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Scheduled service network design with revenue management considerations and an intermodal barge transportation illustration

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ABSTRACT

The objective of the paper is to study the integration of revenue management considerations into service network design models targeting the tactical planning of intermodal consolidation-based freight transportation carriers. Revenue management strategies and mechanisms are broadly used within passenger transportation. Although identified as a desirable feature for freight transportation, interest growing within the industry, few contributions have addressed the topic. Moreover, almost none of those target the challenging issue of the interactions between the planning of the carrier's services and operations, on the one hand, and the revenue-management strategy it could implement, on the other hand. We propose a new scheduled service network design model with resource and revenue management model, which selects the services and schedule to be repeatedly operated over the next season, allocates and routes the main resources supporting the selected services, and routes the demand flows between their respective origins and destinations. The objective of the model is the maximization of the expected net revenue of the carrier when several customer categories, with specific service requirements, as well as several tariff and operation classes are considered. Our interest goes beyond the modeling challenges raised by the problem setting, to exploring the impacts of this new approach on the decision types and on the structure of the service network solutions obtained. The results of extensive experiments, in terms of demand distribution, network topology, fare class and quality-of-service, provide a proof of concept of the proposed modeling framework and its capability for insightful analyses. Experimentation was conducted using an off-the-shelf software to solve the corresponding mixed-integer linear programming formulation for realistically dimensioned barge intermodal transportation instances.

1. Introduction

Intermodal freight transportation is generally defined as moving cargo by a series of at least two transportation modes, the cargo being transferred from one mode to the next at intermodal terminals, e.g., ports and rail yards, without handling the cargo directly (Bektaş & Crainic, 2008; Crainic & Kim, 2007; SteadieSeifi, Dellaert, Nuijten, van Woensel, & Raoufi, 2014). Intermodal cargo is thus generally loaded into containers for most of its journey.

Consolidation-based carriers perform the largest share of intermodal transportation, rail and navigation companies being particularly active in the long-distance segment. Carriers aim to maximize net profits and meet shipper demand and requirements, by setting up a resource- and cost-efficient service network and schedule given the forecast demand. The so-called *tactical* operations *planning* process yields this service network and schedule.

The *Scheduled Service Network Design* (*SSND*) problem class is the methodology of choice to build this tactical plan (Crainic & Hewitt, 2021). It selects the transportation services and schedules the carrier will operate, proposing them to shippers for the next *season* (e.g., six months). The schedule is built for a given *schedule length* (e.g., a week), which is then operated repeatedly for the duration of the season. SSND with *Resource Management* models, *SSND-RM*, also include the determination of the resource (e.g., vessels, locomotives, etc.) routes supporting the selected services (e.g., Andersen, Crainic, & Christiansen, 2009a; Crainic, Hewitt, Toulouse, & Vu, 2014).

Most service network design cases and models in the literature consider a single category of customers, making up what is generally identified as *regular demand*, which is expected to represent most of what is serviced during any "normal" period. SSND models are thus set to minimize the cost of performing the service,

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which may account for both operations and the cost of time for resources and cargo. We take a different view and consider several categories of customers, including regular and so-called spot customers, as well as several tariffs and operation classes, aiming for the maximization of the net revenue through the possibility to capture more demand, or higher priced demand, by offering a different service network. We thus integrate *Revenue Management* (*RM*) considerations into tactical planning SSND with resource management models.

Although identified as a desirable feature for freight transportation (van Riessen, Negenborn, & Dekker, 2015), RM is rather new to the freight transport planning literature, as illustrated by the reviews related to air cargo operations (Feng, Li, & Shen, 2015), railway transportation (Armstrong & Meissner, 2010), and container synchromodal services (van Riessen et al., 2015). Moreover, the few contributions focusing on revenue management and freight transportation (e.g., Bilegan, Brotcorne, Feillet, & Hayel, 2015; Wang, Wang, & Meng, 2015) focus on the operational level, the tactical level being rarely envisaged (Crevier, Cordeau, & Savard, 2012).

Our goal is to contribute to closing this gap by studying the incorporation of RM considerations, usually tackled at the operational planning level, into tactical planning models for consolidation-based freight transportation carriers. Our interest goes beyond the modeling and algorithmic challenges, to exploring the impact of this integration on the structure of the service network (e.g., should the carrier increase the offer of service in order to later be able to capture spot demand?) and the selection of customer demands to service. We thus propose a new *Scheduled Service Network Design with Resource and Revenue Management* (*SSND-RRM*) model for the tactical planning of such carriers. The modeling framework is general for tactical planning of consolidation-based intermodal carriers operating on land, e.g., railroads and motor carriers, as well as on water, deep sea and coastal, river and canal navigation. It is noteworthy, however, that the later has been relatively neglected in the literature, in spite of its importance for intermodal transport in many regions on all continents. We address this shortcoming by using intermodal barge navigation to illustrate of the problem setting, the formulation, as well as its behavior and the structural characteristics of the solutions obtained through an extensive experimentation campaign performed on realistic data.

The contributions of the paper are:

- Introduce what we believe to be the first comprehensive tactical planning model for freight carriers that integrates revenue management, resource management, and scheduled service network design;
- Present a rather comprehensive description of barge intermodal transportation, including infrastructure (port terminals), vehicle (vessels) and economic characteristics;
- Provide a proof of concept by using an off-the-shelf software to solve the corresponding mixed-integer linear programming (MILP) formulation for realistically dimensioned barge intermodal transportation instances;
- Analyze the impact of various problem settings, in terms of, e.g., demand distribution, network topology, and fare and quality-of-service (e.g., delivery time, etc.) classes, on the structure of the scheduled service network and the carrier revenues.

The paper is organized as follows. Section 2 presents the relevant literature review on service network design and revenue management topics. Section 3 describes the problem setting and discusses issues related to combining tactical planning and RM. Section 4 is dedicated to the revenue management modeling at the tactical level and the proposed SSND-RRM formulation. The experimental plan and the analysis of the numerical results are described in Section 5, and we conclude in Section 6.

2. Literature review

The section is dedicated to a brief tour of the relevant literature with the goal of relating our work to the field. We touch on tactical planning of consolidation-based freight carriers, service network design, barge transportation, and revenue management.

Bektaş and Crainic (2008); Bontekoning, Macharis, and Trip (2004); Crainic and Kim (2007); Macharis and Bontekoning (2004) and SteadieSeifi et al. (2014) offer general reviews on planning intermodal freight transportation systems, including the medium-term, tactical, level of planning for consolidation-based freight carriers. Recall that, the goal of *carrier tactical planning* is to set up a service network to maximize net profits while satisfying the regular estimated shipper (i.e., customer) demand over the next *season* (e.g., six months) of operations. The main tactical-planning decisions address the selection of services and their schedules, the determination of the terminal policies, such as classification and consolidation of cargo and vehicles and the formation of convoys (when relevant), as well as the optimization of the cargo flow distribution on the resulting network to satisfy the multi-commodity demand. The planning process takes place some time (i.e., a few weeks or a few months, depending on the application) before the start of the season. The resulting resource- and cost-efficient scheduled service network is built for a given *schedule length* (e.g., a week), which is then operated repeatedly for the duration of the season.

As indicated in the Introduction, the Scheduled Service Network Design problem class is the methodology of choice to build such tactical plans (Crainic, 2000; Crainic & Hewitt, 2021). There is a rather rich literature on SSND for consolidation-based freight carriers, reviewed by, e.g., Crainic (2003); Crainic and Hewitt (2021) for long-haul transportation, Cordeau, Toth, and Vigo (1998) for rail, Christiansen, Fagerholt, Nygreen, and Ronen (2007); Christiansen, Fagerholt, and Ronen (2004) for maritime, and Crainic and Kim (2007) for intermodal transportation, as well as Crainic, Perboli, and Ricciardi (2021) for City Logistics. SSND with Resource Management include explicitly into the tactical planning models some high-level representation of the management of key resources, e.g., power units, vehicles or crews, necessary to operate the selected services. Encountered initially in articles targeting particular applications (e.g., Armacost, Barnhart, & Ware, 2002; Lai & Lo, 2004; Smilowitz, Atamtürk, & Daganzo, 2003), the SSND-RM problem was formally modeled by Pedersen, Crainic, and Madsen (2009) as a network design problem with *design-balance* constrains, the latter imposing that the numbers of services (or resources) entering and leaving terminal-representing nodes be balanced. Extensions are presented by Andersen et al. (2009a,b) and Crainic et al. (2014, 2018) who, among other contributions, model the time-dependency of decisions through time-space networks, enrich the range of resource management concerns, and emphasize the circular nature of the routes resources must follow to support the selected services. It is noteworthy that, most service network design cases and models in the literature consider a single category of customers, making up what is generally identified as the *regular demand*, which is expected to represent most of what is serviced during any “normal” operation period.

Barge transportation, or, more generally, river and canal freight navigation, is economical in terms of unit transportation cost and eco-friendly in terms of environmental impacts. Although slower than other land-based transportation modes, barges may thus play an important role in intermodal transportation, both in exchanges between maritime ports and the hinterland and among river ports. This role is expanding in Europe, where the European Commission (2011) identifies barge transportation as the instrument for modal shift and encourages its use for intermodal freight transport, as well as elsewhere, most notably in China (Notteboom, 2012). Yet, compared to other transportation modes, studies focusing on barge transportation, particularly in the context of intermodal transportation, are still very few. In most cases, one may class these contributions into one of two categories. The first category includes descriptive analyses of intermodal transportation, including barge transport, within a territory or corridor (e.g., Caris, Macharis, & Janssens, 2012; Frémont & Franc, 2010; Zuidwijk, 2015). One may also mention within this group, the work of Konings, Kreutzberger, and Maraš (2013), who identify the need for a hub-and-spoke network structure for intermodal barge transport linked to major sea ports, with the port of Rotterdam as illustration, and that of van Riessen et al. (2015), who examine, in the same context, the issues and research opportunities related to synchromodal container assignment to available transportation modes and carriers. The second group of contributions addresses mostly operational issues in ports (e.g. Douma, Schuur, & Jage, 2011; Konings, 2007; Taylor, Whyte, DePuy, & Drosos, 2005), and in routing and dispatching out of ports (e.g., Braekers, Caris, & Janssens, 2013; Fazi, Fransoo, & van Woensel, 2015).

We found only one publication addressing the tactical planning of an intermodal barge fleet (Sharypova, Crainic, van Woensel, & J.C., 2012). The authors propose a SSND-RM model for the particular case of direct services (no intermediate stops), unique customer and service types, single container type, and single homogeneous barge fleet. The authors propose a continuous-time formulation with particular care being paid to the modeling of the terminal service synchronization and the associated load/unload/transfer operations. Revenue management issues are not addressed. The numerical results obtained on very small instances are encouraging, particularly in showing the interest of SSND-RM for planning barge transportation systems. The formulation we propose, based on a discrete-time representation, takes into account a significantly richer set of problem characteristics, notably heterogeneous barge fleets, several service levels, and several customer types, as well as explicitly including revenue management aspects.

Indeed, none of the contributions reviewed above address the issue of revenue management. Revenue, or yield, management was initially developed for passenger air transportation, and was later applied more broadly to passenger rail transportation, hotel room management, etc. (e.g., Kasilingam, 1997). The benefits observed in these domains appear promising for the freight transport industry as well. Yet, one cannot simply transpose the models and procedures from one industry to the other. Thus, e.g., Kasilingam (1997) presents the characteristics and complexities of air cargo transportation (see Feng et al., 2015, for a review of air cargo operations) from the perspective of RM by emphasizing the differences between air cargo and air passenger transportation. The author points out, in particular, that a correct and relevant model of RM for freight transportation requires the comprehensive understanding of customers' behavior, the consecutive identification of customer categories, the so-called *customer classification*, and the definition of different products and fares charged, i.e., the *fare differentiation*.

The contributions integrating RM and freight transportation of which we are aware address operational-level issues only. Crevier et al. (2012) propose a bi-level mixed-integer formulation to jointly determine fares and the capacity utilization of a given set of services proposed by a rail freight carrier. Bilegan et al. (2015) present an operational RM model applied to rail container transportation in which different fare classes are defined with respect to how early the booking is performed and how long the delivery time is. Armstrong and Meissner (2010) survey RM applied to railway transportation, Tawfik and Limbourg (2018) discuss pricing issues in intermodal transportation and review the related scarce literature, while van Riessen et al. (2015) identify RM as an important topic in synchromodal-related research. Finally, Wang, Bilegan, Crainic, and Artiba (2016) studies through simulation a RM-based capacity allocation problem for the operations of an intermodal barge transportation system. The only contribution related to our work is the study of Wang, Bilegan, Crainic, and Artiba (2014), which focuses on the classification and analysis of *performance indicators* (*PIs*) generally used to evaluate tactical planning solutions in freight transportation. The authors used an early version of the model described in this paper (unpublished but presented at the VeRoLog conference 2014; Bilegan & Crainic, 2014) to perform their simulation and identify adequate PIs for SSND with revenue management considerations.

Surveying the literature, one finds a few freight transportation tactical planning settings which include issues related to RM concepts, e.g., shipper differentiation based on delay value (Crainic, Ferland, & Rousseau, 1984; Crainic & Rousseau, 1986), the possibility not to service all the demand (Andersen & Christiansen, 2009; Braekers et al., 2013; Thapalia, Wallace, Kaut, & Crainic, 2012), the maximization of the net revenue and the possibility to accept demands only partially (Agarwal & Ergun, 2008; Gelareh & Pisinger, 2011; Teypaz, Schrenk, & Cung, 2010), and the segmentation of the transportation demands according to the obligation to service them (Stålhane, Andersson, Christiansen, & Fagerholt, 2014). But none integrates them all into a comprehensive RM-based tactical planning formulation. Our work addresses the issue and sets the cornerstone of research in the field.

We define a new problem setting for the tactical planning of consolidation-based intermodal freight carriers operating according to revenue management concepts of customer classification as well as service and fare differentiation. We propose a new model integrating scheduled service network design, resource management, and revenue management. The model is general. Yet, to both make the description more realistic and to introduce SSND-RRM to intermodal river, canal, and coastal navigation transportation, we present this integrated model in Section 4 for the intermodal transportation problem described next.

3. Problem statement

We address the problem of setting up the tactical plan of an intermodal freight transportation carrier to maximize its revenues, while satisfying the estimated demand and requirements of its customers, and making the best use of its resources. As previously indicated, the problem setting and associated modeling framework (Section 4) are general but, without loss of generality, we illustrate them for the tactical planning of intermodal barge navigation.

We describe the problem we address along three dimensions. For the first dimension, we focus on the physical network and resources of a barge/coastal intermodal navigation carrier, including the infrastructure, the containers that need to be moved, and the vessels that transport them. For the second one, we describe the customers of the system, that is, the shippers generating the demand for transportation of various types of containers, together with their requirements and expectations in terms of cost and service quality. The last one considers the fares, services, and schedule the carrier is setting up to satisfy this demand and addresses these requirements over a medium-term, tactical planning horizon. The challenges and aims related to the representation of RM mechanisms into the scheduled service network design with resource management formulation (detailed in Section 4) are discussed within the second and third dimension, respectively.

Physical network and resources A barge intermodal transportation system is defined over a *physical network* of rivers and canals plus, eventually, coastal and short-sea-shipping navigation corridors. A number of physical characteristics often constrain navigation on this network, e.g., the maximum draft of fully loaded vessels sailing on a given part of a river or canal, and the number of vessels that may simultaneously navigate, in both directions, on the same part of a river or canal during a given period of time.

A number of ports with *container terminals* are located along these rivers and canals or on the sea shore. The layout and physical organization of a terminal, together with the equipment available and the operation policies (as well as the conventions stating the working rules for the personnel) constrain the activities that may be performed within and influence the associated costs and performance measures. Prominent among these limits and measures for the problem at hand are the maximum draft of fully loaded vessels berthing at the terminal, the number of vessels and associated length that may simultaneously berth, the number of containers that may be stored within the terminal for a given period of time, and the rate of vessel loading and unloading operations in terms of containers per period of time. Costs are associated to terminal activities and are charged to carriers using the port. Given the problem addressed in this paper, we target particularly the cost of calling at the port, which varies by vessel type and the duration of the presence in the port, as well as the container loading/unloading (per container) and holding (per container and time period) costs.

The carrier operates a number of vessels to transport the containers shipped by its customers. *Containers* come in several types. They differ in terms of dimensions, 20 and 40-foot long being the standard dimension for maritime and river navigation, while longer boxes are used within land-based intermodal transportation systems, such as the 53-foot ones found in North America. Containers also differ in scope and requirements, e.g., insulated, refrigerated, bulk, tank, open top, high cube, and so on and so forth. For tactical planning purposes, the standard twenty-foot equivalent unit (TEU) measure is generally used, where 20-foot containers measure 1 TEU, while 40-foot ones account for 2 TEUs. *Vessels* also come in several types defined by their characteristics in terms of dimensions, draft, maximum number of TEUs carried, speed, etc. A limited number of vessels of each type is available for the next season (vessels may be owned or rented, but we will treat them in a similar way in this paper). Without loss of generality, we assume in this paper that all vessel types considered may navigate over the network and berth at all ports. Operating a vessel incurs costs. Other than the port-related costs mentioned above, we consider in this paper the travel costs between particular pairs of ports, as well as the cost (maintenance, depreciation, etc.) associated with not using a vessel for the considered schedule length.

Customer demand. Customers ship loaded and empty containers of given types among particular pairs of terminals in the network. Shippers have quality requirements and price expectations for each demand for transportation of a certain number of TEUs. “Quality” may involve the type of vehicle and handling equipment required for the particular type of containers involved. It always involves, however, requirements in terms of travel time and delivery date. In this paper, we represent the quality requirements as the *due date* associated to the demand, that is, the latest date containers have to be delivered at destination. The price expectations of shippers are related to the value of the cargo and the urgency of delivery. Obviously, they desire the lowest fare possible.

In traditional settings, including navigation-based intermodal transportation, a single service type (in terms of delivery time between two terminals in the network) is offered to shippers, the fare being determined mainly by the distance involved, and the cargo characteristics such as volume, weight, cargo type and handling requirements (e.g., dangerous goods require special treatment), etc. On these bases, the final price paid by the shipper then results from the negotiations it and the carrier engage into, the existence of long-term contracts or understandings with regular and trustworthy customers strongly influencing the proceedings.

Following this commercial model, most service network design cases and models in the literature consider a single category of customers, making up what is generally identified as *regular demand*. One generally finds in this category customers, or groups of customers in particular zones, that are strongly believed to bring business on a regular basis for the coming season. This prediction (formal forecasting methods may or may not be involved) is based on a combination of signed long-term contracts, informal understanding with long-standing, trustful customers, and market estimation by sales and customer-relation personnel. Regular demand is expected to make up a good part (a 80% figure is often mentioned) of what is serviced during any “normal” period.

When revenue management mechanisms are in place, or contemplated, the situation is different. At a strategic level, one establishes a service and tariff policy, e.g., segmenting the potential demand and defining a number of traffic/tariff classes and service levels to attract the targeted customers and volume of demand. One also negotiates long-term contracts or understandings with important customers to ensure a good level of regular business, which translates into regular levels of demand and traffic. During actual operations, the revenue management mechanisms are used to determine the acceptance and tariff of each request for transportation and, thus, to adjust the actual demand to the offer of services with fixed capacities, regular schedules, and so on, which was planned based on demand forecasts. The questions then are, how to represent such mechanisms within tactical planning models, and what is the benefit of using RM-based information and knowledge when building the transportation plan.

Services and schedules. Each potential *service* is defined by an origin terminal and the associated departure time within the schedule length, a destination terminal, a route through the physical network, a sequence of intermediary calls at ports along this route (the sequence is empty for direct services), and a schedule indicating the arrival and, for the intermediate stops, the departure times at ports. Without loss of generality, and because it reflects actual practice for the problem setting we examine, we assume the longest service duration to be less than the schedule length. A vessel of particular characteristics is associated to each service. Each service is thus characterized by the attributes of its designated type of vessel, as well as by the costs to set up and operate it on the links of its route.

Symmetrically, a vessel is assigned to a set of services during the schedule length. Without loss of generality, we assume vessels return to their home port. Consequently, each operated vessel supports a circular sequence of services starting and ending at the same port. These cycling vessel routes, that we call *service cycles* in the following, ensure that there are no empty-repositioning movements.

The set of services selected by the carrier to efficiently and profitably satisfy the estimated demand, makes up the transportation plan and defines its *service network* and *operating schedule*. Each customer demand is moved over this service network by one of the possible itineraries for the particular demand. Remark that the same physical customer may have several shipments over the schedule length, and that these shipments may differ in volume, characteristics, and requested service level. We represent such cases as different customer demands. Remark also that, while some demand estimations may be made individually, for major and regular customers, most demands represent an aggregation of potential customers within a given zone and with similar transportation requests.

A demand *itinerary* is then defined by the origin terminal of the shipment and its availability time (i.e., the time period it is supposed to arrive at the origin terminal), the sequence of services until the associated destination terminal, and the number and type of containers moved. The sequence of services thus yields the schedule of the itinerary, i.e., the arrival and departure moments at each port terminal, together with the time spent in the terminal to 1) unload the cargo from the incoming service, 2) wait in the terminal for the next service, and 3) load on that next service. We assume unloading operations take place immediately after the arrival of the service at the terminal, followed by loading operations taking place before leaving the terminal.

The SSND-RRM problem. As indicated earlier, the carrier aims to meet demand and the shipper requirements in the most resource- and cost-efficient way, through planned operations that maximize its net profit. The aim is thus to (1) select the services, out of a set of potential feasible ones, and, through their departure times, the schedule to operate; (2) determine the circular asset routes, the service cycles, supporting the selected services; and (3) identify the demand itineraries. The combination of these three objectives also yields the loads of vessels during their movements from one stop of the corresponding service to the next, and the amount of work to be performed on vessels and containers at each port of call in the network.

The integration of revenue management considerations to tactical planning is performed through two major modifications to the traditional problem setting and modeling approach.

First, we take the different view of explicitly considering several categories of customers, and several types of delivery and fare classes. The first category of customers is made up of regular ones, as discussed above. Two other categories correspond to spot customers, with demand that is potentially there, and that the carrier might accept or not, given the estimated revenue and the capacity it plans to deploy. Such demand is usually explicitly accounted for in fleet (e.g., Crainic, Gendreau, & Dejax, 1993; Powell & Topaloglu, 2005) and revenue management (e.g., Bilegan et al., 2015), but is not normally included into tactical-planning formulations. The challenge of integrating it into a SSND-RRM formulation comes from the difficulty to translate the business relationship a carrier holds with its customers. This translation is performed following two dimensions: customer characteristics and demand types, i.e., based on customer contractual behavior considerations, as well as on the level of service (urgency of delivery) requested for each individual demand.

Second, contrary to service network design literature, the goal here is the maximization of the net revenue. The net revenue is computed as the difference between the estimated profit of servicing the regular and the accepted spot potential customers and the cost of performing the planned services. The cost accounts both for setting up the services and for operating vessels and transporting containers. It is thus summing up the cost of operating the vehicles and the cost associated to using the fixed resources and transporting the cargo, given the levels of service and fare classes offered (remark that service differentiation was considered in a number of earlier contributions, e.g., Crainic et al., 1984; Crainic & Rousseau, 1986, without being materialized into additional revenues for the carrier).

The resulting SSND-RRM model may therefore be used both to plan the operations for the next season and as a tool to evaluate RM policies. It aims, in particular, to provide the means to answer questions such as, whether it is profitable to assume a higher total vessel cost to increase the level of service, in terms of service frequencies or capacities, in order to attract additional higher-priced demand (assuming, of course, such demand has been identified)? Are the current or contemplated differentiated customer categories, service levels, and fare classes adequate? Is the contemplated contract or business relationship for regular demand actually profitable? Which and how much of the potential demand should/could be serviced within a given schedule length, while optimally using the available resources? We describe in the next section the methodology used to address these issues and formulate the planning problem at the tactical level.

4. The SSND-RRM formulation

We present the formulation of the scheduled service network design with resource and revenue management (SSND-RRM) model for the tactical planning of intermodal barge transportation in three steps. We first discuss the representation of the revenue management considerations in terms of customer service and fare differentiation (Section 4.1). We then introduce the time-space representation of operations, the demand, and the services one has to select in order to satisfy it (Section 4.2). The formulation is presented next (Section 4.3).

4.1. Revenue management modeling for the SSND-RRM

Let $\mathcal{D}$ represent the set of regular and potential customer demands, with $d \in \mathcal{D}$ a particular demand. We model customer service and fare differentiation through a two-dimensional mechanism: *business relationship* and *service requirement*.

Business relationship addresses principally the contractual profile of customers, that is, the commitment to work with the carrier: regular customers with long-term contracts or understandings, which must be served, and customers present on the spot market, which we may service or not. The latter correspond to a pool of irregular potential customers, who may arrive to the system as “short-notice” requests. Individually, these customers could be “small” in terms of volume and, even, not regularly present but, taken collectively, they form a significant and consistent demand in terms of total volume per origin-to-destination pair. Identified within a given geographical zone - around a port that is the origin of their requests for transportation - the decision to service them is to be made according to their particular requirements and the available planned capacity on the transportation network.

We define three categories of business relationships (and customers), partitioning the customer demands set, $\mathcal{D} = \mathcal{D}^{\mathrm{R}} \cup \mathcal{D}^{\mathrm{P}} \cup \mathcal{D}^{\mathrm{F}}$, as follows:

- *Regular* customer demands, grouped within set $\mathcal{D}^{\mathrm{R}}$, representing customers with long-term contracts or understandings; this category corresponds to the regular demand in classical SSND formulations and must be always satisfied;
- *Partial-spot* customer demands, set $\mathcal{D}^{\mathrm{P}}$, which may be fragmented and only partly satisfied, which means a fraction of it could be integrated in the demand to be serviced by the planned services, the rest not being served at all by the carrier; we model this decision further down in this section through continuous decision variables yielding the percentage of the demand that is going to be serviced;
- *Full-spot* customer demands, set $\mathcal{D}^{\mathrm{F}}$, consisting of demands which may be either entirely accepted and serviced or not accepted at all; binary selection variables are introduced in the formulation to represent these decisions.

Two service levels are defined with respect to the service requirement dimension of the proposed mechanism, *standard* and *express* delivery reflecting the due times at destination requested by customers. Fares normally reflect service level differentiation, e.g., express-delivery requests would be priced higher than standard-delivery ones. We consequently introduce *fare classes* to characterize each demand:

- *class*(d): fare class for demand $d \in \mathcal{D}$, related to the type of delivery requested, *standard* or *express*;
- $f(d)$: unit fare value for demand $d \in \mathcal{D}$ with fare class *class*(d).

4.2. Network modeling

Let the directed graph $\mathcal{G}^{\mathrm{ph}} = (\mathcal{N}^{\mathrm{ph}}, \mathcal{A}^{\mathrm{ph}})$ represent the *physical network* supporting the operations of the carrier. The set $\mathcal{N}^{\mathrm{ph}}$ represents intermodal terminals. Each terminal $i \in \mathcal{N}^{\text{ph}}$ is characterized by a berthing capacity Q_i in number of vessels per time period, and a container holding capacity H_i in number of TEUs per time period. The former is defined with respect to the average length of the vessels used on the network, which is reasonable given the rather limited range of vessels used in such systems.

The set $\mathcal{A}^{\text{ph}}$ groups the physical arcs of the network, each representing a possible navigation movement between two "consecutive" ports, that is, no intermediary port exists between the initial and final nodes of the arc. To simplify the presentation, but without loss of generality, we assume uncapacitated physical arcs.

Let the schedule length be discretized into T periods of equal length by $T+1$ time instants $t \in 0, \dots, T$. The period length is generally defined according to the particular operational context of the application, e.g., average travel time along links or stopping time at ports, and the schedule length. For a week-long schedule on a river/coastal navigation network, a period length of a couple of hours appears appropriate. By convention, activities, e.g., demand arrival at terminals and vessel arrivals and departures at and from ports, occur at the beginning of a period.

Let Γ be the set of container types, with $\gamma \in \Gamma$ a particular container type. Then, as discussed above, each demand $d \in \mathcal{D} = \mathcal{D}^{\text{R}} \cup \mathcal{D}^{\text{P}} \cup \mathcal{D}^{\text{F}}$ is characterized by:

- $vol(d)$: volume in number of TEUs;
- $\gamma(d)$: container type, $\gamma(d) \in \Gamma$;
- $orig(d)$: origin node, $orig(d) \in \mathcal{N}^{\text{ph}}$;
- $in(d)$: period the cargo becomes available for transportation at $orig(d)$;
- $dest(d)$: destination node, $dest(d) \in \mathcal{N}^{\text{ph}}$;
- $out(d)$: due date at destination, that is, the latest period the cargo may arrive at the destination terminal;
- $cat(d)$: category of customer demand (R or P or F), according to whether $d \in \mathcal{D}^{\text{R}}$ or $\mathcal{D}^{\text{P}}$ or $\mathcal{D}^{\text{F}}$;
- $class(d)$: fare class, *standard* or *express*;
- $f(d)$: unit fare value.

The carrier operates vessels of various types, that it owns or rents for the season, according to the scheduled set of services. The set of vessel types is noted $\mathcal{L}$, each vessel type $l \in \mathcal{L}$ being characterized by:

- $cap(l)$: capacity in TEUs;
- $speed(l)$: speed of vessel of type $l \in \mathcal{L}$ in normal operations, yielding $\delta_{ij}(l)$, the normal travel time of an l type vessel over arc $(i,j) \in \mathcal{A}^{\text{ph}}$;
- B_l: maximum number of vessels of type $l \in \mathcal{L}$ available.

The formulation is defined on a time-space network capturing the time-dependency and repetitiveness of the demand and schedule (services and resource utilization), taking the form of a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, with node and arc sets $\mathcal{N}$ and $\mathcal{A}$, respectively. The network (and the transportation plan and schedule) is circular over the schedule length, which means that any arc in $\mathcal{A}$ of length (duration) δ that starts at time t, arrives at destination at time $(t+\delta) \bmod T$.

The node set $\mathcal{N}$ is obtained by duplicating all physical nodes at all periods in the schedule length, so that node $it \in \mathcal{N}$ corresponds to the physical node $i \in \mathcal{N}^{ph}$ at time instant $t,\ t = 0, \dots, (T-1)$. The set of arcs $\mathcal{A}$ is the union of the set of holding arcs at terminals, and the set of possible movements performed by services. A *holding* arc $(it, i(t+1))$ captures a one time period waiting at terminal i at time t for vessels, cargo, and services. Movements in the time-space network are performed by services traveling physical paths between two consecutive stops on their respective routes. We call such movements *service legs* and these define the *moving* arcs of $\mathcal{A}$.

A service $s \in \mathcal{S}$ is thus defined in the time-space network $\mathcal{G}$ by a number of physical and time-related attributes, illustrated in Figs. 1 and 2, and described as follows:

- $orig(s)$: physical origin terminal, $orig(s) \in \mathcal{N}^{ph}$;
- $dest(s)$: physical destination terminal, $dest(s) \in \mathcal{N}^{ph}$;
- $\eta(s) = \{i_k(s) \in \mathcal{N}^{\text{ph}}, k = 0, \dots, (K-1)\}$: ordered set of consecutive stops of the service, where $K = |\eta(s)|$ and k indicates the k^{th} stop of the service;
- $a_k(s) = (i_k(s), i_{k+1}(s))$: k^{th} leg of the service, $k = 0, \dots, (K-2)$;
- $r(a_k(s)) \subseteq \mathcal{A}^{\text{ph}}$: path of $a_k(s)$ in the physical network;
- $\delta_k(s)$: travel time of leg $a_k(s)$;
- $w_k(s)$: stopping time at terminal $i_k(s)$;
- $\alpha_k(s)$: arrival time of the service at its terminal $i_k(s)$; by convention:

  $\alpha_0(s)$: availability time of the service to load at the origin terminal, i.e., the initial loading time $w_0(s) = \tau_0(s) - \alpha_0(s)$;
  $\alpha_{K-1}(s)$: arrival time of the service at destination;

- $\tau_k(s)$: departure time of the service from its terminal

$$\tau_k(s) = \tau_0(s) + \sum_{j=0}^{k-1} (\delta_j(s) + w_{j+1}(s)) \quad k = 1, \dots, (K-1); \qquad (1)$$

  by convention:

  $\tau_0(s)$: departure time of the service from its origin terminal;
  $\tau_{K-1}(s)$: time at destination when the vessel is completely unloaded and ready for the next service, i.e., the final unloading time $w_{K-1}(s) = \tau_{K-1}(s) - \alpha_{K-1}(s)$;

- $\delta(s) = \alpha_{K-1}(s) - \tau_0(s)$: total duration of service s;
- $l(s)$: vessel type of service s, $l \in \mathcal{L}$;
- $cap(l(s))$: capacity of service s, in TEUs;
- $\phi(s)$: fixed cost of setting up and operating the service.

Fig. 1 illustrates the time-related attributes of a multi-leg service. Fig. 2 illustrates a time-space network with 9 time periods and four terminals. Horizontal dashed arcs are the holding arcs at terminals, while the plain arrows stand for service legs. Two services are displayed. The first one, s_0, is a three-leg service that originates at Terminal A and ends up at Terminal D. The two intermediate stops are one and two periods long, respectively. The second service, s_1, travels from Terminal D to Terminal A with an intermediary stop of one period at Terminal C. The availability times of both services are indicated as well.

The following unit costs are defined:

- $c_k(\gamma(d), l(s))$: transportation of a container of type $\gamma(d)$, by a vessel of type $l(s)$, on the k^{th} leg of service s;
- $c(i, \gamma(d))$: holding a container of type $\gamma(d)$ at terminal i for one period;
- $\kappa(i, \gamma(d))$: loading/unloading a container of type $\gamma(d)$ at terminal i;
- $h(i, l)$: holding cost for a vessel of type l at terminal i for one time period;
- $\rho(l)$: penalty for a vessel of type l that is not used in the optimal plan.

4.3. SSND-RRM model formulation

We define the following decision variables:

- $y(s) = 1$ if service s is selected, 0 otherwise;
- $\xi(d) \in [0, 1]$ = percentage of the volume of demand (number of containers) $d \in \mathcal{D}^{\text{P}}$ that is selected and will be serviced;

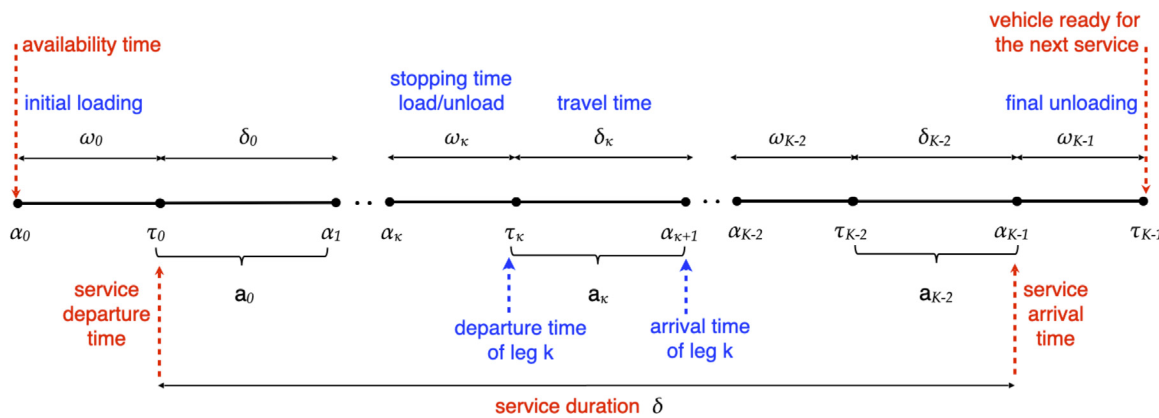

Fig. 1. Time-related attributes of service s.

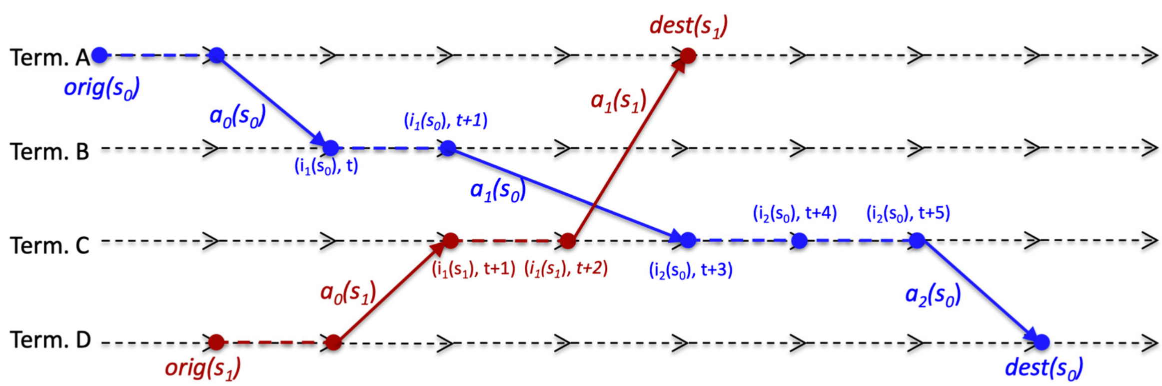

Fig. 2. Time-space representation of the service network with two services.

- $\zeta(d) \in \{0,1\} = 1$ if the demand $d \in \mathcal{D}^{\mathrm{F}}$ is selected to be serviced, 0, otherwise;
- $z(l,i,t)$ = number of temporarily idle vessels of type l at terminal i, waiting at period $(t,t+1)$ for the departure of the next service it supports;
- $\upsilon(l)$: total number of vessels of type l used by the service plan; due to the circular nature of the schedule, $\upsilon(l)$ is the same for all time periods (although, at any given period, vessels may be moving or be idle in ports);
- $x(d,s,k)$ = volume of demand $d \in \mathcal{D}$ transported by service s on its leg k;
- $x^{out}(d,s,k)$ = volume of demand $d \in \mathcal{D}$ to be unloaded at terminal i_{k+1} when arriving at time $\alpha_{k+1}(s)$ on leg k of service s;
- $x^{in}(d,s,k)$ = volume of demand $d \in \mathcal{D}$ to be loaded on leg k of service s before leaving terminal i_k at time $\tau_k(s)$;
- $x^{hold}(d,i,t)$ = volume of demand $d \in \mathcal{D}$ on hold at terminal i during time period $(t,t+1)$;

The SSND-RRM model formulation then becomes:

$$\begin{aligned}\max & \sum_{d\in\mathcal{D}^{\mathrm{R}}} f(d)vol(d) + \sum_{d\in\mathcal{D}^{\mathrm{P}}} f(d)\xi(d)vol(d) + \sum_{d\in\mathcal{D}^{\mathrm{F}}} f(d)\zeta(d)vol(d)\\ & - \sum_{l\in\mathcal{L}} \rho(l)(B_l - \upsilon(l)) - \sum_{s\in\mathcal{S}} \phi(s)y(s) - \sum_{t\in T}\sum_{i\in\mathcal{N}^{\mathrm{ph}}} h(i,l)z(l,i,t)\\ & - \sum_{s\in\mathcal{S}}\sum_{k\in\eta(s)}\sum_{d\in D} c_k(\gamma(d),l(s))x(d,s,k) - \sum_{t\in 0,\dots,T}\sum_{i\in\mathcal{N}^{\mathrm{ph}}}\sum_{d\in\mathcal{D}} c(i,\gamma(d))x^{hold}(d,i,t)\\ & - \sum_{s\in\mathcal{S}}\sum_{k\in\eta(s)}\sum_{d\in D} \kappa(i,\gamma(d))(x^{in}(d,s,k) + x^{out}(d,s,k))\end{aligned} \tag{2}$$

Subject to

$$x^{hold}(d, orig(d), in(d)) + \sum_{s\in\mathcal{S}: i_k(s)=orig(d), \tau_k(s)=in(d)} x^{in}(d,s,k)$$

$$= \begin{cases} vol(d), & \forall d \in \mathcal{D}^{\mathrm{R}}\\ \xi(d)vol(d), & \forall d \in \mathcal{D}^{\mathrm{P}}\\ \zeta(d)vol(d), & \forall d \in \mathcal{D}^{\mathrm{F}}\end{cases} \tag{3}$$

$$\sum_{in(d)<t\le out(d)}\ \sum_{s\in\mathcal{S}: i_{k+1}(s)=dest(d), \alpha_{k+1}(s)=t} x^{out}(d,s,k) = \begin{cases} vol(d), & \forall d \in \mathcal{D}^{\mathrm{R}}\\ \xi(d)vol(d), & \forall d \in \mathcal{D}^{\mathrm{P}}\\ \zeta(d)vol(d), & \forall d \in \mathcal{D}^{\mathrm{F}}\end{cases} \tag{4}$$

$$\begin{aligned}& x^{hold}(d,i,t-1) + \sum_{s\in\mathcal{S}: i_{k+1}(s)=i, \alpha_{k+1}(s)=t} x^{out}(d,s,k)\\ & - x^{hold}(d,i,t) - \sum_{s\in\mathcal{S}: i_k(s)=i, \tau_k(s)=t} x^{in}(d,s,k) = 0\\ & \forall (i,t) \ne (orig(d), in(d)), \forall i \ne dest(d), \forall d \in \mathcal{D}\end{aligned} \tag{5}$$

$$x^{in}(d,s,k) - x(d,s,k) = 0, \forall s \in \mathcal{S},\ i_k(s) = orig(s),\ d \in \mathcal{D} \tag{6}$$

$$x(d,s,k-1) - x^{out}(d,s,k-1) = 0, \forall s \in \mathcal{S},\ i_k(s) = dest(s),\ d \in \mathcal{D} \tag{7}$$

$$\begin{aligned}& x(d,s,k-1) - x^{out}(d,s,k-1) + x^{in}(d,s,k) - x(d,s,k) = 0,\\ & \forall s \in \mathcal{S},\ i_k(s) \ne orig(s), i_k(s) \ne dest(s),\ d \in \mathcal{D}\end{aligned} \tag{8}$$

$$\sum_{d\in\mathcal{D}} x(d,s,k) \le cap(l(s))y(s), \quad \forall s \in \mathcal{S}, k = 0\dots(K-2) \tag{9}$$

$$\upsilon(l) = \sum_{i\in\mathcal{N}^{\mathrm{ph}}} z(l,i,0) + \sum_{s\in\Lambda_{0l}} y(s), \quad \forall l \in \mathcal{L} \tag{10}$$

$$v(l) \le B_l, \quad \forall l \in \mathcal{L} \tag{11}$$

$$\sum_{s \in S^-_{itl}} y_s + z(l,i,t-1) = \sum_{s \in S^+_{itl}} y_s + z(l,i,t) \quad \forall l \in \mathcal{L}, \ \ it \in \mathcal{N} \tag{12}$$

$$\sum_{l \in \mathcal{L}} z(l,i,t) + \sum_{l \in \mathcal{L}} \sum_{s \in S: i_k(s)=i, l(s)=l, \alpha_k(s) \le t < \tau_k(s)} y(s) \le Q_i, \quad \forall it \in \mathcal{N} \tag{13}$$

$$y(s) \in \{0,1\} \quad \forall s \in \mathcal{S} \tag{14}$$

$$\xi(d) \in [0,1] \quad \forall d \in \mathcal{D}^{\mathrm{P}} \tag{15}$$

$$\zeta(d) \in \{0,1\} \forall d \in \mathcal{D}^{\mathrm{F}} \tag{16}$$

$$z(l,i,t) \ge 0 \quad \forall l \in \mathcal{L}, \quad it \in \mathcal{N} \tag{17}$$

$$v(l) \ge 0 \quad \forall l \in \mathcal{L} \tag{18}$$

$$x(d,s,k) \ge 0 \quad \forall d \in \mathcal{D}, \ s \in \mathcal{S}, \ k = 0 \dots (K-2) \tag{19}$$

$$x^{out}(d,s,k) \ge 0 \quad \forall d \in \mathcal{D}, \ s \in \mathcal{S}, \ k = 0 \dots (K-2) \tag{20}$$

$$x^{in}(d,s,k) \ge 0 \quad \forall d \in \mathcal{D}, \ s \in \mathcal{S}, \ k = 0 \dots (K-2) \tag{21}$$

$$x^{hold}(d,i,t) \ge 0 \quad \forall d \in \mathcal{D}, \ it \in \mathcal{N}. \tag{22}$$

The objective function (2) maximizes the net profit, where the first three terms correspond to the revenue obtained by servicing the complete demand of regular customers (which is constant here), the selected proportion of demand of the partial-spot customers, and the complete demand of the selected full-spot customers respectively. Remark that the first term (revenue obtained by servicing the complete demand of regular customers) is kept in the formulation to have the objective function as a homogeneous mathematical expression. The following terms stand for the activity and time-related costs of operating the selected service network and resource routes, that is, the penalty cost of having but not using vessels (never assigned to a service during the entire schedule length), the fixed cost of setting up and operating services, the cost of the vessels idling at a port waiting for their next service departure, the cost of transporting containers on services, and the cost of holding and handling containers in terminals.

Eqs. (3)–(5) are flow-conservation constraints for containers of all customer types, at their particular origins, destinations, and intermediary nodes, respectively. Similarly, Eqs. (6)–(8) enforce the conservation of container flows, for all customer types, on each service at its origin, destination and intermediary stops, respectively. Constraints (9) enforce the service capacity on each leg.

Eq. (10) computes the number of vessels used in the plan as the sum of vessels idling in ports or moving between them performing services. Due to the resource management concerns and the resulting circular vessel routs, $v(l)$ is the same at all periods, only the relative proportion of idle versus active vessels being different at different time periods. We therefore compute this number for the first period, i.e., $t = 0$, the set $\Lambda_{0l} = \{s \in S, l(s) = l | (\alpha_{K-1}(s) \mod T) < \tau_0(s)$ and $\tau_0(s) \ge 0\} \subseteq \mathcal{S}$ containing all services, of the appropriate vessel type, that operate one of its legs during the first period. Constraints (11) enforce the fleet size for each vessel type, while Eq. (12) are the so-called design-balance constraints, enforcing the vehicle-flow conservation at terminals (the number of services and vessels entering a node equals the number exiting the node), where sets S^-_{itl} and S^+_{itl}

$$S^-_{itl} = \{s \in S \mid dest(s) = i, \tau_{K-1}(s) = t, l(s) = l\} \tag{23}$$

$$S^+_{itl} = \{s \in S \mid orig(s) = i, \alpha_0(s) = t, l(s) = l\} \tag{24}$$

group the services of type l that arrive at their destination or depart from their origin i at time t, respectively. Finally, Constraints (13) enforce the terminal berthing capacity at each time period, while decision-variable domains are defined by Constraints (14)–(22).

5. Analysis of experimental results

We aim to explore the behavior and performance of the proposed model and its capability to provide meaningful managerial insights. We aim for two intertwined goals: analyze the model behavior impacted by a number of important problem characteristics (type of demand, topology of the network, number of potential services, cardinality of the demand sets, fare differentiation, mix of customer categories, ...) and provide a proof-of-concept and validation framework for the proposed model.

Along with analyzing the experimental results, important additional research questions have been addressed: first, exploring the applicability of the proposed model under different well-characterized situations (e.g., proportion and network distribution of express demands, proportion of spot customers); second, evaluating the propensity of the modeling approach and solutions obtained to constitute a relevant decision-making support, providing meaningful insights, when choosing among alternatives in applying RM tactical policies and parameter tuning (e.g., number and price ratios of fare classes, categories of customers, transportation network and demand characteristics, etc.).

An experimental campaign was designed in order to work towards achieving these objectives and answer the research questions. A realistic set of test instances was built based on the North of France and Belgium network and exchanges with the barge transportation industry of the region. The set was then gradually enriched, by introducing additional characteristics to the test instances, as needed to answer the research questions. We first show that fare differentiation (based on demand characteristics) is a condition to guarantee the profitability of offered services. The problem setting for this initial (basic) version combines different network topologies and combinations of *express* and *standard* demands. Second, we focus on analyzing the model behavior when fare differentiation and customer categories are introduced. We allow the RM model to act (sequentially fixing values for certain decision variables) in three different ways, following three different decision policies, thus gradually increasing the flexibility of the decision-making process, by increasing the *degree of freedom* of the service selection. The results are then compared and conclusions are drawn. The proof of concept is based on an analysis of the behavior of the model under these varying conditions, showing that the model reacts to changes as expected and in a reasonable way.

The characteristics of test instances generated for the purpose of the experiments are presented in Section 5.1. The transportation system and RM-specific performance indicators used to perform the evaluation are presented in Section 5.2. The numerical results and analyses of the model behavior corresponding to the different problem settings are the scope of Sections 5.3 and 5.4, each corresponding to one of the research questions discussed above.

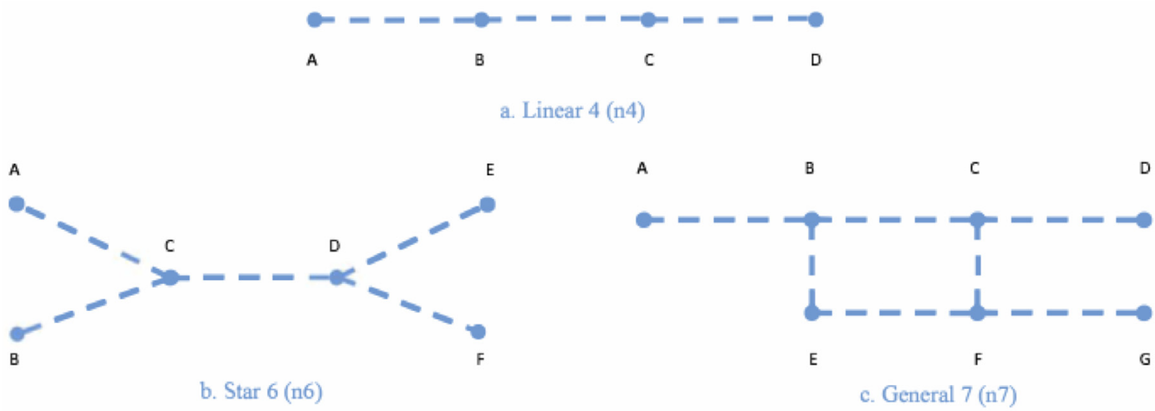

Fig. 3. The physical network topologies considered for the SSND-RRM model validation.

5.1. Test instances

The SSND-RRM formulation belongs to the network design problem class, which is NP-Hard in all but the most trivial cases. We aimed for exact optimal solutions, obtained in reasonable computing times, in order to correctly characterize behavior and compare performances. Hence, we focused the experimental study on relatively small-size test instances. Each instance contains transportation system information in terms of physical network characteristics, available fleet of vehicles to be operated by the carrier, and the size (in time-periods) of the schedule length.

Examples of physical networks were chosen based on representative topologies of barge transportation networks, corresponding to the following three particular situations: (1) a linear network, with four terminals; it corresponds to a common corridor network type, quite representative for the North of France and Belgium; it is named *Linear 4 (n4)*; (2) a hub-and-spoke network with six terminals, including a single common leg to be shared by distant OD pairs; this is a more challenging network configuration from the perspective of service planning and demand routing; it is named *Star 6 (n6)*; (3) a more general network with seven terminals, combining linear and hub-and-spoke topologies, and representative of transportation systems covering a larger geographic zone; it is named *General 7 (n7)*. These three configurations are illustrated in Fig. 3.

The fleet of vehicles operated by the carrier is assumed to include two types of vessels, large and small. The large vessels are set to offer 2.5 times more capacity than the small ones (50 TEUs and 20 TEUs, respectively), with the fixed cost of operating large vessels set at around twice that of small ones (reflecting economies of scale). Each type of vessel is able to travel everywhere in the network, in both directions, and thus the set of potential services consists of all possible origin-destination itineraries (paths) in the network, for all vessel types available.

The schedule length (cyclically repeated over the planning horizon), is considered to be one week (7 days) and is divided into 14 equal time periods (half day). This corresponds to common practice in inland waterway transportation, since operational considerations make departures, arrivals and other service-related actions to be generally planned on time windows corresponding to the morning or afternoon of working days.

Test instances were generated for each network topology, n4, n6 and n7, applying the procedure detailed in Wang et al. (2014), of which we just give the main lines. A set of demands was randomly generated for each instance, assuming origin-destination demands are uniformly distributed over the network and each origin-destination pair appearing at least twice. The demand volumes for each test instance were generated uniformly between zero and an upper bound value (half the capacity of a large vessel, i.e., 25 TEUs). Note that the volume of a demand might exceed the capacity of a small vessel. This is not restrictive, however, since demand splitting is allowed. A number of instances contain *R* customers, whereas others contain a mix of *R*, *P*, and *F* customers. The former are used in the experiments of Section 5.3, the latter being part of experiments analyzed in Section 5.4. A parameter indicating the proportion of *R* versus *P*/*F* customers characterizes each instance.

To ensure consistency when comparing results, instances present the same total volume of demand. We vary, however, the proportion *p* of volume of *express*,versus *standard* demand within this total. Different *fare classes* are associated to different delivery types. A *low fare* corresponds thus to a *standard* delivery, while a *high fare* is associated with an *express* one.

The distances between any two consecutive ports in the physical network are considered to be, without loss of generality, almost the same. The delivery times for demands (time ranges between the availability date, in(d), and the due date, out(d)) are generated based on the distance between the origin and destination of each demand, as well as the delivery type (express or standard). The express delivery time values (in number of time periods) are set according to the shortest travel time between the origin and destination of the corresponding demand on the carrier's physical network. As a general rule, the standard delivery time values are two times longer than the express delivery ones for the same origin and destination pair.

R customers have demand of either *standard* or *express* delivery type, the choice being governed by an instance-specific *fare ratio*. *P* and *F* customers have a single type of demand, *standard* and *express* delivery, respectively. Based on this procedure, 20 instances were randomly generated for each specific value of the parameter, varied from one column to another in each of the following tables (100 instances per table, so 600 in total, in the 6 tables discussed in Section 5.3; 80 instances per table, solved 3 times each, for each decision-making policy, so 240 instances and 720 problems solved for the 3 tables discussed in Section 5.4).

The MILP optimization problems were solved with the help of a commercial solver (IBM CPLEX 12.8) on a multi-processor server running under Linux 64-bit with an Inter Xeon X5675, 3 GHz and 30 GB of RAM. The computational effort required to address the NP-Hard SSND-RRM problem is detailed in Annex A. Not surprisingly, this effort increases considerably with the number of demands (commodities), the number of potential services examined to answer to these demands, and the number of periods in the time discretization of the schedule length. The impact of network topology is less noticeable.

Table 1
Express demand; uniform distribution; *n4* network; no fare differentiation.

Performance indicator	0% express	25% express	50% express	75% express	100% express
Total cost	9175.37	9459.17	9946.92	10364.02	10996.47
Opening services cost	4567.5	5040	5557.5	6198.75	6997.5
# Open services (small)	5.7	13.2	17.1	22.15	24.5
# Open services (large)	7.3	4.6	3.8	2.7	3.3
Distance*Capacity usage (%)	70.17	69.34	64.46	59.32	52.62
Waiting at origin	469.05	377.25	347.6	216.25	115.45
Transshipment	1.60	6.95	3.7	2.45	0
Split standard (%)	27.82	43.46	48.92	56.68	NA

5.2. Performance indicators

The following *performance indicators* (*PI*) are used to evaluate experimental results, where all volumes are measured in container TEU (Twenty-feet Equivalent Unit):

- **Total cost**: sum of all fixed (opening services) and variable (holding barges while in use of not, holding containers, transporting and handling containers) costs;
- **Service cost**: total fixed cost of the opened services, which provide the total transportation capacity made available in the optimal solution on the network;
- **Relative yield**: net profit divided by the total cost; indicator of profitability of accepted demands;
- **# Open services (small)**: number of open services with small vessels;
- **# Open services (large)**: number of open services with large vessels;
- **Distance*Capacity usage**: proportion of selected transportation capacity *effectively used*, computed as the ratio of total volume-km moved with respect to the total capacity-km operated (Eq. (25))

$$\text{Distance*Capacity usage} = \frac{\sum_s \sum_k \sum_d dis(k) * x(d,s,k)}{\sum_s \sum_k dis(k) * cap(s)} \quad (25)$$

- **Waiting at origin**: volume-weighted sum of demand waiting times at origins;
- **Transshipment**: volume-weighted sum of demand waiting times at intermediate stops;
- **Split standard**: ratio of the volume of *standard* demands for which the routing solution will split the flow (will transport different parts of the same demand) among several different itineraries;
- **Additional TEU**: total volume of *P* or *F* customer demands accepted for transportation.

5.3. Model behavior

We analyze in this subsection experiments performed with the basic version of the problem setting and model, showing that, in order to improve carrier profitability, differentiation in fare and customer categories is necessary. In this first group of experiments, test instances contain regular customers only. *Standard* and *express* delivery types are considered, depending on customer requirements, but no differentiation in price between the two service requirements is applied.

Two sets of experiments were run with different distributions of the customers requiring *express* service. The origins of *express* demands were uniformly distributed over the network in the first case; results on the *n4* network are summarized in Table 1. For the second set of experiments, *express* demands were assumed to accumulate in a single *main* terminal (e.g., the port with the highest throughput), i.e., each express demand either originates or terminates at thst terminal; Table 2 displays the results of these experiments on the *n4* network. The values in both tables are averages over 20 different instances for different proportions of customers requiring *express* delivery, columns *0% express* and *100% express* providing the lower and upper bounds on the total cost, respectively. It is noteworthy that no profit-related performance indicators are used to evaluate results in these experiments, because the same regular customers, paying the same type of fare (no fare differentiation is applied), are considered in all cases.

The results obtained when the customers requiring *express* delivery are uniformly distributed over a linear network (Table 1) confirm that more small, direct services are needed, which implies a higher total cost, as the volume of *express* demand increases. The results also show that the number of selected small vessels providing direct service increases with the proportion of express demands, by almost five times when only express customers are present compared to the 0% express case. This trend may be explained by the double benefit direct services operated by small-capacity vessels bring in such cases. On the one hand, direct services deliver cargo faster than services with intermediary stops; on the other hand, small vessels fill up rapidly (waiting of demand at origins decreases steadily - *Waiting at origin* PI), and may thus leave more rapidly than large vessels, which results in saving more on holding costs. The prevalence of direct services is reflected in the progressive decrease of the volumes transferred between services (*Transshipment* PI). As demand for fast, direct services grows, so does the number of appropriate small vessels. Yet, unused capacity exists, and one observes a drop in resource utilization from 70.17% to 52.62% (*Distance*Capacity usage* PI), and the unit profitability of transport capacity, without fare differentiation, is getting lower.

It is noteworthy that, in order to satisfy *express* delivery demands, some *standard* demands have to be delayed. The percentage of split among *standard* demands (*Split standard* PI) increases with the increase of the number of *express* demands. This behavior follows from the aim of the model (and system) to maximize profitability and, thus, decrease costs by making use of the residual capacity of vessels once the *express* demands are loaded.

Similar trends are observed when customers require *express* transport out of or to a single (main) terminal, while *standard* requests are present at all terminals (Table 2). It is noteworthy, however, that consolidation opportunities for better vessel utilization grow when the volume of demand at the same port grows. The consolidation mechanism embedded in the proposed SSND-RRM model delivers a transportation plan providing such opportunities. Indeed, comparing the results with those of the uniformly-distributed case, one observes less services selected and more vessel capacity used. This results into a higher system performance as measured by lower service-opening and total costs, due to better consolidation opportunities.

Moreover, examining the *Waiting at origin* PI when all express demands are concentrated at a single port, one may notice that total waiting duration is higher than that of the uniformly-distributed case. This is due to the fact that, in this unbalanced de-

Table 2
Express demand concentrated at main port; *n4* network; no fare differentiation.

Performance indicator	0% express	25% express	50% express	75% express	100% express
Total cost	9175.37	9426.67	9619.72	9886.52	10204.87
Opening services cost	4567.5	4927.5	5175	5535	5940
# Open services (small)	5.7	11.7	15.6	19.4	21.6
# Open services (large)	7.3	5.1	3.7	2.6	2.4
Distance*Capacity usage (%)	70.17	69.59	68.27	65.37	61.97
Waiting at origin	469.05	431.4	388.9	335	282.85
Transshipment	1.60	4.15	3.4	0.7	0.7
Split standard (%)	27.82	38.02	47.06	48.00	48.83

Table 3
Varying customer categories, fare classes, decision processes - *n4* network.

Performance indicator	Decision-making policy	*R* only	$R+P$	$R+F$	$R+F+FareDiff$
Relative Yield	Fixed service	0.13	0.24	0.22	0.33
	Extra service	0.13	0.25	0.23	0.46
	Global service	0.13	0.29	0.26	0.51
# Open services (small)	Fixed service	5.7	5.7	5.7	5.7
	Extra service	5.7	7.2	9.5	11.7
	Global service	5.7	0.8	2.1	3.8
# Open services (large)	Fixed service	7.3	7.3	7.3	7.3
	Extra service	7.3	12.9	11.6	14.5
	Global service	7.3	15.6	15.3	17.5
Additional TEU	Fixed service	0	173.65	135.35	151
	Extra service	0	488.4	446.75	576.1
	Global service	0	503.25	480.75	577.55

mand network situation, profitability is higher when holding costs are paid, and then small services with less stops are used, instead of opening additional services. Indeed, waiting at origin is generated by the combined effect of standard and express demands which wait to be transported by the high number of small direct services concentrated at the main port, the one where express demands are concentrated as well. These higher values of waiting at origin may also be interpreted in correlation with the values of the *Distance*Capacity usage* PI. The latter shows a decrease in resource utilization, from 70.17% to 61.97%, which is less important than in the uniformly-distributed case; this is a direct indicator of a higher and better consolidation of flows.

Similar experiments were conducted on the other network topologies. The result tables are in Annex B of the Supplementary Material. The same general trends were observed in all cases. A few small differences may be observed, however, and we explain them in the following.

For the linear network, in contrast with the other topologies, little transshipment is needed when no express demand is to be served (Columns 0% express in Tables 1 and 2). Indeed, the optimal SSND-RRM solution for such a demand composition and particular topology opens services with large vehicles and several stops to accommodate standard demands within the standard delivery delays. This corresponds to a very low level of transshipment, due to the linearity of the network. Indeed, any service along the corridor which stops at each terminal may serve any demand. When express demands have to be accommodated, an increasing number of small, with less stops and thus faster, services are open. To accomplish optimality, many of the standard demands are then transshipped in order to take advantage of the empty space available on those open small direct services and some of the large services are consequently closed. The growing number of small direct services, implying more frequent services open on shorter distances, yields higher levels of consolidation and lower volumes of transshipped demands.

The role of consolidation is particularly enhanced when looking at the results corresponding to the *Star 6 (n6)* network (Tables 2 and 3, of the Supplementary Material), where the number of open services with large vessels in also getting higher with the increase of the proportion of express demands. This is due to the particular topology of the network, which presents a unique link between the two hubs, namely the segment [CD]. Since many OD demands have to pass on this particular physical link, an increasing number of large vehicle services is open, as the number of express demands increases. However, this is only true in the case where the express demands are uniformly distributed over the network. Indeed, when express demands are concentrated at a single terminal, the balance in demand is lost, and the central segment [CD] cannot play the same role any more.

We conclude the first part of the model-behavior analysis observing that, even though *express* customer requests consume more resources, one may take advantage of consolidation to increase profitability, provided transportation activities are organized and planned properly. The proposed SSND-RRM model offers the methodology to achieve that purpose. Yet, the results of the first series of experiments also show clearly that, irrespective of the type of network and distribution over that network of customers requiring a high level of service, providing high-quality services without fare differentiation results in low overall profitability for the company. We explore further the role of differentiation in customer categories and service levels next.

5.4. Model behavior - advanced version

The analysis of the role and impact on model and system behavior of fare differentiation, customer categories, and decision-making policies is the topic of this subsection. The definitions used for the first two elements in this phase of our numerical experimentation are stated in Section 5.4.1, while decision-making policies are presented in Section 5.4.2. Section 5.4.3 presents and analyses the results.

5.4.1. Customer categories & fare differentiation

We consider the typical resource-management situation when different fares are charged according to the customer request for service type, *express* and *standard* delivery in our case.

We consider a "complete" gamut of customer types with respect to the carrier-customer contractual agreements or understandings, or the lack thereof. Three categories are defined: Regular customers (*R*), *Partial-spot (P)* customers, for which the carrier has the possibility to decide how much (from nothing to all) demand to accept, and *Full-spot (F)* customers, for which the only possible decision is to accept, and transport all of their demand, or reject. The total volume of demand of spot customers (*P* and *F*) equals that of the regular (*R*) ones.

R and *P* customers request *standard* delivery, while *F* demands request *express* delivery. The fare ratio of *standard* to *express* delivery is 1:1.5. *Express* delivery requests are uniformly spread over the network. Four different cases of customer and fare combinations are defined:

- *R only*: basic configuration; only regular customers, no fare differentiation;
- *R + P*: mix of regular and partial-spot customers, no fare differentiation;
- *R + F*: mix of regular and full-spot customers, no fare differentiation;
- *R + F + FareDiff*: mix of regular and full-spot customers; fare differentiation between *standard* and *express* delivery demands.

5.4.2. Decision-making policies

Another important characteristic of the problem is how the carrier makes use of a tactical-planning SSND-RRM model to build up the operations plan for the next season. We aim to evaluate the potential gain, if any, of integrated planning, versus more defensive policies of considering only regular customers to build the plan and address the other customer categories at a latter moment. We thus examine three policies, with increasing flexibility in the service selection and the optimization of the system operations and resource utilization.

The first two represent two-step decision processes, where the traditional plan, based on regular customers only, is devised first. The plan is then adjusted to add the other customer-demand types in a second step. The third policy optimizes the system in an integrated way, in a single-step decision process. The three policies are described in more details in the following.

Fixed service: the most rigid policy solves first the SSND-RRM considering *R* customers only; the operations plan, i.e., the scheduled service network and resource utilization, is thus fixed (i.e., *open* and *closed* services are fixed); then, in a second step, the flow distribution is re-optimized considering all customer demands (*R, P*, or *F*) together; no new services may be added, no change is performed on the selected vessels either, but additional *P* or *F* customer demands may be accepted to fill up the residual capacities of the already selected vessels;

Extra service: the first step is the same as for the previous policy, considering *R* customers only, but additional services may be open; thus, the services selected in the first step are fixed (i.e., *open* services only are fixed); then, in a second step, the SSND-RRM is solved again, including regular and spot (*P* or *F*) customer demands; it is thus possible to select (and open) additional services, among those not selected initially; compared to the first policy, larger volumes of additional demand may thus be serviced, the demand flow distribution being re-optimized on the resulting larger service network;

Global service: the most flexible case corresponds to solving the SSND-RRM in a single step, with the objective of selecting the best profit-maximizing plan, integrating all customer-demand types, *R, P*, or *F*, simultaneously.

5.4.3. Results and analysis

Table 3 summarizes the results of the second wave of experiments, performed with the various combinations of customer categories, fare classes, and decision-making policies described above. These results measure the impact on system performance of differentiating customers and fares, in terms of profitability, resource utilization, and additional demand serviced, under the three levels of decision-making integration. Table 3 corresponds to the experiments performed on the *Linear 4* (*n4)* network. The experiments conducted on the other network topologies show the same trends; the result tables are in Annex C of the Supplementary Material.

A number of interesting observations may be made based on the results of the second wave of experiments.

First, considering several categories of customers and demands is always beneficial as underscored by the higher relative yields (consecutive to additional freight moved) of all cases with several customer categories compared to the *R only* situation.

Second, the possibility to accept less than the total demand of some spot customers is beneficial in all cases, as indicated by comparing the relative yield of the *R + P* case to those of the *R only* and *R + F* ones. This is not surprising because, in this situation, the carrier may accept additional demand and fill up the vessels for higher total revenue.

Third, fare differentiation is beneficial, as illustrated by the relative yield of *R + F + FareDiff* compared to the *R + F* and *R + P* cases. The former comparison involves the same problem setting except for the presence or absence of fare differentiation. The benefit is clear, the latter comparison indicates that higher profits may be attained by accepting demands bringing in more revenue per unit moved, even when one must accept and move all the demand, which might imply adding capacity to the system. This observation holds even in the case of a very strict decision-making process, e.g., *Fixed service*, when less additional freight (TEUs) is accepted, but each additional customer brings in more revenue.

Fourth, the decision-making process may have a marked consequence on performance. Indeed, planning flexibility and accounting in the initial tactical planning step for the estimated volume and type of spot demand is clearly beneficial, as indicated by the relative yield figures of the three policies over various problem settings. Providing flexibility is beneficial even when one desires to avoid committing too soon to calling on additional resources for estimated spot demand. A two-step decision process providing the possibility to add resources offers superior performance in terms of additional demand services and relative yield.

A final observation emerged from the experiments, enforcing the idea that optimization models and methods are required to achieve the best results, as not everything which appears profitable when considered individually, is profitable when the system is globally optimized. We set the basic fare for the regular customers to cover costs (to move one individual container) and be profitable, fares for spot customers and express service being higher (up to 1.5 times higher). One would then expect that, when there is sufficient capacity available to call upon, all the spot demand would be serviced, most of the time. This was not observed, however, even for the highest fares considered. Some individually-profitable demands were turned down as acceptance would have involved operating additional vessels with little loads. This observation reinforces the idea of customer and fare differentiation, and points to the need to correctly define those. This is beyond the scope of this paper but makes up an interesting research perspective.

The results of experimentation also illustrate the interest and value of including revenue management considerations into tactical planning, as well as the worth of flexible and adaptable planning models to propose highly profitable operation plans. The SSND-RRM modeling framework introduced in this paper presents these desirable characteristics and fulfills these goals.

6. Conclusions

We proposed in this paper what we believe to be the first comprehensive scheduled service network design model, targeting the tactical planning of intermodal consolidation-based freight transportation carriers, which integrates both revenue and resource management considerations. The model selects the services and schedule to be repeatedly operated over the next season, allocates, routes, and manages the main resources supporting the selected services, and routes the demand flows between their respective origins and destinations. The objective of the model is the maximization of the expected net revenue of the carrier when several customer categories, service types, and fare classes are considered.

The proposed *Scheduled Service Network Design with Resource and Revenue Management* modeling framework is general for the tactical planning of consolidation-based intermodal carriers operating on land, e.g., railroads and motor carriers, as well as on water, deep sea and coastal, river and canal navigation. We illustrate the problem setting and the modeling framework through an application to intermodal barge navigation, which has been largely neglected in the literature, in spite of its importance for intermodal transport in many regions on all continents.

Extensive experimentation has been carried on, using an off-the-shelf software to solve the corresponding mixed-integer linear programming formulation, on data and test instances based on the North of France and Belgium network and exchanges with the barge transportation industry of the region. The result analysis provided the means to assess behavior of the proposed formulation and the structural characteristics of the solutions obtained. It also provided a proof of concept of the proposed model and its capability for insightful analyses. We explored, in particular, the impact of various problem settings in terms of, e.g., demand distribution, network topology, customer categories, and fare and quality-of-service classes, on the structure of the scheduled service network and the carrier revenues. The results showed that customer, service, and fare differentiation have an important impact on the utilization of resources, the additional demand serviced, and increasing profitability.

Several research directions appear worthy of exploring. A first one relates to modeling more refined customer, service, and fare differentiation policies. These should be combined with the quest for models to set up these policies. Integrating into the problem setting and model more resource types and the corresponding operation rules makes up a second, complementary, research avenue. The third one is, clearly, integrating explicitly uncertainty on demand (regular and spot) and activity time (in port and while moving) into the tactical models.

Algorithmic developments for these formulations and large-size applications make up a very challenging research avenue. Tailored "exact" algorithms should be developed but the complexity of the problems at hand indicates that metaheuristics are needed as well. Matheuristics combining exact algorithmic components (e.g., column generation techniques to generate services and resource cycles) and metaheuristic concepts (e.g., activity-based decomposition and integrative parallel cooperative search) appears as the avenue to follow. We hope to share results on some of these challenging issues in the near future.

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Supplementary material

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