \qquad k \in \mathcal{K}, a \in \mathcal{A}^{\mathtt{E}} \tag{15}$$

$$\xi^k_a \in \{0,1\} \qquad k \in \mathcal{K}, a \in \mathcal{A}^{\mathtt{H}} \tag{16}$$

$$y_\sigma \in \{0,1\} \qquad \sigma \in \Sigma \tag{17}$$

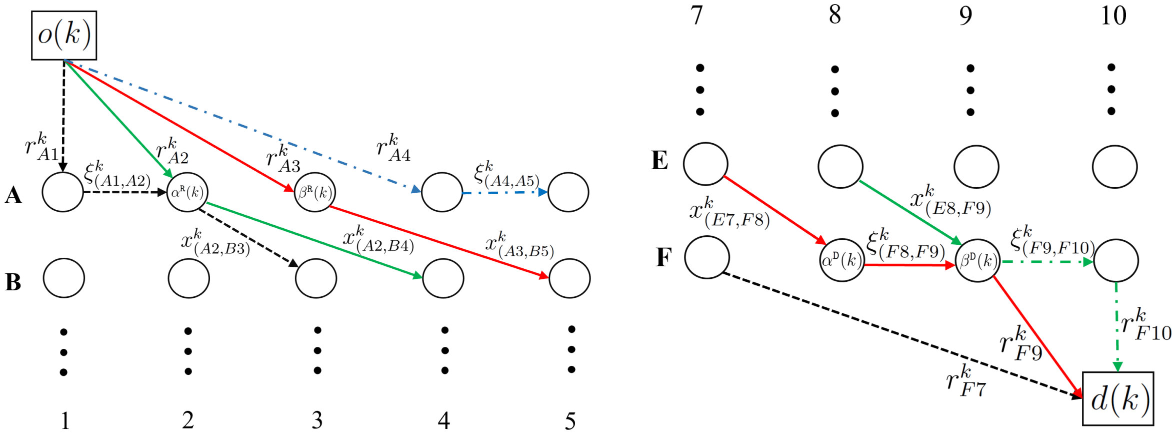
$$\gamma_b \in \{0,1\} \qquad b \in \mathcal{B} \tag{18}$$

$$\lambda_n \in \{0,1\} \qquad n \in \mathcal{N}^{\mathtt{P}}. \tag{19}$$

The objective function (1) maximizes the net profit. The net profit is calculated by summing up the total revenue obtained from serving the demand of both contract-based and non-contract shippers, minus the total costs, which include the penalty costs for early and late pick-up and delivery of shipments, the transportation and holding costs of shipments, the selection costs of services and bundles offered by the carriers, and the warehousing costs in terminals.

Constraints (2) and (3) ensure that each shipper-demand request is picked up from its origin and delivered to its destination as a whole, respectively. Constraints (4)-(6) represent the flow balance for each shipper-demand request at its origin, its destination, and for all intermediary terminals, respectively. Constraints (2)-(6) also determine the optimal itinerary for each shipper-demand request out of the available feasible options as illustrated in Figure 4. This figure represents several feasible options for pick-up and delivery times and routing of a particular shipper-demand request k from its origin and to its destination on the space-time network, respectively. Figure 4(a) shows origin (terminal A) of the shipper-demand request k along with its desired time interval for picking up the request indicated by the full lines from $o(k)$ to terminal A between time interval $[2,3]$. This figure represents several feasible alternatives for the pick-up time and routing of the shipment from its origin terminal. The shipper allows to pick up the shipment one period earlier and one period later than its preferred time window with a penalty cost indicated by dashed lines from $o(k)$ to terminal A. Similarly, Figure 4(b) represents the destination (terminal F) of the shipper-demand request k along with its desired time interval for dropping off the request indicated by the full lines from terminal F to $d(k)$ between time interval $[8,9]$. This figure represents several feasible options for the delivery time and routing of the shipment at its destination terminal. The shipper allows the delivery to be performed one period earlier and one period later than its preferred time window with a penalty cost illustrated by dashed lines from terminal F to $d(k)$. Since the formulation addresses the unsplit version of the problem, the demand volume of request k should be picked up from $o(k)$, moved, and delivered at $d(k)$ as a whole. The proposed SSND formulation selects the option that minimizes the moving cost of shipper-demand request k from its origin to its destination.

Constraints (7) ensure that any particular service is selected either individually or with a bundle. This equation also ensures that if any particular service is included



(a) Origin of shipper-demand request k

(b) Destination of shipper-demand request k

Figure 4: Several feasible options for pick-up and delivery times and routing of the shipper-demand request k from its origin and at its destination on the space-time network, respectively.

in several bundles, then it is selected at most once. Constraints (8) impose, on each service leg, the capacity limit with respect to the total amount of shipments that can be accommodated. The right-hand side of this equation consists of two terms. The first term corresponds to the case where the service is selected individually and the second term corresponds to the case where the service is selected with a bundle. According to Constraints (7), at most one of these two terms can be equal to one. Constraints (9) limit the maximum amount of shipments that can be handled at each terminal and time period.

Constraints (10) restrict the total amount of shipments on the holding arc with respect to the warehousing capacity of the terminal. Constraints (11) guarantee that all the demands of contract-based shippers are served. Constraints (12)-(19) impose the binary and non-negative requirements on the decision variables.

By defining $r^k_{(o(k),t)}$, x^k_a, ξ^k_a, and $r^k_{(d(k),t)}$ as binary variables, we assume that the demand cannot be split at all. To relax this assumption partially and consider the case where the shipment must be picked up from its origin and delivered at its destination as a whole, but can be split and transported by several services while it moves, we need to define x^k_a and ξ^k_a variables as follows: $0 \leq x^k_a \leq 1$, specifying the percentage of the shipper-demand request $k \in \mathcal{K}$ served by $a \in \mathcal{A}^{\mathtt{E}}$, and $0 \leq \xi^k_a \leq 1$ indicating the percentage of shipper-demand request $k \in \mathcal{K}$ held on holding arc $a \in \mathcal{A}^{\mathtt{H}}$. In order to consider the case where the shipments can be split when they are picked up, moved, and delivered, we need to further define the $r^k_{(o(k),t)}$ and $r^k_{(d(k),t)}$ variables as follows: $0 \leq r^k_{(o(k),t)} \leq 1$ and $0 \leq r^k_{(d(k),t)} \leq 1$, determining the percentage of shipper-demand request $k \in \mathcal{K}$ that is picked up from its origin $o(k)$ and delivered at its destination $d(k)$ at time $t \in \mathcal{T}$, respectively.

Finally, it should be noted that if the decision maker sets the pick-up and delivery costs of the shipper-demand requests $k \in \mathcal{K}$ to a sufficiently large value (i.e., $\psi^k_{(o(k),t)} = \psi^k_{(d(k),t)} = M$, where M has a large value) when the request is outside of its time-window, then the model can produce a solution where the requests are served within their desired time-window without considering any penalty cost.

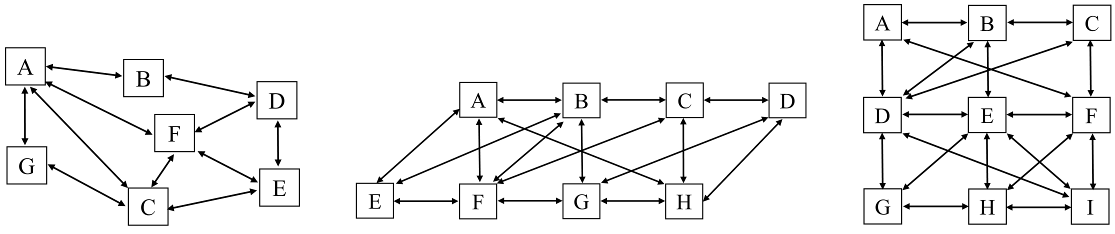
5 Experimental Results and Analysis

In this section, we report the results of a series of computational experiments performed to first test and evaluate the performance of the proposed model in terms of computational time and, second to evaluate the impact of different settings incorporated into the problem for planning the M1M system at the tactical level. This will be done by exploring the performance and structural characteristics of the solutions obtained from the proposed model.

The organization of this section is as follows: in Section 5.1, we present the characteristics of the instances generated for the computational experiments based on realistic cases. We examine the behavior of the model in terms of computational time in Section 5.2. In Section 5.3, we define performance indicators required for analysing the computational results. In Section 5.4, we present the numerical results and analyze the behavior and characteristics of the solutions obtained from the proposed model. In this section, we also explore how the modeling framework is beneficial to the decision maker by providing meaningful managerial insights. This section is divided into several subsections to consider the impact of different problem settings on the solutions, separately (i.e., shipper categories and demand classification, penalty costs, and offering services in bundles). Finally, Section 5.5 compares the solutions obtained from the split and unsplit shipment-flow versions of the problem.

5.1 Test Instances

We generate a set of test instances based on three different physical network topologies represented in Figure 5: (a) hyper-corridor network with 7 terminals , (b) bipartite network with 8 terminals, and, (c) grid network with 9 terminals. The hyper-corridor and grid networks are inspired by the Canadian and European networks including the location of the main cities, respectively. We considered a scheduled length of 7 days (one week), which is divided into 14 time periods of half a day each.



(a) Hyper-corridor (7,11) (b) Bipartite (8,16) (c) Grid (9,19)

Figure 5: The physical network ($\mathcal{G}^{\mathrm{P}}$) topologies.

The instances are generated following the uniform distribution based on realistic cases for each network topology. We first explain the generation of the data for the demand side of the M1M system (i.e., shipper-demand requests) as follows:

- For each of the three networks, we consider four different sets of shipper demands with an increasing size as follows: 30, 60, 90, and 120 requests for the hyper-corridor network, 60, 80, 100, and 120 requests for the bipartite network, and 70, 90, 110, and 130 requests for the grid network. The detailed information on each demand set is provided in Table 1.
- The volume of the shipper-demand requests for each test instance is generated randomly using an uniform distribution between 10% and 50% of the capacity of the service legs (i.e., between 40 and 200).
- Recall that the demand of both contract-based and non-contract shippers are classified into two types based on delivery duration: standard and urgent. Each standard demand request has a unit revenue given by the shipper, considered here to be a random value generated by an uniform distribution between 25 and 50, and for the urgent demands, between the same origin and destination pair, the unit revenue is twice higher.
- The desired time interval for picking up each request from its origin is a value uniformly generated between 1 and 7. The duration for delivering the request to its destination depends on the type of the request. For an urgent request, the delivery duration is generated randomly between 1 and 3. The delivery duration of a standard request is twice as large as the duration for an urgent request with the same origin and destination.
- Pick up and delivery of the shipments may take place at most two periods earlier or later than their desired time window. Penalties for urgent requests are twice as large as that of a standard one. The unit penalty cost per time period for standard and urgent requests are equal to 0.5 and 1, respectively.

Table 1: Number of standard and urgent request for both contract-based and non-contract shippers for all instances.

$\lvert\mathcal{K}\rvert$	Contract-based ($\lvert\mathcal{K}^{\texttt{C}}\rvert$)		Non-contract ($\lvert\mathcal{K}^{\texttt{NC}}\rvert$)	
	Standard	Urgent	Standard	Urgent
Hyper-corridor network				
30	10	7	8	5
60	19	13	17	11
90	28	19	26	17
120	37	25	35	23
Bipartite network				
60	20	15	15	10
80	25	20	20	15
100	30	20	30	20
120	35	25	35	25
Grid network				
70	20	20	15	15
90	25	25	20	20
110	30	30	25	25
130	35	35	30	30

The generation of the data for the supply side of the M1M system (i.e., carrier-capacity offers) is as follows:

- There are two categories of services based on their travel time: regular and fast.
- Services are generated based on the physical network topologies and they consist of all possible routes in the network. For the hyper-corridor network, for all instances, we generated 70 regular services with one or two intermediary stops and 100 fast and direct services (without any stop in between). For the bipartite network, we generated 90 regular and 120 fast services for all instances. For the grid network, we generated 110 regular and 140 fast services for all instances.
- The duration of fast services is uniformly generated between 1 and 2 periods, and regular services are generated with a duration of 2, 3, or 4 periods.
- The capacities of all service legs are homogeneous and are equal to 400.
- The fixed selection cost of a fast service is inversely proportional to its duration, i.e., $f_\sigma = \frac{300}{\tau_\sigma}$. The selection cost of a regular service is 50% less than the selection cost of fast services that are needed for the same route.
- The unit transportation cost per unit of volume of demand for both regular and fast services are homogeneous and are equal to 2.

- The number of generated bundles for all instances in the hyper-corridor network is 35, for the bipartite network 45, and for the grid network 55. Each bundle contains a set of 4 services. From the generated set of services, bundles mostly include the back and forth services with both fast and regular type services. The selection cost of a service within a bundle is 10% less than the cost of the corresponding service if selected individually.
- The warehousing capacities of terminals are randomly generated between 40% to 60% of the total demand.
- The fixed cost for using the warehousing space of each terminal is proportional to its capacity, i.e., $f_n = \frac{u^{w}_{n}}{50}$.
- The unit holding costs per demand volume are homogeneous and are equal to 1.
- The maximum amount of shipment that can be handled at each terminal and time period is homogeneous and is equal to 10% of the total demand.

For each demand set presented in table 1, we generated 10 instances, which gives a total of 120 instances. We report the average values obtained in the following section.

Computational experiments were carried out on a laptop with an Intel Core i7-6700HQ 2.6GHz CPU and 16GB of RAM. The mathematical model was solved using IBM ILOG CPLEX 20.1. All the instances were solved to optimality (10^{-5} gap) using the default settings.

5.2 Model Performance

It this section, we evaluate the performance of the unsplit demand version of the proposed model in terms of computational time. To this end, we analyse the run-times based on demand and service sizes for three different network topologies. For this analysis, we solve the model using all the instances described in Section 5.1. The results are reported in Table 2. The table is horizontally divided into three parts to present the results for the hyper-corridor, bipartite, and grid networks, respectively. The first two columns represent the demand and service sizes, respectively. The next two columns indicate each instance problem size by showing the number of decision variables and constraints, respectively. The last two columns report the average and the standard deviation of run-times in seconds, respectively.

All the instances in Table 2 were solved to optimality. As expected, enlarging the demand size and network size results in increasing the instance size and hence the computation time. When we compare the run time of instances with different network topologies,

Table 2: Computational times for the hyper-corridor, bipartite, and grid networks with different demand sizes.

$\lvert\mathcal{K}\rvert$	$\lvert\Sigma\rvert$	# of DV	# of constraints	Time (s)	Std (s)
Hyper-corridor network					
30	170	11,715	9,875	759	97
60	170	23,115	18,785	1,297	165
90	170	34,515	27,695	2,568	287
120	170	45,915	36,605	5,579	554
Bipartite network					
60	210	27,555	21,475	2,481	268
80	210	36,615	28,255	4,746	686
100	210	45,675	35,035	8,329	862
120	210	54,735	41,815	13,616	1,353
Grid network					
70	250	36,560	27,980	6,785	896
90	250	46,880	35,600	9,368	1,316
110	250	57,200	43,220	13,260	1,824
130	250	67,520	50,840	18,580	2,754

we observe that solving hyper-corridor network instances is less time consuming compared to the bipartite and grid networks. Our initial understanding was that this is mainly because of the network size. However, when we compare, for example, the instance with demand size 120 and service size 170 from the hyper-corridor network to the instance with demand size 100 and service size 210 from bipartite network and the instance with demand size 90 and service size 250 from grid network, which are almost analogous in terms of instance size, we observe that solving the instance for the hyper-corridor network is considerably less time consuming. This implies that the network topology and the number of service paths on the corresponding time-space networks have a significant impact on the computation time of instances.

To better understand the performance of the model, we next fix the demand size and change the service sizes and evaluate the computational times. For this analysis, we pick a demand size from each network topology and take runs with different service sizes. The demand, service, and size of each instance along with the computational times for all three network topologies are reported in Table 3.

All the instances in Table 3 were solved to optimality. Analogous to the observations that are drawn from Table 2, the results in Table 3 show that when the instance size increases, the computation time increases as well. When we compare the run times of Table 3 to those of Table 2, we observe that the impact of demand size on the computational complexity is higher than that of the service size. This can be attributed to the fact that, in our mathematical formulation, the demand set size has a significant

Table 3: Computational times for the hyper-corridor, bipartite, and grid networks with different service sizes.

$\lvert\mathcal{K}\rvert$	$\lvert\Sigma\rvert$	# of DV	# of constraints	Time (s)	Std (s)
			Hyper-corridor network		
60	120	19,465	18,675	785	64
60	150	21,295	18,735	1012	89
60	180	23,125	18,815	1,362	179
60	210	26,155	18,875	1,412	218
			Bipartite network		
80	190	30,990	28,165	3,574	594
80	220	36,635	28,280	4,837	714
80	250	39,065	28,340	5,913	519
80	280	42,295	28,410	7,428	762
			Grid network		
90	220	42,335	35,505	8,318	1,084
90	250	46,865	35,585	9,368	1,316
90	280	49,595	35,645	9,574	1,397
90	310	51,425	35,695	10,934	1,716

impact on the number of decision variables and hence the instance problem size. The standard deviation column in both Tables 2 and 3 indicates that the run-times do not vary significantly for the 10 generated instances with the same demand and service sizes, respectively. This observation indicates that the average time values are fairly reliable.

5.3 Performance indicators

We define the following performance indicators for the M1M system to evaluate the computational experiments and analyze the behavior of the solutions obtained from the proposed model:

- Total cost: sum of all costs computed as the penalty, traveling and holding, selecting services and bundles, and using terminal s warehousing facilities. We further break down this cost to explore the contribution of each variable and fixed cost on total cost as % of penalty cost, total traveling cost, regular service cost, fast service cost, bundle cost, holding cost, and terminal cost.
- Total profit: sum of all revenues obtained from satisfying standard and urgent requests from both contract-based and non-contract shippers minus total cost.
- Relative yield: total profit divided by total cost. This metric indicates the profitability of the satisfied demand.

- # of open regular services: number of selected regular services.
- # of open fast services: number of selected fast services.
- # of open bundles: number of selected bundles.
- % of capacity usage: percentage of total capacity of selected services (individually and with bundles) used effectively. To provide a better insight, we calculate this metric as the ratio of total demand volume-distance moved with respect to total capacity-distance operated as follows:

$$\text{Capacity usage (\%)} = 100 \times \frac{\sum_{k \in \mathcal{K}} \sum_{a \in \mathcal{A}^{\mathrm{E}}} dis_{a_l(\sigma)} w_k x^k_{a_l(\sigma)}}{\sum_{a \in \mathcal{A}^{\mathrm{E}}} dis_{a_l(\sigma)} u_{a_l(\sigma)}} \tag{20}$$

- % of demand moved outside of their time window: the percentage of total demand volume on the network that leave their origin or (and) arrive at their destination outside of their desired time window.
- % of demand on transshipment (T): the total demand volume transferred at least once and expressed as the percentage of total demand volume.
- # of open terminals: number of terminals with warehousing space used over the planning horizon.

5.4 Model Behavior

This section first presents the behavior and structural characteristics of the solutions obtained from the proposed model using the generated instances for each of the three topologies. The results are reported in Table 4. The values of each row in the table are averaged over 10 different instances.

From Table 4, we observe that when the demand size in each network topology increases, the profit value increases as well. This observation indicates that most of the demand requests from both contract-based and non-contract shippers are profitable. This implication can be further confirmed by the relative yield values indicating the profitability of the satisfied demand in each instance. The relative yields in all instances show that satisfying more demand with the same attributes from both contract-based and non-contract shippers can result in more profit for the IDSP, which provides valuable insight to the decision maker.

Based on the columns under the label "# of open services" in Table 4, the total number of open services selected individually and with bundles increases when enlarging the demand set size in each network topology. Recall that each bundle contains 4 services. Hence, while summing the number of open services, the values under the column "Bundle" are multiplied by 4. We observed that the number of open regular and fast services in each instance depends on the volume of standard and urgent requests from both contract-based and non-contract shippers (Table 1). More fast services are required as the volume of urgent requests increases. In all instances, more than 40% of open services are selected with bundles. Since the bundles include back and forth services, selecting services with bundles results in more balanced quantity of the services assigned to different geographic areas and hence a more balanced service network.

Table 4: Computational results for the hyper-corridor, bipartite, and grid networks.

$\lvert\mathcal{K}\rvert$	$\lvert\Sigma\rvert$	Total profit	Relative yield	# of open services			Capacity usage (%)	% of demand moved outside time-window		# of open terminals	T (%)
				Regular	Fast	Bundle		Standard	Urgent		
Hyper-corridor network											
30	170	179,978	18.2	4.8	3.0	2.0	55.4	20.3	12.1	1.40	16.2
60	170	315,478	16.4	10.2	5.2	2.8	58.7	22.1	13.0	3.20	17.6
90	170	521,706	18.9	17.4	7.3	4.1	65.7	24.1	14.2	4.40	20.8
120	170	674,238	16.2	20.4	10.7	6.1	68.5	28.0	16.2	4.60	25.6
Bipartite network											
60	207	381,780	14.8	6.2	8.4	2.6	67.7	23.2	14.0	2.4	14.6
80	207	624,025	17.0	8.5	11.3	3.7	71.6	25.3	15.2	3	16.3
100	207	720,319	15.5	11.6	14.2	4.3	67.5	26.6	16.6	3.6	18.4
120	207	1,133,533	19.6	12.1	14.7	5.7	71.1	29.2	18.4	4.1	21.9
Grid network											
70	250	504,979	15.8	8.7	11.2	3.8	57.6	20.9	18.7	2.5	13.6
90	250	768,892	17.2	11.9	14.5	4.6	67.4	22.5	19.6	3.2	16.7
110	250	939,961	18.6	12.3	15.7	5.9	62.8	26.3	22.4	3.7	18.6
130	250	1,336,922	21.3	12.7	16.2	6.4	69.7	28.5	24.3	4.2	22.3

Note that, in Table 4, the total number of selected services for each demand size is quite small compared to the number of services offered to the IDSP. This observation implies that, rather than opening more services, the IDSP prefers to make a better use of the capacity of the selected services, which results in more effective consolidation as well as gaining more profit for the platform. In all instances, more than half of the total capacity of selected services has been used as shown in the table under the column labeled "Capacity usage (%)". The total percentage of standard and urgent demand volumes moved outside of their time window presented in the table further verifies such model behavior, which provides room for more flexible demand routing and thus more efficient consolidation. As indicated in the table, in all instances, the percentage of standard demand volume moved outside of the time-window with respect to its proportion (Table 1) in each instance is higher than that of the urgent one. This is because the unit penalty cost for the urgent demand is twice as large as that of the standard one; hence, the IDSP prioritizes for satisfying the urgent demand volumes inside their desired time-window over standard ones.

For each network topology, when the demand set size increases, the number of open terminals and the percentage of demand on transshipment increase as well. In all instances, at least one terminal's warehousing space has been used for the shipments that need to be stored temporarily.

Next, for each instance reported in Table 4, we break down the total cost to investigate the contribution of each variable and fixed cost involved in our problem setting. The percentage contribution of each cost is reported in Table 5. The results indicate that, in all instances, traveling cost has the highest contribution on the total cost while the sum of fixed cost of services, selected individually and with bundles, is the following one. It is noteworthy that in all instances, the cost contribution of services selected with bundles (Table 5) with respect to their quantity (Table 4) is lower compared to the sum of contribution of regular and fast services selected individually with respect to their quantity. Hence, selecting services in bundles results in higher profit for the IDSP.

In all instances, the penalty cost ranks third in terms of cost contribution in Table 5. As indicated in Table 4, relatively, a high portion of total demand (more than 32%) in each instance is satisfied outside of its desired time window. This might be because the offered services do not cover all time periods forcing the IDSP to move some demands outside of their time window. To better understand the concept of penalty cost in our problem, we dedicate a subsection (Section 5.4.2) to provide a comparative analysis between the possibility to satisfy the shipper-demand requests inside their time window or outside, with penalty costs, respectively. Table 5 shows that terminal and holding costs have the lowest contribution in all instances.

Table 5: Percentage contribution of variable and fixed costs on total cost.

$\lvert\mathcal{K}\rvert$	Penalty cost (%)	Total traveling cost (%)	Service cost (%)			Holding cost (%)	Terminal cost (%)
			Regular	Fast	Bundle		
			Hyper-corridor network				
30	9.5	57.5	8.7	5.9	11.8	6.3	0.3
60	11.2	56.3	8.2	6.8	8.8	7.6	1.1
90	10.8	55.5	8.6	6.2	8.8	8.6	1.5
120	12.7	54.4	7.3	5.4	8.9	9.8	1.6
			Bipartite network				
60	11.2	59.0	5.8	8.1	8.4	6.2	1.3
80	9.4	60.2	5.6	7.5	8.4	7.5	1.4
100	13.9	55.7	6.0	7.5	7.7	7.5	1.7
120	15.5	54.6	5.1	6.2	8.2	8.5	2.0
			Grid network				
70	14.5	54.1	7.1	8.7	9.8	4.6	1.2
90	15.5	53.9	6.9	8.1	8.6	5.7	1.3
110	17.0	52.4	5.9	7.6	9.7	6.0	1.6
130	18.5	52.9	5.0	6.2	8.4	7.1	2.0

5.4.1 Shipper categories and demand classification

In this section, we first analyse the impact of considering two categories for the shippers (contract-based and non-contract) on the optimal solutions. To this end, we select two demand sizes from each network topology. We exclude the demand requests from non-contract shippers and solve each instance comprising just contract-based shippers. We then compare the obtained solutions with the ones obtained from the same instance including demand requests from both contract-based and non-contract shippers. The results, in particular the profit values, relative yields, and the percentage of capacity usage of services, for both types of instances without and with non-contract shippers are reported in Table 6.

From Table 6, we observe that in each instance, the profit value increases when including demand requests from non-contract shippers. Note that, since just profitable demands of non-contract shippers are satisfied, the profit values of the instances without non-contract shippers (left side of the table) always provide a lower bound for their counterpart instances with non-contract shippers (right side of the table). The relative yield values in the instances without non-contract shippers indicate that satisfying most of demand requests from contract-based shippers is profitable in this set of test instances. As reported in the table, the relative yield value of each instance with non-contract shippers is slightly higher than that of the instance without non-contract shippers. This is mainly because the demand attributes from both contract-based and non-contract shippers are similar to each other in this set of test instances. In all instances, the capacity usage of selected services in the instances with non-contract shippers is at least 8% higher compared to the instances without non-contract shippers. To summarize, this comparison highlights the advantage of including non-contract shippers in the M1M system yielding not only more profit for the IDSP by satisfying high priced contribution demand requests but also more effective consolidation by better capacity usage of services.

Table 6: Computational results for the instances without and with non-contract shippers.

Without non-contract shippers				With non-contract shippers			
$\lvert\mathcal{K}^{\mathtt{C}}\rvert$	Total profit	Relative yield	Capacity usage (%)	$\lvert\mathcal{K}^{\mathtt{C}} \cup \mathcal{K}^{\mathtt{NC}}\rvert$	Total profit	Relative yield	Capacity usage (%)
Hyper-corridor network							
47	289,174	17.7	51.4	90	521,706	18.9	65.7
62	376,434	14.9	53.5	120	674,238	16.2	68.5
Bipartite network							
50	428,268	14.1	58.8	100	720,319	15.5	67.5
60	634,058	18.0	62.7	120	1,133,533	19.6	71.1
Grid network							
60	595,029	16.2	54.2	110	939,961	18.6	62.8
70	842,397	19.2	61.4	130	1,336,922	21.3	69.7

We next analyse the impact of demand classification on the structure of optimal solutions. We use the same instances employed for evaluating the impact of shipper categories in this section. To better evaluate the revenue management concept through demand classification, we decrease the unit revenue values for this set of instances with the aim that part of demand requests from non-contract shippers are rejected. Hence, we scale down the unit revenue for both the standard and urgent demand requests with a 1:5 ratio decrease. We further decrease the discount rate on the bundles selection cost from 10% to 0% (i.e., no bundle) to perform an unbiased analysis. Using this set of test instances, we perform runs with and without revenue differentiation between standard and urgent demand. In the latter, the unit revenue set for urgent demand equals that of standard one.

We then analyze and compare the solutions, in particular relative yield, number of open services, percentage of capacity usage, and the rejection percentage of urgent requests of non-contract shippers. The computational results are reported in Table 7.

Table 7: Computational results for the instances without and with revenue differentiation.

$\lvert\mathcal{K}\rvert$	Without revenue differentiation					With revenue differentiation				
	Relative yield	% of rejected urgent demand	# of open services		Capacity usage (%)	Relative yield	% of rejected urgent demand	# of open services		Capacity usage (%)
			Regular	Fast				Regular	Fast	
Hyper-corridor network										
90	1.02	27.4	23.5	7.6	52.4	2.1	8.5	25.2	9.7	55.7
120	0.84	29.7	29.6	14.0	55.3	1.5	9.3	32.2	17.1	58.3
Bipartite network										
100	0.89	28.6	14.7	17.4	51.7	1.4	10.8	16.8	20.0	54.9
120	0.94	32.7	18.8	20.5	54.7	1.7	12.4	20.1	23.3	59.0
Grid network										
110	0.91	31.8	19.1	21.5	52.6	1.6	11.7	20.7	24.7	56.3
130	0.97	34.2	19.5	22.7	54.2	1.9	13.2	20.6	25.6	57.6

The results in Table 7 show that considering different demand types with revenue differentiation is always beneficial as the relative yield values in all instances are higher compared to the case without revenue differentiation. Moreover, the platform accepts more urgent demand from non-contract shippers in the case with demand classification and revenue differentiation to obtain more profit. Hence it selects more services and makes a better use of their capacity. Note also that the increase rate of the fast services is higher compared to that of the regular services. This observation indicates that the platform needs more fast services for satisfying urgent demand.

5.4.2 Impact of penalty cost

In this section we evaluate the impact of penalty cost on the structure of the optimal solutions. As mentioned in Section 2.2, in most applications, it may not be possible to satisfy all the shipper demand requests within their predefined time window due to limited availability of the services in different geographic areas and time periods. However, to provide a comparable analysis between moving the shipments within their predefined time window and outside of it with penalty cost, in this section, we pick two demand sizes from each network topology and double the number of services in each one so that for all shipper-demand requests, there are services available to move shipments within their desired time-window. We also reduce the unit penalty cost for these instances with the aim that the penalty cost can compete with the fixed selection cost of the services. Accordingly, in all instances, we scale down the unit penalty cost for both standard and urgent requests with a 1:5 ratio resulting in 0.1 and 0.2 as the unit penalty cost for the standard and the urgent requests, respectively. We then perform runs using this new set of test instances and analyse the characteristics of the obtained solutions in terms of open number of services selected individually and with bundles, percentage of capacity usage of the selected services, and percentage of demand moved outside of the time-window. The computational results are reported in Table 8.

Table 8: Computational results of the instances with doubled-size services.

$\lvert\mathcal{K}\rvert$	$\lvert\Sigma\rvert$	# of open services			Capacity usage (%)	% of demand moved outside of time-window	
		Regular	Fast	Bundle		Standard	Urgent
Hyper-corridor network							
30	340	5.4	4.7	2.3	53.8	9.2	5.1
60	340	11.4	7.3	3.1	55.3	11.3	5.9
Bipartite network							
60	420	7.8	9.4	2.9	65.2	10.6	5.8
80	420	10.1	12.2	4.1	69.4	12.5	7.2
Grid network							
70	500	9.4	13.6	4.2	56.3	10.7	7.5
90	500	13.2	16.8	5.2	64.5	13.1	8.5

In line with our observation from Table 4, the results reported in Table 8 show that when the demand size increases for each network topology, the total number of open services selected individually and with bundles increases as well. Note that, the open number of services in this new set of test instances is still quite small compared to the number of offered services. This observation confirms the model behavior that takes advantage of consolidation to gain more profit rather than opening more services. The capacity usage of selected services in all instances in Table 8 is more than 50%. Note that the values under the column "% of demand moved outside of time window" indicate that although there are enough available services for moving the shipments within their time-window, it is still more profitable for the IDSP to pay the penalty cost and move the shipments outside their time window. This suggests the positive effect of allowing shipments to be moved outside of their time window with penalty cost on the quality of the solutions in terms of more flexible demand routing and thus more efficient consolidation.

5.4.3 Impact of offering services in bundles

In this section, we evaluate the impact of offering services in bundles to the system. To this end, we first consider the case in which there is no discount on the cost of selecting services with bundles (i.e., no bundle case). We then consider other variants for selecting services with bundles. In the base case, carriers offer bundles containing back and forth services so that the open services selected with bundles cover the symmetric demand on the network. We then consider two new cases for selecting services with bundles: 1) carriers offer bundles of services to cover the high intensity origin-destination pairs on the network; 2) the services included in each bundle are random. The number of services and the discount factor in these two new cases are the same as in the base case, i.e., 4 and 10%, respectively. We then evaluate and compare the relative yields, open number of services selected individually and with bundles, and the capacity usage of selected services obtained from these variants. To provide a better insight on the impact of offering services in bundles, we use the same instances in Section 5.4.1 employed for evaluating the impact of demand classification with revenue differentiation. The results are reported in Table 9. The table is divided into four parts to show results for no bundle case (Case 0), the case where services are selected randomly (Case 1), the case where bundles include services that cover the high intensity origin-destination pairs (Case 2), and the base case where bundles contain back and forth services (Case 3), respectively.

Table 9: Computational results for the instances with different types of bundles.

$\|\mathcal{K}\|$	Case 0			Case 1				Case 2				Case 3			
	Rela. yield	# of open services	Capacity usage (%)	Rela. yield	# of open services		Capacity usage (%)	Rela. yield	# of open services		Capacity usage (%)	Rela. yield	# of open services		Capacity usage (%)
					Indiv.	Bun.			Indiv.	Bun.			Indiv.	Bun.	
Hyper-corridor network															
90	2.13	34.9	55.72	2.28	32.2	0.8	56.09	2.46	24.9	2.8	56.83	2.72	21.6	3.7	57.34
120	1.51	49.3	58.28	1.64	44.9	1.2	58.72	1.81	31.6	4.7	59.28	2.08	27.4	5.8	59.72
Bipartite network															
100	1.38	36.8	54.87	1.57	32.9	1.1	55.34	1.84	27.9	2.5	56.12	2.10	23.7	3.6	56.75
120	1.43	43.4	59.04	1.64	38.6	1.3	59.38	1.89	28.5	4	60.17	2.16	25.0	4.9	60.86
Grid network															
110	1.57	45.4	56.27	1.76	39.4	1.6	56.93	2.08	29.5	4.2	57.64	2.36	25.3	5.3	58.14
130	1.92	46.2	57.63	2.15	39.5	1.8	58.24	2.39	29.8	4.5	59.11	2.64	26.4	5.4	59.70

The results in Table 9 show that offering services with bundles (cases 1-3) always outperforms no bundle case (case 0) as the relative yields and the percentage of capacity usage of services from left (i.e., no bundle case) to right (i.e., base case) increase. When we compare the solutions of the instances with bundles (case 1-3), the results indicate that bundles including randomly selected services (case 1) and back and forth services (case 3) have the least and most impact on the quality of the solutions, respectively. The number of selected bundles in case 1 to 3 indicates that offering bundles with back and forth services is the most efficient scenario in this set of test instances.

5.5 Split vs Unsplit Shipment

In this section, we present computational results for the split shipment-flow versions of the problem and compare them with the results obtained for the unsplit counterpart, presented in Sections 5.2 and 5.4. For this analysis, we pick two demand sizes from each network topology. Similar to the previous section, we generate 10 instances for each demand size and report the average value. Computational results are presented in Table 10. The table is vertically divided into three parts to show the results for three cases of the volume of the shipper-demand requests: 1) the demand volume cannot be split (named unsplit); 2) the demand volume cannot be split while it is picked up from its origin and delivered at its destination, it just can be split when it is moved (named partially split); 3) the demand volume can be split when it is picked up, moved and delivered (named split).

Table 10: Computational results for the split and unsplit demand

$\|\mathcal{K}\|$	$\|\Sigma\|$	Unsplit				Partially split				Split			
		Total profit	Relative yield	Capacity usage (%)	Time (s)	Total profit	Relative yield	Capacity usage (%)	Time (s)	Total profit	Relative yield	Capacity usage (%)	Time (s)
Hyper-corridor network													
30	170	179,978	18.2	53.4	759	180,746	19.7	55.6	3,204	181,002	19.8	55.6	7,385
60	170	315,478	16.4	58.7	1,297	315,984	16.9	60.2	5,847	316,152	17.1	60.2	13,472
Bipartite network													
60	207	381,780	14.8	67.7	2,481	382,745	15.4	70.8	13,548	383,650	15.6	71.6	31,432
80	207	624,025	17.0	71.6	4,746	626,217	18.1	74.5	21,294	627,005	18.4	75.8	45,974
Grid network													
70	250	504,979	15.8	55.6	6,785	507,769	17.1	59.4	33,978	508,467	17.4	60.7	71,325
90	250	768,892	17.2	67.4	9,368	773,015	19.0	71.2	54,373	774,046	19.3	71.9	114,971

The "Time (s)" columns in Table 10 indicate that the unsplit version outperforms its partially split and split counterparts in terms of computational time. This is mainly because relaxing the unsplit assumption and allowing the possibility of splitting demand volume considerably increases the number of feasible options for transferring any shipment from its origin to its destination resulting in an increase in the computational complexity of the problem by orders of magnitude.

The profit values, relative yields, and the percentage of capacity usage of services obtained for the unsplit version provide lower bounds for both the partially split and split versions. In the same manner, the solutions obtained for the partially split version provide a lower bound for the split counterpart. Accordingly, by relaxing the unsplit assumption, the value of the mentioned metrics improve for each instance from left to right in Table 10. It is worthwhile to note that, unlike the computational times, the improvements turned out to be negligible, particularly between the partially split and the split versions. This observation suggests that the decision maker can achieve good enough solutions (lower bounds) within a reasonable time frame by using the unsplit version of the problem.

6 Conclusions

In this paper, we studied tactical planning issues of an integrated multi-stakeholder system, which explicitly incorporates acceptance decisions on shipper requests and carrier offers, consolidation in time and space of multi-stakeholder shipments within multi-stakeholder shared service capacity, as well as revenue management concerns including shipper categories, demand classification, service types, bundle of service offers, and penalty costs for demand satisfaction outside of its time-window. To the best of authors' knowledge, planning such advanced and integrated systems at tactical level was not studied in the literature before. We proposed a scheduled service network design formulation on a space-time network to build a transportation plan to be repeatedly performed over the planning horizon by selecting profitable requests from non-contract shippers, selecting subsets of individual or bundles of scheduled services, identifying the itineraries of the shipments, finding the terminals for handling and storing the shipments temporarily. The proposed model designs a plan that maximizes profit. The formulation is generic and covers the split and unsplit shipment-flow versions of the problem.

We performed extensive computational experiments for both the unsplit and split shipment-flow versions using realistic-size instances generated for three different network topologies to evaluate the performance of the model in terms of computational time as well as providing a proof-of-concept of the proposed model. We further analyzed the impact of different settings incorporated into the problem including shipper categories, demand classification, penalty cost, and offering services in bundles on the structure of optimal solutions and the structure of the scheduled service network and the system profit. The results showed that all these new settings significantly improve the system behavior resulting in more efficient consolidation, more demand satisfaction, and higher profit.

For future research, in terms of modeling, one may consider scheduling services as decision variables rather than input parameters. The mathematical model can be also extended by enlarging the revenue management properties in the problem setting including shipper categories, demand and service types. Moreover, in addition to revenue management, resource management decisions can be also incorporated into the problem setting. Another future research direction would be to embed uncertainty in the problem by considering demand and time as uncertain parameters, which is definitely worth pursuing. In terms of algorithmic developments, given the computational times required for solving some instances, particularly the split versions, efficient solution algorithms are needed to solve larger-size instances within a reasonable time frame.

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