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Service Design Models for Rail Intermodal Transportation

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Abstract. Intermodal transportation forms the backbone of the world trade and exhibits significant growth resulting in modifications to the structure of maritime and land-based transportation systems, as well as in the increase of the volume and value of intermodal traffic moved by each individual mode. Railroads play an important role within the intermodal chain. Their own interests and environment-conscious public policy have railroads aiming to increase their market share. To address the challenge of efficiently competing with trucking in offering customers timely, flexible, and "low"-cost transportation services, railroads propose new types of services and enhanced performances. From an Operations Research point of view, this requires that models be revisited and appropriate methods be devised. The paper discusses some of these issues and developments focusing on tactical planning issues and identifies challenging and promising research directions.

Keywords. Intermodal transportation, freight rail carriers, tactical planning, full-asset utilization policies, intermodal shuttle networks, design-balanced service network design.

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1 Introduction

Intermodal transportation forms the backbone of the world trade and exhibits significant growth. The value of multimodal shipments in the U.S., including parcel, postal service, courier, truck-and-rail, truck-and-water, and rail-and-water, increased from about 662 billion US dollars to about 1.1 trillion in a period of nine years (1993 to 2003 [31]). In the same period, the total annual world container traffic grew from some 113.2 millions of TEUs (20 feet equivalent container units) to almost 255 millions, reaching an estimated 304 millions of TEUs by 2005.

Intermodal transportation involves, sometimes integrates, at least two modes and services of transportation to improve the efficiency of the door-to-door distribution process. The growth in intermodal traffic thus resulted in significant modifications to the structure of maritime and land-based transportation systems as well as in major increase of the volumes and value of intermodal traffic moved by each individual mode. Thus, for example, in 2003, for the first time ever, intermodal freight surpassed coal as a source of revenue for major, Class I, U.S. railroads, representing 23% of the carriers' gross revenue [31]. The growth of intermodal rail traffic in the U.S., which reached 11 million trailers (26% of total) and containers (76%) in 2004, is the direct result of the rapid growth in the use of containers for international trade, imports accounting for the majority of the intermodal activity [31].

Governmental policy may also contribute to re-structuring intermodal transportation and shifting parts of the land part of the journey from trucking toward rail and water (interior and coastal navigation). This is, for example, the main focus of the European Union as stated in its 2001 White Paper on transportation [20]. The reason for this is to reduce road congestion and promote environmentally friendlier modes of transportation. The instruments favored to implement such policies vary from road taxes to penalize truck-based transportation to the support of new rail services for intermodal traffic.

The performance of intermodal transportation depends directly on the performance of the key individual elements of the chain, navigation companies, railroads, motor carriers, ports, etc., as well as on the quality of their interactions regarding operations, information, and decisions. The Intelligent Transportation Systems and Internet-fueled electronic business technologies provide the framework to address the latter challenges. Regarding the former, carriers and terminals, on their own or in collaboration, strive to continuously improve their performance. Railroads are no exception. Indeed, for intermodal as for general traffic, railroads face significant challenges to efficiently compete with trucking in offering customers timely, flexible, and "low"-cost, long-haul transportation services.

Railroads are rising to the challenge by proposing new types of services and enhanced performances. Thus, North-American railroads have created intermodal subdivisions that operate so-called "land-bridges" providing efficient container transportation by long, double-stack trains between the East and the West coasts and between these ports and the industrial core of the continent (so-called “mini” land-bridges). Most North-American railroads are now enforcing some form of scheduled service. In Europe, where congestion has long forced the scheduling of trains, the separation of the infrastructure ownership from service providing increases the competition and favors the emergence of new carriers and services. Moreover, the expansion of the Community to the east provides the opportunity to introduce new services that avoid the over-congested parts of the European network. New container and trailer-dedicated shuttle-train networks are thus being created within the European Community.

The planning and management processes of these new railroad-based intermodal systems and operations are generally no different from those of “traditional” systems in terms of issues and goals, profitability, efficiency, and customer satisfaction. The “new” operating policies introduce, however, elements and requirements into the planning processes which, from an Operations Research point of view, require that models be revisited and appropriate methods be devised.

This paper aims to discuss some of these issues and developments. It focuses on the tactical planning of rail intermodal services in North America and Europe and is based on a number of observations and on-going projects. Its goal is to be informative, point to challenges, and identify opportunities for research aimed at both methodological developments and actual applications.

2 Intermodal and Rail-based Transportation

Many transportation systems are multimodal, their infrastructure supporting various transportation modes, such as truck, rail, air, and ocean/river navigation, carriers operating and offering transportation services on these modes. Then, broadly defined, intermodal transportation refers to the transportation of people or freight from their origin to their destination by a sequence of at least two transportation modes. Transfers from one mode to the other are performed at intermodal terminals, which may be a sea port or an in-land terminal, e.g., rail yards, river ports, airports, etc. Although both people and freight can be transported using an intermodal chain, in this paper, we focus on the latter.

The fundamental idea of intermodal transportation is to consolidate loads for efficient long-haul transportation performed by large ocean vessels and, on land, mostly by rail and truck. Local pick-up and delivery is usually performed by truck. Most of the freight intermodal transportation is performed by using containers. Intermodal transportation is not restricted, however, to containers and intercontinental exchanges. For instance, the transportation of express and regular mail is intermodal, involving air and land long-haul

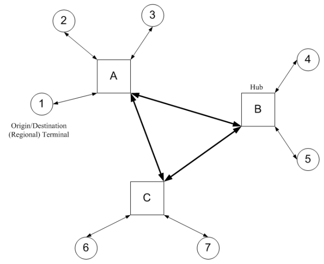


Figure 1: A Hub-and-Spoke Network [7]

transportation by rail or truck, as well as local pick up and delivery operations by truck [16]. Moving trailers on rail is also identified as intermodal. In this paper, we focus on container and trailer-based transportation by railroads.

Intermodal transportation systems and railroads may be described as being based on consolidation. A consolidation transportation system is structured as a hub-and-spoke network, where shipments for a number of origin-destination points may be transferred via intermediate consolidation facilities, or hubs, such as airports, seaport container terminals, rail yards, truck break-bulk terminals, and intermodal platforms. An example of such a network with three hubs and seven regional terminals is illustrated in Figure 1 [7]. In hub-and-spoke networks, low-volume demands are first moved from their origins to a hub where traffic is sorted (classified) and grouped (consolidated). The aggregated traffic is then moved in between hubs by efficient, “high” frequency and capacity, services. Loads are then transferred to their destination points from the hubs by lower frequency services often utilizing smaller vehicles. When the level of demand is sufficiently high, direct services may be run between a hub and a regional terminal.

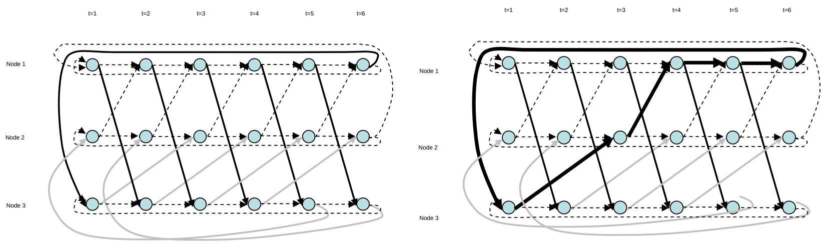
Railroads operate most of their services according to a double-consolidation policy based on a series of activities taking place at rail hubs, the so-called classification or marshaling yards. The first consolidation activity concerns the sorting and grouping of railcars into blocks. A block is thus made up of cars of possibly different origins and destinations, which travel as a single unit between the origin and destination of the block. Consequently, the only operation that could be performed on a block at a yard which is not its destination is to transfer it from one service to another. The second consolidation activity taking place at yards, known as train make up, concerns the grouping of blocks into trains. Although a hub-and-spoke network structure results in a more efficient utilization of resources and lower costs for shippers, it also incurs a higher amount of delays and a lower reliability due to longer routes and the additional operations performed at terminals. Carriers thus face a number of issues and challenges in providing services that are simultaneously profitable and efficient for the firm and high quality and cost effective for customers. Operations Research has contributed a rich set of models and methods to assist addressing these issues and challenges at all levels of planning and management, classically identified as strategic (long term), tactical (medium term), and operational (short term). A more in-depth treatment of these topics may be found, for example, in the reviews of Cordeau, Toth, and Vigo [11], Crainic [12, 13], Crainic and Laporte [17], and Crainic and Kim [16]. In this paper, we focus on tactical planning issues.

3 New Rail Intermodal Services

Rail transportations systems evolved according to the geographic, demographic, economic, and sociological characteristics of the countries and continents they belong to. North American and European railroads were no exception. Yet, recently, a number of similar trends emerge. Traditional North American railroad operating policies were based on long-term contracts for the transportation of high volumes of mostly bulk commodities. Cost per ton/mile (or km) was the main performance measure, with somewhat little attention being paid to delivery performance. Consequently, rail services in North America, and mostly everywhere else in the world, were organized around loose schedules, indicative cut-off times for customers, "go-when-full" operating policies, and significant marshaling activities in yards. This resulted in rather long and unreliable trip times that generated both inefficient asset utilization and loss of market share. This was not appropriate for the requirements of intermodal transportation and the North American rail industry responded through [14]:

1. A significant re-structuring of the industry through a series of mergers, acquisitions, and alliances which, although far from being over, has already drastically reduced the number of companies resulting in a restricted number of major players.
2. The creation of separate divisions to address the needs of intermodal traffic, operating dedicated fleets of cars and engines, and marshaling facilities (even when located within regular yards). Double-stack convoys have created the land-bridges that ensure an efficient container movement across North America.
3. An evolution toward planned and scheduled modes of operation and the introduction of booking systems and full-asset-utilization operating policies.

Booking systems bring intermodal rail freight services closer to the usual mode of operation of passenger services by any regular mode of transportation, train, bus, or air. In this context, each class of customers or origin-destination market has a certain space allocated on the train and customers are required to call in advance and reserve the space they require. The process may be phone or Internet based but is generally automatic, even though some negotiations may occur when the train requested by the



Service Network

Vehicle Circuit

Figure 2: Full-Asset-Utilization-Based Service Network and Vehicle Circuit [3]

customer is no longer available. This new approach to operating intermodal rail services brings advantages for the carrier, in terms of operating costs and asset utilization, and the customers (once they get used to the new operating mode) in terms of increased reliability, regular and predictable service and, eventually, better price. A full-asset-utilization operation policy generally corresponds to operating regular and cyclically-scheduled services with fixed composition. In other words, given a specific frequency (daily or every given number of days), each service occurrence operates a train of the same capacity (length, number of cars, tonnage) and composition, that is, the same blocks make up all the occurrences of the service, each block displaying a fixed definition: origin, destination, number of total cars, and number of cars for each origin-destination included in its composition.

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Assets, engines, rail cars and even crews, assigned to a system based on full-asset-utilization operation policies can then “turn” continuously following circular routes and schedules (which include maintenance activities for vehicles and rest periods for crews) in the time-space service network, as schematically illustrated in Figure 2 for a system with three yards and six time periods [3]. The solid lines in the service-network (left) part of Figure 2 represent services. There is one service from node 1 to node 3 (black arcs) and one service from node 3 to node 2 (gray arcs), both with daily frequency. Dotted arcs indicate repositioning moves (between different nodes) and holding arcs (between different time representations of same node). One feasible vehicle circuit in the time-space service network is illustrated in the right part of Figure 2. The vehicle operates the service from node 3 to node 2, starting in time period 1 and arriving in time period 3. Then from period 3 to period 4 the vehicle is repositioned to node 1, where it is held for two time periods. In period 6 the vehicle operates the service from node 1 to node 3, arriving at time 1 where the same pattern of movements starts all over again. The planning of systems operating according to such policies requires the development of new models and methods, as described in the next section.

Most Western Europe railroads have for a long time now operated their freight trains according to strict schedules, similarly to their passenger trains. This facilitated both the interaction of passenger and freight trains and the quality of service offered to customers. Particular characteristics of infrastructure (e.g., low overpasses and infrastructure for electric traction) and territory (short inter-station distances) make for shorter trains than in North America and forbid double-stack trains. Booking systems are, however, being implemented and full-asset-utilization and revenue management operating policies are being contemplated. Moreover, intermodal shuttle-service networks are being implemented in several regions of the European Union to address the requirements of the European Commission policy and the congested state of the infrastructure (e.g., [1, 27]).

Indeed, European railroads face a number of particular challenges. First, the rail infrastructure, as almost the entire transportation infrastructure in Europe, is very congested. Second, the liberalization of the rail industry in Europe has led to the separation of the traditional national rail companies into infrastructure owners and service operators. The former manage the infrastructure and associated network capacity, while the latter operate trains according to the capacity acquired from the infrastructure managers. This liberalization favors the emergence of new rail operators providing specialized services, in particular intermodal rail shuttle services between cities with high traffic demand.

The limited capacity of most of the infrastructure, at least in the western part of the network, together with the increasing number of operators, forces the allocation of capacity according to pre-defined routes and times, which makes planning decisions and the efficient utilization of resources more difficult. The European Union, the member states, and the corresponding rail authorities are implementing steps, however, toward interoperability and an interconnected trans-European rail network for freight trains, the so-called freight freeways [19]. As a result, one assists at the emergence of large service networks across the European continent operated by single operators or by alliances of operators, similar to those seen in the airline industry. The resulting service networks will be complex to plan and operate and appropriate models and methods must be developed. Pedersen and Crainic [27] detail the case and propose a first service network design model.

To alleviate the congestion in the "central" part of the network while working toward the goal of increasing the market share of rail and navigation, new intermodal services are being studied using the networks of countries that have recently joined the Union. Andersen and Christiansen [1] describe such a project. The Longchain Polcorridor study [24] aims to develop a new intermodal transport corridor between Northern and South-Eastern Europe taking advantage of previously unused railway capacity in Poland, the

Czech Republic and Austria, and thus create a fast and reliable transport solution than can compete with the more traditional route through Germany. The authors propose a formulation to determine an optimal service level and design that accounts for both operating costs and a number of service quality criteria. An extensive network of inland waterways, sea transport, trucking services, and other railway lines will be used as distribution networks at the extremities of the new network. This requires external synchronization of schedules with partner carriers. Internal synchronization is also required to account for power-equipment switching at particular borders due to different technical standards between participating national railroads. Andersen, Crainic, and Christiansen [3] propose formulations for this case.

4 Impact on Planning Models

A study of the trends observed in North America and Europe, illustrated by the cases mentioned in the previous section, indicates a number of converging issues. One may sum up these issues by noticing that the operations and asset management of intermodal railroads are more and more similar to those of long-haul passenger transportation, airlines and fast rail, in particular. Services are thus precisely scheduled and service space is booked in advance. Moreover, schedules are repetitive (cyclic) and synchronized, both internally among the railroad's own services and externally with those of partner carriers. This implies tighter consolidation, classification, transfer, and make-up operations at terminals, as well as scheduling assets for maximum but efficient utilization.

Traditionally, planning was performed through a series of tasks, planning models being used one after another to address particular issues: design of the service network and schedules, power (locomotive) assignment and management, empty railcar repositioning and fleet management, and so on. This approach was not particular to railroads or freight transportation; it was typical of the traditional management structure and planning processes of most industrial firms facing complex issues. From an Operations Research point of view, it reflected the limitations of our capabilities in addressing large-scale combinatorial formulations with complex additional constraints. Managerial structures evolve, however, and our capabilities are continuously being enhanced, both in terms of computer power and methodology sophistication. The trend toward integrated models addressing in a comprehensive formulation several issues previously treated separately, initially observed within the airline industry (e.g., [5]) is now influencing the development of planning methods for railroad operations, most particularly within the field of intermodal transport.

To briefly illustrate these issues and the corresponding challenges, we turn to service network design in the context of full-asset-utilization operating policies. We conclude the section by identifying a number of other "new" planning issues offering exiting research perspectives.

4.1 Service Network Design

Recall that service network design is concerned with the planning of operations related to the selection, routing, and scheduling of services, the consolidation and make-up activities at terminals, and the routing of freight of each particular demand through the physical and service network of the company (see, for example, the surveys of Crainic for service network design [12] and long-haul land transportation [13], Crainic and Kim [16] and Macharis and Bontekoning [25] for intermodal transportation, Christiansen *et al.* [10, 9] for maritime navigation, and Cordeau, Toth, and Vigo [11] for railroads. These activities are a part of tactical planning at a system-wide level. The two main types of decisions considered in service network design address the determination of the service network and the routing of demand. In the railroad context, the former refers to selecting the train routes and attributes, such as the frequency or the schedule of each service. The latter is concerned with the itineraries that specify how to move the flow of each demand, including the services and terminals used, the operations performed at these terminals, etc. The objective is generally concerned with the minimization of a global measure of the performance of the system that includes the operating costs of providing services, performing yard operations, and moving freight, as well as service-quality measures usually based on delays to equipment and loads. The term "generalized cost" is often used in these cases.

The basic service network design mathematical models take the form of deterministic, fixed cost, capacitated, multicommodity network design (CMND) formulations [26, 12, 16]. Let $\mathcal{S}$ represent the service network, defined on a graph representing the physical infrastructure of the system (yards, stations, and the rail links connecting them), which specifies the transportation services that could be offered. Each potential service $s \in \mathcal{S}$ is characterized by a number of attributes such as its route, capacity measured in number of vehicles, length, total weight, or a combination thereof, service class indicating the speed and priority, as well as, eventually power type, preferred traffic or restrictions, etc. When schedules are to be determined, a time-space network $\mathcal{G} = \{\mathcal{N}, \mathcal{A}\}$ is introduced (see Figure 2). Nodes representing the terminals (yards and stations) of the system are repeated at all periods (e.g., days) of the considered planning horizon (e.g., a week) yielding the set $\mathcal{N}$. Nodes in $\mathcal{N}$ representing the same terminal at two consecutive time periods are connected by holding arcs, and departure times from origin, as well as arrival at and departure times from intermediary stops are associated to each service. Set $\mathcal{A}$ is then the union of the holding and service arcs. The service network is used to move commodities $p \in \mathcal{P}$ defined by their origins, destinations, the period of availability at origin and, eventually the due date at destination, the type of product or vehicle to be used, priority class, and so on. The demand for product p is denoted d_p. Traffic moves according to itineraries defined within the model as service paths $l \in \mathcal{L}^p$ for commodity

p, each specifying the intermediary terminals where operations (e.g., consolidation or transfer) are to be performed and the sequence of services between each pair of consecutive terminals where work is performed.

Flow routing decisions are then represented by decision variables h_l^p indicating the volume of product p moved using its itinerary $l \in \mathcal{L}^p$, and *service selection* decision variables y_s, $s \in \mathcal{S}$, define whether the particular service is operated (i.e., it will leave at the associated departure time) or not. Let $y = \{y_s\}$ and $h = \{h_l^p\}$ be the decision-variable vectors. Let also f_s denote the "fixed" cost of operating service s and c_l^p stand for the unit transportation cost along itinerary $l \in \mathcal{L}^p$ of commodity p. The core service network design model minimizes the total generalized system cost, while satisfying the demand for transportation and the service standards:

$$\text{Minimize} \quad \sum_{s \in \mathcal{S}} f_s y_s + \sum_{p \in \mathcal{P}} \sum_{l \in \mathcal{L}^p} c_l^p h_l^p + \phi(y,h) \tag{1}$$

$$\text{subject to} \quad \sum_{l \in \mathcal{L}^p} h_l^p = d_p, \quad p \in \mathcal{P}, \tag{2}$$

$$y_s \in \{0,1\}, \quad s \in \mathcal{S}, \tag{3}$$

$$h_l^p \geq 0, \quad l \in \mathcal{L}^p,\ p \in \mathcal{P}, \tag{4}$$

$$(y,h) \in \chi, \tag{5}$$

where $\phi(y,h)$ indicates additional restrictions, e.g., service capacity, expressed as utilization targets, which may be allowed to be violated at the expense of additional penalty costs. Relations 5 stand for the classical linking constraints (i.e., no flow may use an unselected service), as well as for additional constraints reflecting particular characteristics, requirements, restrictions, and policies (e.g., particular routing or load-to-service assignment rules) particular to the carrier considered in application.

The class of models represented by the previous formulation does not account for the utilization of assets. Yet, to adequately plan operations according to a full-asset-utilization operating policy requires the asset circulation issue to be integrated into the service network design model. Adding constraints enforcing the conservation of the flow of vehicles at terminals is the first step in reaching this goal. These constraints take the form

$$\sum_{s \in \mathcal{S}} y_{si^+} - \sum_{s \in \mathcal{S}} y_{si^-} = 0, \quad i \in \mathcal{N}, \tag{6}$$

where si^+ indicates the services that arrive and stop or terminate at node (yard) $i \in \mathcal{N}$, while si^- stands, symmetrically, for the services that initiate their journeys or stop and depart from node i. The resulting models, denoted *design-balanced capacitated multi-commodity network design* (DBCMND) by Pedersen, Crainic, and Madsen [28], account for coherent movements in and out of terminals (particularly when"empty" movements are allowed) and yield cyclic and repetitive schedules for the fleet of vehicles associated to services.

This generalization of the CMND model has not been studied much. A few applications may be found in planning maritime liner [9] or ferry [22] routes and express postal services, e.g., [6, 21], where vehicles, ships and airplanes, have high acquisition and utilization costs and their management is central to the efficient operation of the system. For land-based carriers, while empty-vehicle considerations were usually part of the most comprehensive service network design models, the emphasis was not on the management of the fleet. Thus, for example, Powell [29] considered the balance of loaded and empty truck balance at terminals in a static model for designing Less-Than-Truckload motor-carrier services that did not consider vehicle schedules. For rail, Crainic, Ferland, and Rousseau [15] (see also [18]) addressed the issue by adding a product to represent the demand for empty-car repositioning movements. The model was static and no asset schedule or route considerations were explicitly included. More recently, Smilowitz, Atamtrk, and Daganzo [30] developed a time-dependent formulation similar to the one presented above for truck operations within an express postal network and proposed a particularly tailored procedure where, first, the linear programming relaxation of the problem is solved (approximately, for large problem instances) using column generation and, second, a feasible solution is obtained by applying repetitively a sequence of rounding and cut-generation procedures.

The DBCMND is a difficult problem with an added "complexity layer" compared to the CMND and much work is required to study it and develop efficient exact and heuristic solution methods. A few efforts are under way. Pedersen and Crainic [27] studied the design of a network of shuttle intermodal trains in Europe using a DBCMND model that included detailed yard operations (excluding car classification). The resulting formulation was sufficiently small, however, to allow commercial software to be used. Pedersen, Crainic, and Madsen [28] introduced arc and cycle-based DBCMND formulations and proposed a two-stage, tabu search-based meta-heuristic that is shown to be efficient for problem instances up to 700 service arcs and 400 commodities. Andersen, Crainic, and Christiansen [3] extended the arc-based formulation to account for coordination of multiple fleets and synchronization of schedules among subsystems. The analysis was performed within the scope of the design of new north-south intermodal services in Central Europe and emphasized the benefit of increased inter-system integration and coordination. The same authors also studied various DBCMND formulations, where product flows were represented either by arc or path variables, while design decisions were represented either by arcs or cycle variables [2]. Notice that the latter correspond to circuits of vehicles, the service selection (design) decisions becoming thus implicit in the selection of strategies for fleet management. Commercial software was used for experimentation and results showed a very good computational behavior for cycle-based formulations in terms of computational efficiency and quality of the final solution (when the optimal solution could not be reached within the time available). Recently, Andersen *et al.* [4] proposed a first branch-and-price algorithm for the generic cycle-based DBCMND formulation.

The contributions briefly reviewed above are very encouraging, but significant work is still required on models, algorithms, and applications. Regarding models, we need to better understand the DBCMND class of formulations and their properties. Initial results seem to indicate that cycle-based formulations outperform arc-based ones, but more in-depth studies are required to fully characterize the various formulations and explain their respective behaviors. Work is also required in developing tighter lower and upper bounds on the optimal solution to these formulations. Lagrangean relaxation and decomposition approaches have provided interesting results for other classes of network design problems and are worthy of investigation in developing good lower bounds for DBCMND problems. Using the solutions of lower bound methods to compute "good" upper bounds proved difficult for CMND problems and we expect it to present an even greater challenge for DBCMND problems for which identifying feasible solutions is proving to be far from trivial [28].

Turning to applications, stating a DBCMND formulation is generally only the first step to a complete model. Actual railroad planning applications bring a rich set of additional constraints that add both to the realism and the complexity of the formulation. Pedersen and Crainic [27] thus discussed the need for a more general definition of "period" within time-dependent formulations to capture adequately the time intervals when services overlap at terminals and inter-service transfers may be performed. The authors also emphasized the need for a more detailed representation of terminal operations than it is usually the case in service network design models to capture their delay and capacity impacts on the general performance of the system. This aspect is also emphasized by Andersen, Crainic, and Christiansen [3] who detailed the operations in terminals connecting the system studied to adjacent maritime and land systems, and presented a first quantification of the benefits of synchronizing services both internally, among services using possibly different vehicle fleets, and externally with services belonging to neighboring systems. The authors also examined and quantified the impact of a number of fleet-management considerations, such as limits on the length of vehicle routes and bounds on the number of departures for particular services. One need to follow up on these early efforts by focusing on two main areas. One the one hand, the study of integrating fleet management and service network design must be continued to identify relevant issues and the most appropriate modeling approaches, and to analyze their impact on the resulting transportation plan and, ultimately, on the performance of the rail system. On the other hand, the models must be enriched to account for other important planning issues, such as congestion related to yard (and, eventually, line) operations and the management of more than one class of assets.

Last but not least, significant algorithmic work is required. The methods proposed so far addressed simple model formulations and have often been tested on problem instances that do not cover the full dimensions of actual large-scale applications. Both exact and meta-heuristic solution methods must be developed for the models described above. Given the dimensions and complexity (e.g., in the number of interacting and possibly conflicting components) of these formulations, we expect parallel optimization approaches to play an important role in addressing real-life applications.

4.2 Additional issues

Many other issues related to the planning and operations of intermodal and, more generally, consolidation-based freight transportation offer rich research challenges and opportunities.

Consider, for example, that, although bookings tend to “smooth” out demand, the variability inherent to the system is not altogether eliminated since regular operations tend to be disrupted by a number of phenomena. Thus, for example, ocean liner ships do not always arrive at container port terminals according to schedule and custom and security verifications may significantly delay the release of containers. When this occurs, rail intermodal operations out of the corresponding ports are severely strained: there might be several days without arrivals, followed by a large turnout of arriving containers. Optimization approaches [14] may be used to adjust service over a medium-term horizon in such a way that a full-asset-utilization policy is still enforced, but a certain amount of flexibility is added to services to better fit service and demand. Such approaches may become even more effective when appropriate information sharing and container-release time mechanisms are implemented.

Among the other relevant challenging research issues, let’s not forget the explicit consideration of stochastic elements in tactical planning models. Preliminary results [23] indicate that the plans thus obtained are different and “better” from a robustness point of view than those of traditional deterministic models, but much more work is needed in this field. Terminal planning issues also require attention. While the literature dedicated to container port terminals is rather rich, there is almost nothing dedicated to rail yards within the intermodal context (the work by Bostel and Dejax [8] is the only exception we are aware of and it is directed toward an innovative but as yet not implemented rail transportation system). On a more operational level, work is required relative to detailed fleet management procedures to mitigate the impact of incidents and accidents on service and to guide the process of getting back to normal operations following such disruptions.

5 Conclusions

We have discussed a number of service and operating strategies railroads propose to improve the performance of their operations, increase their market share of intermodal traffic, and efficiently compete with trucking in offering customers timely, flexible, and "low"-cost transportation services. This evolution, including the advance bookings and full-asset-utilization policies increasingly implemented by existing and planned railroad intermodal systems, challenges current models and methods for the design of services and the management of operations. Focusing on tactical planning issues, we have briefly examined these impacts and have identified research challenges and opportunities.

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