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Scheduled Service Network Design with Revenue Management Considerations for Intermodal Barge Transportation

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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 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.

Keywords: Scheduled service network design; revenue management; resource management; consolidation-based intermodal freight transportation; barge transportation.

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1 Introduction

Intermodal freight transportation is generally defined as moving cargo by a series of at least two transportation modes, being transferred from one mode to the next at intermodal terminals, e.g., ports and rail yards, without handling the cargo directly (Bektaş and Crainic, 2008; Crainic and Kim, 2007; SteadieSeifi et al., 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 network and schedule.

The *scheduled service network design* (*SSND*) problem class is the methodology of choice to build this tactical plan (Crainic and Hewitt, 2020). It selects the transportation services and schedule the carrier that will operate, and propose 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 et al., 2009a; Crainic et al., 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, 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 demands, 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-RM models.

Although identified as a desirable feature for freight transportation (van Riessen et al., 2015), RM is rather new to the freight transport planning literature, as illustrated by the reviews related to air cargo operations (Feng et al., 2015), railway transportation (Armstrong and 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 et al., 2015; Wang et al., 2015) focus on the operational level, the tactical level being rarely envisaged (Crevier et al., 2012).

Our goal is to contribute 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 perform this study within the context of intermodal barge transportation, a field relatively neglected in the literature. We thus present a *scheduled service network design with resource and revenue management* (*SSND-RRM*) model for the tactical planning of such carriers, and study its behavior and the structural characteristics of the solutions obtained through an extensive experimentation campaign.

The contributions of the paper are:

- Introduce what we believe to be the first comprehensive tactical planning model for freight carriers that integrates revenue (and resource) management considerations;
- 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 barge transportation, service network design for consolidation-based freight carriers, and revenue management. Bontekoning et al. (2004); Macharis and Bontekoning (2004); Crainic and Kim (2007); Bektaş and Crainic (2008)

and SteadieSeifi et al. (2014) offer general reviews on planning intermodal freight transportation systems, while Crainic and Hewitt (2020) synthesize service network design issues, models, and solution methods.

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 instrumental 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., Frémont and Franc, 2010; Caris et al., 2012; Zuidwijk, 2015). One may also mention within this group, the work of Konings et al. (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 the issues and research opportunities related to synchronodal container assignment to available transportation modes and carriers in the same context. The second group of contributions addresses mostly operational issues in ports (e.g. Taylor et al., 2005; Konings, 2007; Douma et al., 2011), and in routing and dispatching out of ports (e.g., Fazi et al., 2015; Braekers et al., 2013).

There is a rather rich literature on service network design for consolidation-based freight carriers (Crainic, 2000; Crainic and Hewitt, 2020), reviewed by, e.g., Crainic (2003) for long-haul transportation, Cordeau et al. (1998) for rail, Christiansen et al. (2004, 2007) for maritime, and Crainic and Kim (2007) for intermodal transportation. Scheduled service network design aims to generate the tactical operations plan for a consolidation-based freight carrier to, generally, minimize its costs or, more rarely, maximize revenues. The main decisions making up the models 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), and the optimization of the cargo flow distribution on the resulting network to satisfy the multi-commodity demand.

SSND with resource management models 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., Lai, M.F. and Lo, H.K., 2004; Armacost et al., 2002; Smilowitz et al., 2003), the SSND-RM problem was formally modeled by Pedersen et al. (2009) as a network design problem with *design-balance* constraints, 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. (2009b,a) and Crainic et al. (2014) who, among other contributions, model the time-dependency of decision 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.

We found only one publication addressing the tactical planning of an intermodal barge fleet (Sharypova et al., 2012). The authors propose a SSND-RM model for the particular case of direct services (no intermediate stops), unique customer and service types, a single container type, and two homogeneous vehicle fleets representing barges and trucks. 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. 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, as well as explicitly including revenue management aspects.

Indeed, none of these contributions found in the literature addressed 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. Thus, 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) also present a RM model applied to rail freight 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.

RM-related concepts are found in a number of tactical-planning studies for various transportation modes, e.g., the possibility not to service all the demand (Braekers et al., 2013; Andersen and Christiansen, 2009; Thapalia et al., 2012), the maximization of the

net revenue, and the possibility for demands to be only partially accepted (Teypez et al., 2010; Agarwal and Ergun, 2008; Gelareh and Pisinger, 2011), and the segmentation of the transportation requests according the obligation to service them (Stålhane et al., 2014).

In a recent review of research work in this field, Tawfik and Limbourg (2018) cite some of the very few studies regarding tactical and operational aspects of RM applied in an intermodal transportation context, namely Bilegan et al. (2015), van Riessen et al. (2015), and Wang et al. (2016), some of which are directly related to barge transportation.

We did not find, however, contributions integrating scheduled service network design, resource management and revenue management. We propose such an 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. The *tactical plan* thus determines the transportation services and schedule, together with the assignment of resources to the selected services, that the carrier will operate for the next cycle of activities, the next “season” (six months, for example), to answer this demand. The transportation plan actually specifies how operations are to be performed for a given time length, e.g., a week, that we call *schedule length*. The plan is then operated repeatedly for the duration of the season.

We therefore describe the problem we address along three dimensions. For the first dimension, we focus on the physical network and resources of a barge/coastal navigation carrier performing intermodal transportation, including the port infrastructure and facilities, 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 address these requirements over a medium-term, tactical planning horizon. The challenges and aims related to the representation of RM activities into the scheduled service network design with resource management formulation (detailed in Section 4) are discussed at 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). 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 and price requirements 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 a given 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 forecast (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 customers 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 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 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 in the system we study.

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 demand estimations may be made individually for major and regular customers, most demands represent an aggregation of regular and 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 period (i.e., the time 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, tariff and operation classes. The first category is the regular demand as discussed above. Two other categories correspond to demand that is potentially there and that

the carrier could 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 et al., 1993; Powell, W.B. and Topaloglu, H., 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 an SSND-RRM formulation comes from the required qualitative and quantitative translation of the business relationship the carrier holds with its customers into a compact representation adequate for the aggregated tactical level. This translation is logically performed in terms of demand characterization, starting with customer behavior (segmentation) considerations, but also including service-level (delivery delays) requirements.

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 demand 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 the cost of operating the vehicles and the cost associated to using the fixed resources and transporting the cargo, given the level of service and the mix of fare classes offered (remark that service differentiation was considered in a number of earlier contributions, e.g., Crainic et al., 1984; Crainic and Rousseau, 1986; Crainic and Roy, 1988, 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, e.g., is it profitable to increase the level of service in terms of service frequencies or capacities, resulting in higher fixed and variable costs, in order to attract more, higher-priced, demand? Are the current or contemplated differentiated customer categories, and fare classes with their associated values 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 predefined 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, and the notation $d \in \mathcal{D}$ will denote 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, and customers present on the spot market that 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 set, $\mathcal{D} = \mathcal{D}^R \cup \mathcal{D}^P \cup \mathcal{D}^F$, as follows:

- *Regular* customer demands, grouped within set \mathcal{D}^R , representing customers with long-term contracts or understandings; This class corresponds to the regular demand in classical SSND formulations and must be always satisfied;
- *Proportional-punctual* customer demands, set \mathcal{D}^P , that 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-punctual* demands, set \mathcal{D}^F , consisting of demands that 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 types are defined with respect to the service requirement dimension of the proposed mechanism, *slow/normal* and *fast* delivery reflecting the due times at destination requested by customers. Fares normally reflect service differentiation, e.g., fast delivery requests would be priced higher than slow delivery ones. We consequently introduce two *fare classes*:

- $class(d)$: Fare class for demand $d \in \mathcal{D}$, related to the type of delivery, *slow/normal* or *fast* requested;
- $f(d)$: Unit fare value for demand $d \in \mathcal{D}$ with fare class $class(d)$.

4.2 Network modeling

Let the oriented graph $\mathcal{G}^{\text{ph}} = (\mathcal{N}^{\text{ph}}, \mathcal{A}^{\text{ph}})$ represent the *physical network* supporting the operations of the carrier. The set \mathcal{N}^{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}^{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, and the notation $\gamma \in \Gamma$ will denote 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 demand d 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 $d \in \mathcal{D}^R$ or \mathcal{D}^P or \mathcal{D}^F ;
- $class(d)$: Fare class, *slow/normal* or *fast*;
- $f(d)$: 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:

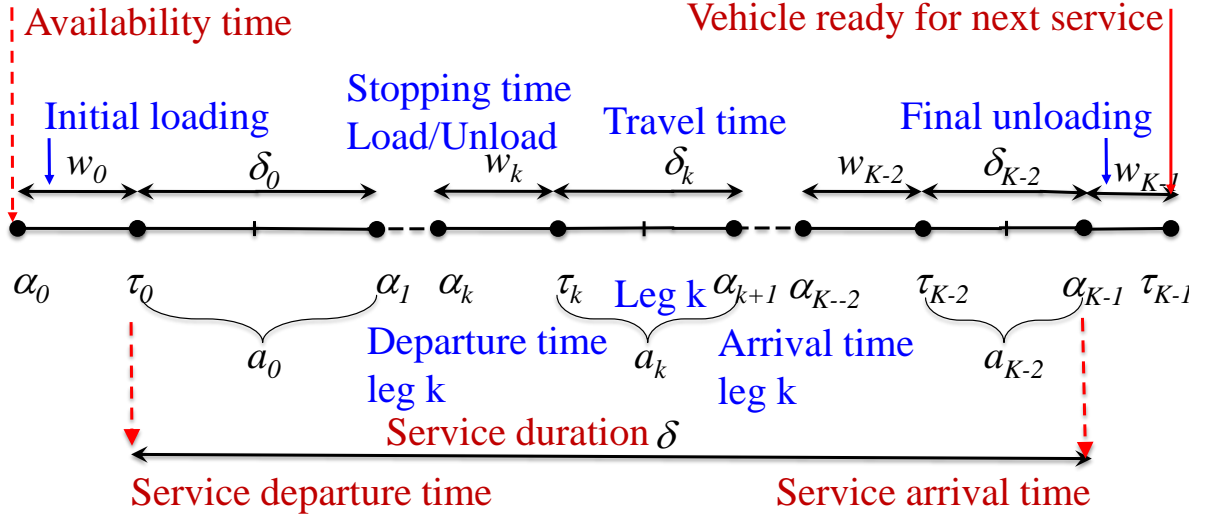
- $cap(l)$: Capacity in TEUs;
- $speed(l)$: Speed of vessel of type $l \in \mathcal{L}$ in normal operations, yielding $\delta_{ij}(l)$, the normal travel time of an l type vessel over arc $(i, j) \in \mathcal{A}^{ph}$;
- B_l : Maximum number of vessels of type $l \in \mathcal{L}$ available.

The formulation is defined on a circular time-space network capturing the time-dependency and repetitiveness of the demand and schedule (services and resource utilization), taking the form of an oriented graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, with node and arc sets \mathcal{N} and \mathcal{A} , respectively. The network (and the 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 Figures 1 and 2, and described as follows:

- $orig(s)$: Physical origin terminal, $orig(s) \in \mathcal{N}^{ph}$;
- $dest(s)$: Physical destination terminal, $dest(s) \in \mathcal{N}^{ph}$;
- $\eta(s) = \{i_k(s) \in \mathcal{N}^{ph}, k = 0, \dots, (K - 1)\}$: Ordered set of consecutive stops of the service, where $K = |\eta(s)|$ and k indicates the k^{th} stop of the service;


 Figure 1: Time-related attributes of service s

- $a_k(s) = (i_k(s), i_{k+1}(s))$: 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 service s to load at the origin terminal, i.e., $w_0(s) = \tau_0(s) - \alpha_0(s)$;
 $\alpha_{K-1}(s)$: Arrival time at destination;
- $\tau_k(s)$: Departure time of the service from its terminal

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

$\tau_{K-1}(s)$: Time at destination when the vessel is completely unloaded and ready for the next service, i.e., $w_{K-1}(s) = \tau_{K-1}(s) - \alpha_{K-1}(s)$ (by convention);

- $\delta(s) = \alpha_{K-1}(s) - \tau_0(s)$: 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.

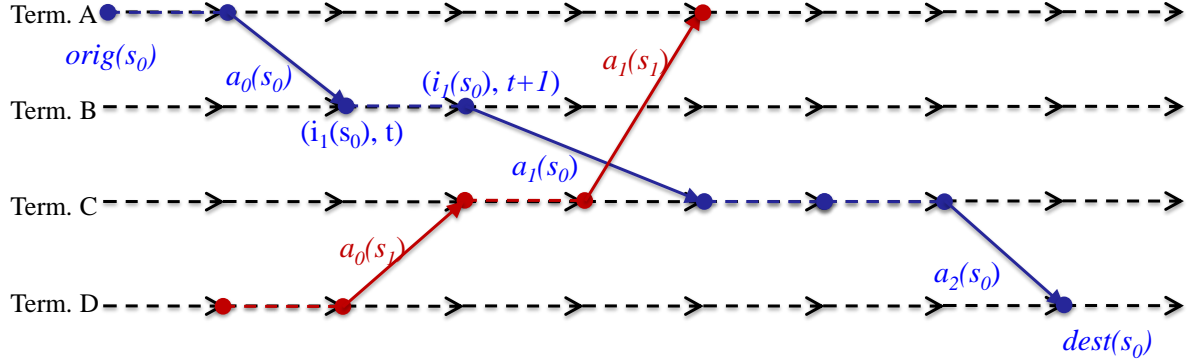


Figure 2: Time-space representation of the service network with two services

Figure 1 illustrates the time-related attributes of a multi-leg service. Figure 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) $d \in \mathcal{D}^P$ that is selected and will be serviced;

- $\zeta(d) \in \{0, 1\} = 1$ if the demand $d \in \mathcal{D}^F$ is selected to be serviced, 0, otherwise;
- $z(l, i, t)$ = Number of temporarily idle vessels of type l at terminal i , waiting the period $(t, t + 1)$ out for the departure of the next service it supports;
- $v(l)$: Total number of vessels of type l used by the service plan; Due to the circular nature of the schedule, $v(l)$ 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:

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

Subject to

$$x^{hold}(d, orig(d), in(d)) + \sum_{s \in \mathcal{S}: i_k(s) = orig(d), \tau_k(s) = in(d)} x^{in}(d, s, k) = \begin{cases} vol(d), & \forall d \in \mathcal{D}^R \\ \xi(d)vol(d), & \forall d \in \mathcal{D}^P \\ \zeta(d)vol(d), & \forall d \in \mathcal{D}^F \end{cases} \tag{3}$$

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

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

$$\forall (i, t) \neq (orig(d), in(d)), \forall i \neq dest(d), \forall d \in \mathcal{D}$$

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

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

$$x(d, s, k - 1) - x^{out}(d, s, k - 1) + x^{in}(d, s, k) - x(d, s, k) = 0, \quad (8)$$

$$\forall s \in \mathcal{S}, i_k(s) \neq orig(s), i_k(s) \neq dest(d), d \in \mathcal{D}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 proportional-punctual customers, and the complete demand of the selected and full-punctual 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 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.

Equations (3), (4) and (5) are flow-conservation constraints for containers of all customer types, at their particular origins, destinations, and intermediary nodes, respectively. Similarly, Equations (6), (7) and (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.

Equation (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 $\Lambda_{0l} = \{s \in S, l(s) = l | (\alpha_{K-1}(s) \bmod T) < \tau_0(s) \text{ and } \tau_0(s) \geq 0\} \subseteq \mathcal{S}$ 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 Equations (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}^+

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

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

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 fast 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 to answer the two categories of research questions. The set of test instances used was gradually enriched throughout experiments by introducing additional characteristics to the problems to solve. 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 *fast* and *slow* 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 in 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 in the expected and reasonable way. We also used a computer simulation framework to project tactical optimal decisions onto simulated operations, and thus assess tactical decision impacts on the exploitation of the system.

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 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. Finally, the proof-of-concept and validation framework are briefly presented in Section 5.5.

5.1 Test instances

The SSND 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) Linear network, corresponding to common type corridors with four terminals, named *Linear 4* (n_4); 2) 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; named *General 7 (n7)*. These three configurations are illustrated in Figure 3.

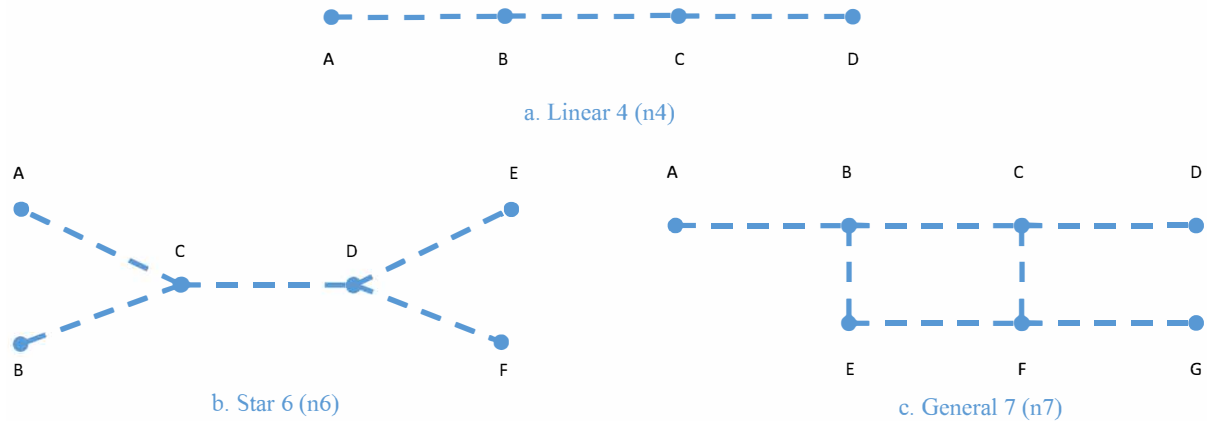


Figure 3: The physical network topologies considered for the SSND-RRM model validation

The fleet of vehicles operated by the carrier is assumed to include two types of vessels, with large and small capacities, respectively. The large vessels are set to offer 2.5 times more capacity than the small ones, with the fixed cost of operating large vessels set at around twice that of small vessels. 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). Briefly, 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 appears 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). 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 R versus P/F customers characterized 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 *fast*, versus *slow*, demand within this total. Different *fare classes* are associated to different delivery types. A *low fare* corresponds to *slow* delivery, while a *high fare* is associated with *fast* delivery. R customers may require *slow* or *fast* delivery (the choice is governed by a *fare ratio*, a parameter for the instance), while P and F customers require *slow* and *fast* 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, in the 6 tables, so 600 in total for Section 5.3; 80 instances per table, solved each 3 times, for each decision-making policy, so 240 instances and 720 problems solved for the 3 tables of 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, 3GHz and 30 GB of RAM. The computational effort required to address the NP-Hare SSND-RM 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 this demand, and the number of periods in the time discretization of the schedule length. The impact of network topology is less noticeable.

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 or not, holding containers, transporting and handling containers) costs;
- **Service cost:** Total fixed cost corresponding to 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;
- **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 (Equation (25))

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

- **Waiting at origin:** Volume-weighted sum of demand waiting times at origins;
- **Transshipment:** Volume-weighted sum of demand waiting times at intermediate stops;
- **Split slow:** Ratio of total volume of *slow* demand split among several itineraries with respect to the total *slow* demand;
- **Additional TEU:** Total volume of P or F customer demands accepted for transportation.

5.3 Model behavior

We analyze in this subsection experiments 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. *Slow* and *fast* 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 *fast* service. The origins of *fast* demands were uniformly distributed over the network in the first case; Results on the n_4 networks are summarized in Table 1. For the second set of experiments, demands were assumed to accumulate in a single *main* terminal (e.g., the one with the highest throughput) where each originates or terminates; Table 2 displays the results of these experiments on the n_4 networks. The values in both tables are averages over 20 different instances for different proportions of customers requiring *fast* delivery, columns *No fast* and *100% fast* providing the lower and upper bounds on the total cost, respectively. No profit-related performance indicators are used to evaluate results in these experiments, because the same regular customers, paying the same fee, are considered in all cases.

Table 1: *Fast* demand uniform distribution; n_4 network; no fare differentiation

Performance indicator	0% fast	25% fast	50% fast	75% fast	100% fast
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
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 slow (%)	27.82	43.46	48.92	56.68	NA

The results obtained when the customers requiring *fast* delivery are uniformly distributed over a linear network (Table 1) confirm that more services are needed, at a higher total cost, as the volume of fast demand increases. The results also show that the number of selected small vessels providing direct service increases with the proportion of fast demands; by almost five times when only fast customers are present compared to the no-fast-customer case. This trend may be explained by the double benefit direct services operated by small-capacity vessels brings 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 and may thus leave more rapidly (waiting of demand at origins decreases steadily - (*Waiting at origin* PI) than large vessels, with somewhat lower unused capacity levels. The prevalence of direct services is reflected in the progressive reduction in the volumes transferred (*Transshipment* PI). Thus, as demand for fast service grows, so does the number of appropriate 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 *fast* delivery demands, other demands, have to be delayed. Moreover, the percentage of *slow* split among services increases with the volume of *fast* demands (*Split slow* PI). The latter 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 loaded the *fast* demands.

Table 2: *Fast* demand concentrated at main port; n_4 network; no fare differentiation

Performance indicator	0% fast	25% fast	50% fast	75% fast	100% fast
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 slow (%)	27.82	38.02	47.06	48.00	48.83

Similar trends are observed when customers require *fast* transport out of or to a single (main) terminal, while *slow* 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 that less services selected and less vessels used. This results into a higher system performance as measured by higher capacity usage levels and lower total costs.

Similar experiments were conducted on the other network topologies. The same trends

were observed in all cases. Hence, for the sake of brevity, we do not repeat them. The result tables are in Annex B.

We conclude the first part of the model-behavior analysis observing that, even though *fast* 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 the high-quality service, providing high-quality service 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 in this phase of our numerical experimentation are stated in Section 5.4.1, while decision policies are presented in 5.4.2. Section 5.4.3 presents and analysis 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, *fast* and normal, called *slow*, 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 types 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 demand to accept, and *Full-spot* (F) customers, for which the only possible decision is to accept, and transport all, or reject. The total volume of the two types of spot customers equals that of the regular ones.

R and P customers request *slow* delivery, while F demands request *fast* delivery. The fare ratio of *slow* to *fast* delivery is 1:1.5. *Fast* 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 *slow* and *fast* service demands.

5.4.2 Decision-making policies

Another important characteristic of the problem is how the carrier makes use of a tactical-planning SSND-RM 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 types 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 for the other customer-demand types in a second step. The third policies optimizes the system in an integrated way. In more details,

Fixed service The most rigid policy solves the SSND-RM considering R only. The operation plan, i.e., the scheduled service network and resource utilization, is than fixed (i.e., *open* and *closed* services are fixed) and the flow distribution is re-optimized considering all customer demands R , P and F together; No new services may be added, no change is performed on the selected vessels either, but additional P or F demand may be accepted to fill up the residual capacity of the selected vessels;

Extra service The first step is the same as for the first, but additional services may be added. Thus, the services selected in the first step are fixed, and the SSND-RM is solved again with the full customer demand and the possibility to select additional services among those not selected initially. Larger volumes of additional P or F demand may thus be serviced, the distribution all demands being optimized on the resulting larger service network;

Global service The most flexible case, it corresponds to solving the SSND-RM once only once, with the objective is to select the best profit-maximizing plan, considering all demands, R , P and F , simultaneously.

5.4.3 Results and analysis

Table 3 summarizes the results of the second wage of experiments, performed with various combinations of the customers categories, fare classes, and decision-making policies de-

scribed above. These results measure the impact of differentiating customers and fares on system performance, in terms of profitability, resource utilization, and additional demand services, under the three levels of decision-making integration. Table 3 corresponds to the experiments performed on the *Linear 4* (n_4) networks. The experiments conducted on the other network topologies show the same trends; The result tables are in Annex C.

Table 3: Varying customer categories, fare classes, decision processes - n_4 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

A number of interesting observations may be made based on the results for 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 *only R* 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 *only R* 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 clearly 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 indeed 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 fast 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-RM modeling framework introduced in this paper presents these desirable characteristics and fulfills these goals.

5.5 A simulation-based proof of concept

We complete the proof of concept of Sections 5.3 and 5.4 of the capability of the proposed SSND-RM model to provide profitable operations plans and valuable managerial insights, with a short discussion of the results of a simulation-based experiment.

The experiment is part of a research effort aiming to develop a decision-support tool for freight intermodal transportation, when revenue management is implemented at the operational decision level of the carrier and is reflected in its tactical-planning method (Wang et al., 2018). The overall objective of the future decision-support tool is to simulate the behavior of the consolidation-based system under various scenarios with respect to the presence or absence of atactical-planning model, various customer categories, fare classes, decision-making processes, demand-prediction method, and customer behavior. A first prototype was used to complete the proof of concept of the SSND-RM model we propose, through an impact study on tactical plans on system profits during operations.

Recall that the goal at the tactical level is to build service and resource-utilization plans and schedules that maximize revenue, while satisfying in the best manner possible the forecast demands of regular and spot customers. Once the service plan is fixed, the operational level decision is to accept or reject transportation demands, at the time the request is made or shortly after. This decision aims to contribute to the long-term global maximization of the shipper's profit. It is based on an optimal predictive routing for the request, based on the customer category, urgency of the request and the associated fare class, as well as a look-ahead prediction on the impact of acceptance could have on the capability of the system to respond to future requests. When a SSND-RM model is used to produce tactical operations plans, the predictive routing and its impact on future system capabilities is to be performed within the guidelines of the plan, in particular, the service and schedule network in operations together with the resources (vessels) assigned to perform the operations.

The simulation framework includes two models at the tactical level, the SSND-RM model propose in this paper, and a somewhat more traditional, without revenue-management considerations, formulation. The latter is the SSND model obtained by dropping the RM decision variables and constraints from the SSND-RM formulation. The capacity-allocation method of (2016) is used to make accept/reject decisions at the operational level, given the service network and schedule provided by tactical planning. Transportation requests arrive at the carrier's booking system in randomly and sequentially. The accept/reject decision for a specific request is made based on the impact of the predictive optimal routing of the demand given the predicted future demands and the residual capacity of the vessels. The same probability distribution is used for demand forecast at both levels, individually at the operational level, aggregated at the tactical one. Communication between the two levels takes place in both directions: service plans and schedules from the tactical to the operational level; aggregated data, e.g., customer behavior, in terms of numbers and characteristics of observed customer categories, service class, volume of demand, and resulting fare (accounting, e.g., for the anticipation level of requests, that is, how early or late the demand is presented before the requested transport), from the operational to the tactical level for adjustment of parameters for the next round of planning.

The customer categories, service types, and fare classes used in the experiments described in the previous subsections were also used here. The scenarios studied included the presence of the SSND-RM or traditional SSND models at the tactical level, different proportions of regular versus spot customers, as well as different levels of prediction accuracy. Notice that the latter also stands for the degree of contract fulfillment of regular customers (are the planned containers at the origin port when agreed upon?).

The experimental results completed the proof of concept. The results show that, according to all performance indicators of Section 5.2, the proposed SSND-RRM model generates more efficient decisions, in terms of net profit and resource utilization, compared to traditional decision-support methods without revenue management considerations.

The introduction of RM concepts at the tactical level improves the interaction between the two levels of decision making for the intermodal barge transportation case-study analyzed. It is observed that taking into consideration the proportion and behavior of regular and spot customers has an important and quantifiable effect on the profits of a carrier, as a consequence of better resource management and more reactive to the market dynamics, opportunistic, and profitable offer of service.

6 Conclusions

In this paper, we proposed what we believe to be the first comprehensive scheduled service network design model targeting the tactical planning of intermodal consolidation-based freight transportation carriers that integrates both revenue and resource management considerations. The model 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, service types, and fare classes are considered.

Extensive experimentation, on data from an intermodal barge freight transport case, provide a proof-of-concept of the proposed model and its capability for insightful analyses, by using an off-the-shelf software to solve the corresponding mixed-integer linear programming formulation. 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 has an important impact on the utilization of resources, the additional demand serviced, and higher 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. Metaheuristics 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 challenges issues in the near future.

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References

- Agarwal, R. and Ergun, O. (2008). Ship scheduling and network design for cargo routing in linear shipping. *Transportation Science*, 42(2):175–196.
- Andersen, J. and Christiansen, M. (2009). Designing new European rail freight services. *Journal of the Operational Research Society*, 60(March):348–360.
- Andersen, J., Crainic, T.G., and Christiansen, M. (2009a). Service network design with asset management: Formulations and comparative analyzes. *Transportation Research Part C: New Technologies*, 17(2):397–207.
- Andersen, J., Crainic, T.G., and Christiansen, M. (2009b). Service network design with management and coordination of multiple fleets. *European Journal of Operational Research*, 193(2):377–389.
- Armacost, A.P., Barnhart, C., and Ware, K.A. (2002). Composite variable formulations for express shipment service network design. *Transportation Science*, 36(1):1–20.
- Armstrong, A. and Meissner, J. (2010). Railway revenue management: Overview and models. Technical report, The Department of Management Science, Lancaster University.
- Bektaş, T. and Crainic, T.G. (2008). A brief overview of intermodal transportation. In Taylor, G.D., editor, *Logistics Engineering Handbook*, chapter 28, pages 1–16. Taylor and Francis Group, Boca Raton, FL, USA.

- Bilegan, I.C., Brotcorne, L., Feillet, D., and Hayel, Y. (2015). Revenue Management for Rail container Transportation. *EURO Journal on Transportation and Logistics*, 4(2):261–283.
- Bontekoning, Y., Macharis, C., and Trip, J. (2004). Is a new applied transportation research field emerging? - A review of intermodal rail-truck freight transport literature. *Transportation Research Part A: Policy and Practice*, 38(1):1–34.
- Braekers, K., Caris, A., and Janssens, G.K. (2013). Optimal shipping routes and vessel size for intermodal barge transport with empty container repositioning. *Computers in Industry*, 64(2):155–164.
- Caris, A., Macharis, C., and Janssens, G.K. (2012). Corridor network design in hinterland transportation systems. *Flexible Services and Manufacturing Journal*, 24(3):294–391.
- Christiansen, M., Fagerholt, K., Nygreen, B., and Ronen, D. (2007). Maritime transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, pages 189–284. North-Holland, Amsterdam.
- Christiansen, M., Fagerholt, K., and Ronen, D. (2004). Ship routing and scheduling: Status and perspectives. *Transportation Science*, 38(1):1–18.
- Cordeau, J.-F., Toth, P., and Vigo, D. (1998). A survey of optimization models for train routing and scheduling. *Transportation Science*, 32(4):380–404.
- Crainic, T.G. (2000). Service network design in freight transportation. *European Journal of Operational Research*, 122(2):272–288.
- Crainic, T.G. (2003). Long-haul freight transportation. In Hall, R.W., editor, *Handbook of Transportation Science*, pages 451–516. Kluwer Academic Publishers, Norwell, MA, second edition.
- Crainic, T.G., Ferland, J.-A., and Rousseau, J.-M. (1984). A tactical planning model for rail freight transportation. *Transportation Science*, 18(2):165–184.
- Crainic, T.G., Gendreau, M., and Dejax, P.J. (1993). Dynamic stochastic models for the allocation of empty containers. *Operations Research*, 41(1):102–126.
- Crainic, T.G. and Hewitt, M. (2020). Network Design with Applications in Transportation and Logistics. In Crainic, T.G., Gendreau, M., and Gendron, B., editors, *Network Design with Applications in Transportation and Logistics*, chapter 12. Springer, Boston. forthcoming.
- Crainic, T.G., Hewitt, M., Toulouse, M., and Vu, D.M. (2014). Service network design with resource constraints. *Transportation Science*, 50(4):1380–1393.

- Crainic, T.G. and Kim, K.H. (2007). Intermodal transportation. In Barnhart, C. and Laporte, G., editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, chapter 8, pages 467–537. North-Holland, Amsterdam.
- Crainic, T.G. and Rousseau, J.-M. (1986). Multicommodity, multimode freight transportation: A general modeling and algorithmic framework for the service network design problem. *Transportation Research Part B: Methodological*, 20:225–242.
- Crainic, T.G. and Roy, J. (1988). O.R. tools for tactical freight transportation planning. *European Journal of Operational Research*, 33(3):290–297.
- Crevier, B., Cordeau, J.-F., and Savard, G. (2012). Integrated operations planning and revenue management for rail freight transportation. *Transportation Research Part B: Methodological*, 46(1):100–119.
- Douma, A., Schuur, P., and Jage, R. (2011). Degrees of terminal cooperativeness and the efficiency of the barge handling process. *Expert Systems with Applications*, 38(4):3580–3589.
- European Commission (2011). White paper 2011: Roadmap to a single European transport area - Towards a competitive and resource-efficient transport system. Technical report, Directorate for Mobility and Transport, European Commission.
- Fazi, S., Fransoo, J.C., and van Woensel, T. (2015). A decision support system tool for the transportation by barge of import containers: A case study. *Decision Support Systems*, 79:33–45.
- Feng, B., Li, Y., and Shen, Z.-J. (2015). Air cargo operations: Literature review and comparison with practices. *Transportation Research Part C: Emerging Technologies*, 56:263–280.
- Frémont, A. and Franc, P. (2010). Hinterland transportation in Europe: Combined transport versus road transport. *Journal of Transport Geography*, 18(4):548–556.
- Gelareh, S. and Pisinger, D. (2011). Fleet deployment, network design and hub location of liner shipping companies. *Transportation Research Part E: Logistics and Transportation Review*, 47(6):947–964.
- Kasilingam, R. (1997). Air cargo revenue management: Characteristics and complexities. *European Journal of Operational Research*, 96(1):36–44.
- Konings, R. (2007). Opportunities to improve container barge handling in the port of Rotterdam from a transport network perspective. *Journal of Transport Geography*, 15(6):443–454.
- Konings, R., Kreutzberger, E., and Maraš, V. (2013). Major considerations in developing a hub-and-spoke network to improve the cost performance of container barge transport

- in the hinterland: The case of the port of Rotterdam. *Journal of Transport Geography*, 29:63–73.
- Lai, M.F. and Lo, H.K. (2004). Ferry service network design: Optimal fleet size, routing and scheduling. *Transportation Research Part A: Policy and Practice*, 38:305–328.
- Macharis, C. and Bontekoning, Y.M. (2004). Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research*, 153(2):400–416.
- Notteboom, T. (2012). Challenges for container river services on the Yangtze river: A case study for Chongqing. *Research in Transportation Economics*, 35(1):41–49.
- Pedersen, M.B., Crainic, T.G., and Madsen, O.B.G. (2009). Models and tabu search meta-heuristics for service network design with asset-balance requirements. *Transportation Science*, 43(2):158–177.
- Powell, W.B. and Topaloglu, H. (2005). Fleet management. In Wallace, S. and Ziemba, W., editors, *Applications of Stochastic Programming*, Math Programming Society - SIAM Series on Optimization, pages 185–216. SIAM, Philadelphia, PA.
- Sharypova, M.B., Crainic, T.G., van Woensel, T., and J.C., F. (2012). Scheduled service network design with synchronization and transshipment constraints for intermodal container transportation networks. Publication CIRRELT-2012-77, Centre interuniversitaire de recherche sur les réseaux d’entreprise, la logistique et le transport, Montréal, QC, Canada.
- Smilowitz, K.R., Atamtürk, A., and Daganzo, C.F. (2003). Deferred item and vehicle routing within integrated networks. *Transportation Research Part E: Logistics and Transportation*, 39:305–323.
- Stålhane, M., Andersson, H., Christiansen, M., and Fagerholt, K. (2014). Vendor managed inventory in tramp shipping. *Omega*, 47:60–72.
- StadieSeifi, M., Dellaert, N., Nuijten, W., van Woensel, T., and Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233(1):1–15.
- Tawfik, C. and Limbourg, S. (2018). Pricing problems in intermodal freight transport: Research Overview and Prospects. *Sustainability*, 10(9):3341.
- Taylor, G.D., Whyte, T.C., DePuy, G.W., and Drosos, D.J. (2005). A simulation-based software system for barge dispatching and boat assignment in inland waterways. *Simulation Modelling Practice and Theory*, 13(7):550–565.
- Teypez, N., Schrenk, S., and Cung, V.-D. (2010). A decomposition scheme for large-scale service network design with asset management. *Transportation Research Part E: Logistics and Transportation Review*, 46(1):156–170.

- Thapalia, B.K., Wallace, S.W., Kaut, M., and Crainic, T.G. (2012). Single source single-commodity stochastic network design. *Computational Management Science*, 9(1):139–160.
- van Riessen, B., Negenborn, R., and Dekker, R. (2015). Synchromodal container transportation: An overview of current topics and research opportunities. In *Computational Logistics*, pages 386–397. Springer.
- Wang, S., Wang, H., and Meng, Q. (2015). Itinerary provision and pricing in container liner shipping revenue management. *Transportation Research Part E: Logistics and Transportation Review*, 77:135–146.
- Wang, Y., Bilegan, I.C., Crainic, T.G., and Artiba, A. (2014). Performance indicators for planning intermodal barge transportation systems. *Transportation Research Procedia*, 3(0):621–630.
- Wang, Y., Bilegan, I.C., Crainic, T.G., and Artiba, A. (2016). A Revenue Management Approach for Network Capacity Allocation of an Intermodal Barge Transportation System. In Paias, A. and Ruthmair, M. and Voß, S., editor, *Computational Logistics*, volume 9855 of *Lecture Notes in Computer Science*, pages 243–257. Springer.
- Wang, Y., Bilegan, I.C., Crainic, T.G., and Duvivier, D. (2018). A reactive decision support system for freight intermodal transportation: a Revenue Management perspective. In *Book of Abstracts Odysseus 2018 - Seventh International Workshop on Freight Transportation and Logistics, June 3-8, 2018, Cagliari, Italy*, pages 286–289. accessed August 11, 2020, <https://convegni.unica.it/odysseus2018/files/2018/06/BookOfAbstracts2.pdf>.
- Zuidwijk, R. (2015). Are we connected? ERIM Inaugural Address Series Research in Management.

Annexes

Annex A - Computational efficiency

The MILP optimization problems were solved with the commercial solver IBM CPLEX 12.8, on a multi-processor server running under Linux 64-bit with an Inter Xeon X5675, 3GHz and 30 GB of RAM. The results are displayed in Table 4 for the three network types,

The computational-performance experiment was performed on the three network types of Section 5.1, *Linear*, *Star*, and *General*. The (average) results are arrayed following that sequence of network topology, with four lines for each topology, corresponding to increasingly higher numbers of services and demands. The $|\mathcal{N}^{ph}|$, $|\mathcal{S}|$, $|\mathcal{D}|$ and $|\mathcal{D}^F|$ columns indicate the number of terminals, potential services, total demands, and F demands, respectively. The size of each instance is given by columns $\# DVs$ and $\# Constraints$ for the numbers of decision variables and constraints, respectively. The corresponding CPU time to the optimum is given in the last column.

Table 4: Computational performance

Test instance	$ \mathcal{N}^{ph} $	$ \mathcal{S} $	$ \mathcal{D} $	$ \mathcal{D}^F $	$\# DVs$	$\# Constraints$	CPU time
1	4	616	12	3.9	2965.9	3176.9	0.16
2	4	616	24	6.6	6801.1	6416.9	0.78
3	4	616	36	13	9934.2	9157.1	2.66
4	4	616	48	16.3	12487.5	11431	5.06
5	6	1848	30	9.3	16531.3	15454.1	4.84
6	6	1848	60	19.6	33419.6	29526.9	142.86
7	6	1848	90	29.7	46291.6	40306.2	1316.23
8	6	1848	120	43.3	61883.5	53260.7	21366.74
9	7	4200	42	12.3	52976.7	48201	7.32
10	7	4200	84	31	108042.7	92926.2	93.37
11	7	4200	126	43.6	157114.9	133473.7	2823.11
12	7	4200	168	54.9	208361	176273	16723.59

As expected, the SSND-RM problem is NP-Hard, the computational efforts increases considerably with the number of demands (commodities) and, thus, the number of potential services. The time discretization of the schedule length also plays an important relative to the computational effort.

Annex B - Experiment I - Result tables for star and general networks

This annex presents the result tables of the model-behavior set of experiments described in Section 5.3. Test instances contain regular customers only. *Slow* and *fast* delivery types are considered 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 *fast* service. The origins of *fast* demands are uniformly distributed over the network in the first case; Demands are assumed to accumulate in a single main terminal (e.g., the one with the highest throughput) where each demand originates or terminates, in the second case. The values all tables are averages over 20 different instances for different proportions of customers requiring *fast* delivery, columns *No fast* and *100% fast* providing the lower and upper bounds on the total cost, respectively.

Tables 5 and 6 illustrate the results for the *Star 6 (n6)* network configuration for the two cases, respectively. Tables 7 and 8 display the results for the *General 7 (n7)* network topology.

Table 5: *Fast* demands uniform distribution; *n6* network; no fare differentiation

Performance indicator	0% fast	25% fast	50% fast	75% fast	100% fast
Total cost	20594.80	21469.37	22727.00	24180.60	25889.55
Opening services cost	10811.25	11418.75	12510.00	14175.00	15975.00
# Open services (small)	20.65	26.95	33.70	37.50	39.60
# Open services (large)	13.70	11.90	10.95	12.75	15.70
Distance*Capacity usage (%)	83.09	80.83	74.72	66.53	58.37
Waiting at origin	110.7	81	68.1	27.8	2.15
Transshipment	187.75	170.22	109.35	48.35	3.35
Split slow (%)	33.49	39.79	44.22	45.49	NA

Annex C - Experiment II - Result tables for star and general networks

Tables 9 and 10 summarize the results of the second wage of experiments for the *Star 6* and *General 7* network topologies, respectively. Recall that these experiments were performed with various combinations of the customers categories, fare classes, and decision-making policies described at Section 5.4.

Table 6: *Fast* demands concentrated at main port; *n6* network; no fare differentiation

Performance indicator	0% fast	25% fast	50% fast	75% fast	100% fast
Total cost	20594.80	20958.70	21510.75	22076.65	22783.55
Opening services cost	10811.25	11002.50	11463.75	11936.25	12757.50
# Open services (small)	20.65	23.40	25.85	26.75	30.60
# Open services (large)	13.70	12.75	12.55	13.15	13.05
Distance*Capacity usage (%)	83.09	82.25	80.32	77.20	73.35
Waiting at origin	110.7	108.9	84.1	75.45	65.8
Transshipment	187.75	191.85	180.8	173.05	126.7
Split slow (%)	33.49	38.38	37.39	37.35	40.26

Table 7: *Fast* demands uniform distribution; *n7* network; no fare differentiation

Performance indicator	0% fast	25% fast	50% fast	75% fast	100% fast
Total cost	22134.75	23129.78	23939.00	24967.10	26461.80
Opening services cost	10552.50	11643.75	12521.25	13995.00	15873.75
# Open services (small)	13.20	30.65	39.65	47.1	53.25
# Open services (large)	16.85	10.55	8	7.55	8.65
Distance*Capacity usage (%)	77.91	76.43	73.11	66.62	58.83
Waiting at origin	64.1	59.5	58	32.51	5.85
Transshipment	209.9	153.5	144.8	67	9.95
Split slow (%)	33.36	48.91	56.5	59.33	NA

Table 8: *Fast* demands concentrated at main port; *n7* network; no fare differentiation

Performance indicator	no fast	25% fast	50% fast	75% fast	100% fast
Total cost	22134.75	22596.10	23018.00	23394.95	23879.40
Opening services cost	10552.50	11002.50	11418.75	11857.50	12465.00
# Open services (small)	13.20	21.1	24.25	30.2	34.9
# Open services (large)	16.85	13.9	13.25	11.25	10.25
Distance*Capacity usage (%)	77.91	76.97	75.84	74.31	71.64
Waiting at origin	64.1	71.35	84.75	88.45	64.35
Transshipment	209.9	192.65	187.25	137.4	138.65
Split slow (%)	33.36	40.14	40.92	44.94	43.31

Table 9: Varying customer categories, fare classes, decision processes - $n6$ network

Performance indicator	Decision-making policy	R only	R+P	R+F no price	R+F with price
Relative Yield	Fixed service	0.14	0.25	0.22	0.31
	Extra service	0.14	0.26	0.23	0.46
	fix no service	0.14	0.30	0.27	0.52
# Open services (small)	Fixed service	20.65	20.65	20.65	20.65
	Extra service	20.65	25.10	29.15	38.95
	Global service	20.65	9.9	14.55	20.10
# Open services (large)	Fixed service	13.70	13.70	13.70	13.70
	Extra service	13.70	25.80	23.55	27.00
	Global service	13.70	32.45	31.30	34.05
Additional TEU	Fixed service	0	310.25	233.35	246.65
	Extra service	0	1033.05	933.75	1191.1
	Global service	0	1063.2	1034.7	1210.7

Table 10: Varying customer categories, fare classes, decision processes - $n7$ network
emphn7

Performance indicator	Decision-making policy	R only	R+P	R+F no price	R+F with price
Relative Yield	Fixed service	0.29	0.40	0.38	0.49
	Extra service	0.29	0.39	0.37	0.64
	Global service	0.29	0.42	0.39	0.68
# Open services (small)	Fixed service	13.20	13.20	13.20	13.20
	Extra service	13.20	15.50	21.25	31.90
	Global service	13.20	1.9	8.70	13.10
# Open services (large)	Fixed service	16.85	16.85	16.85	16.85
	Extra service	16.85	34.55	31.45	32.65
	Global service	16.85	39.55	37.6	40.2
Additional TEU	Fixed service	0	386.6	337	372.45
	Extra service	0	1411.95	1308.75	1487.5
	Global service	0	1406.45	1346.75	1489.4