Blocking and Railcar Fleet Management for Intermodal Rail Transportation

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1 INTRODUCTION AND PROBLEM DESCRIPTION

Railroads offer a cost-effective and eco-friendly way to transport large volumes of diverse goods across long distances. As a key element of worldwide intermodal transportation, they have shown consistent growth in traffic. To ensure railroad activities are efficient and profitable, careful planning of operations and resources is essential. These planning processes are complex, largely because of the interplay between the system's core components and objectives, such as trains, blocks of cars, profitability, resource usage and customer satisfaction.

Railroad operations rely on three planning levels: strategic (long-term decisions such as equipment acquisitions, fleet composition adjustments, network improvements and rule modifications), tactical (medium-term decisions related mainly to the routing of predicted goods), and operational (short-term responses to unexpected events). We focus on making a tactical plan for intermodal rail traffic that also has the ability to give strategic insights. The intermodal market consists in moving containers that are placed onto different types of railcars made of one to several platforms of different sizes. Responsible for holding priority shipments and goods that are moved by multiple modes of transportation (e.g., international shipments that can also be transported by trucks or boats), intermodal containers come in different sizes and railroads are themselves responsible for assigning and loading them onto the appropriate railcars (i.e., made of platforms of a fitting length) to enable them to travel through the rail network.

Whereas there is a body of literature on railway optimization problems, the literature focusing on network planning problems for intermodal traffic is relatively limited. Morganti *et al.* (2020) is closest to our work. They focus on a tactical planning Service Network Design (SND) model that addresses simultaneously the loading and blocking problems for intermodal rail. Important for transporting the demands to their destinations in a cost-effective way, the blocking problem consists in devising a plan that dictates the blocks (group of railcars that travel together as a single unit for a section of their trip) to build at each terminal, their routes in the service network and the assignment of railcars to blocks. As such, the work of Morganti *et al.* (2020) consists in proposing a plan for transporting the demands throughout the railway network and selecting the blocks while taking into account three consolidation processes: containers to railcars, railcars to blocks and blocks to scheduled train services. However, they do not address the management of a limited heterogeneous railcar fleet, which consists in giving instructions on where and when to send different types of loaded and empty railcars so that the demands can be transported.

In this work, we focus on the tactical planning of intermodal railroad operations and introduce the *Intermodal Railroad Blocking and Railcar Fleet-Management* (*IBRM*) problem. Taking the basic train schedule as given by the railroad, we aim to build an economically and customer-service efficient plan, by considering simultaneously the selection of extra train services, the loading of containers on railcars, the blocking of loaded and empty railcars, the selection of blocks, the distribution of demand flows through this service network, and the management of the railcar fleet. The plan is built for a cyclic schedule of given length (e.g., a week), to be repeatedly executed over the tactical-planning horizon (e.g., a season).

We propose a *Scheduled Service Network Design with Resource Management* (*SSND-RM*) model (Crainic & Hewitt, 2021) to address this particularly challenging problem. The SSND-RM model takes the form of an integer linear program based on a cyclic four-layer space-time network representation (namely, the container, car, block and train layers). This approach enables the use of a continuous-time network representation, where the time structure is defined by the arrival and departure times of the train services considered at the terminals on their respective routes. By applying, prior to solving, an exact iterative variable fixing scheme to find a good warm start solution to the problem, this model is directly solvable by a commercial solver and provides good solutions in a reasonable amount of time on real large-scale networks.

Our contributions are summarized as follows: First, we introduce a new problem for intermodal railway traffic that encompasses the blocking problem, the management of a limited heterogeneous railcar fleet with multiple resource types, the loading problem and the addition of extra trains to the schedule. Second, we show that an exact iterative variable fixing scheme allows to solve large-scale instances with a general-purpose solver. Third, we report an extensive computational study and provide managerial insights.

2 SPACE-TIME NETWORK

We propose a four-layer cyclic time-space network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ of length T (e.g., a week) to represent the system dynamics, the activities, and the decisions of the IBRM problem. Nodes $i \in \mathcal{N}$ represent events at specific moments in time $t(i)$ and terminals $\theta(i)$. Arcs stand for activities taking place in time and space between these nodes.

The layers correspond to the main components of the system, train services, blocks, railcars, and containers. *Intra-layer* nodes and arcs model the activities corresponding to each layer at appropriate moments in time, while *inter-layer* arcs capture the interactions among the system components, e.g., loading/unloading of containers onto/from railcars, consolidating the latter into blocks, attaching/detaching the latter to/from train services, and dismantling blocks at the destination. Due to the cyclic nature of the tactical plan, activities initiated before the end of the schedule may end after T, that is, during the next application of the plan. This is modeled by having the corresponding arcs wraparound, times being computed $modulo(T)$ (see, e.g., Chouman & Crainic, 2021). The network is illustrated in Figure 1 for a terminal $\theta \in \Theta$ and a representative time interval featuring a train arrival and a train departure.

The *container layer* represents the arrival of each demand $k \in \mathcal{K}$ at its origin yard, the possible waiting before being loaded onto railcars, the actual loading operation, the symmetric unloading at the destination, and the subsequent exit from the system. The *car layer* models the loading/unloading of railcars and the blocking of loaded and empty railcars. It is also in the *car layer* that the fleets of the various types of railcars are managed through the assignment to container-loading activities, the empty movements to balance the needs within the network, the railcar-pool inventory counts at terminals, as well as the initial fleet size and allocation at terminals. Blocks are handled on the *block layer*: building at origin by consolidating empty and loaded railcars, attachment to a train, transfer between two train services, and detachment from the last train at the destination for dismantling.

The *train layer* plays a special role in the proposed formulation. It obviously represents the movements between terminals and the time spent therein to pick up or drop off blocks of regular and extra train services. Furthermore, it also defines the time instances of the time-

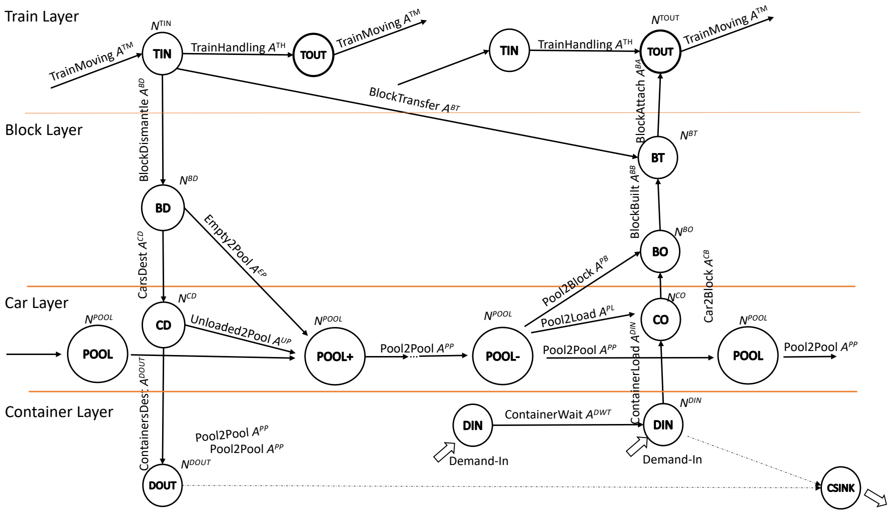

Figure 1 – *Four-Layer (Train, Block, Car, Container) Time-Space Network Illustration*

space network and, thus, the pacing of activities and decisions. Different than most time-space networks proposed in the service network design literature, our network is based on the schedules of the given train-service set Σ making it *continuous* in time. The arrival and departure times of each train service to/from each terminal on its route yield corresponding arrival (TIN) and departure (TOUT) nodes, defining the time structure of the entire network (Figure 1). In other words, container, railcar, and block activities are synchronized with train departures and arrivals, the associated waiting being represented on the inter-layer arcs.

3 MODEL

We propose an integer linear programming (ILP) formulation with four groups of decision variables: (i) *Block selection*, binary variables equal to 1 if a block is selected, and 0 otherwise; (ii) *Container flow distribution*, numbers of containers of appropriate demands on each block respecting loading rules; (iii) *Railcar distribution*, numbers of loaded and empty railcars of each type on each block, inventory arc, and loading/unloading arc; (iv) *Extra train selection*, binary variables equal to 1 if a service is to be added and 0 otherwise. Due to space limitations we briefly describe the model without providing the full mathematical formulation.

The objective function minimizes the total cost of the system over the planning horizon. It encompasses the cost of selecting, operating and transferring blocks, the costs of handling and moving railcars and containers, the cost of selecting services to be added to the schedule, the time-related costs for containers and railcars idling at train stops, as well as penalties for late arrival of demand. Since potential blocks are pre-generated, there is no need for flow conservation constraints in the block and train layers. Yet, they are needed in the car layer at the inventory POOL nodes to ensure the empty railcar flow. Loading constraints yield the appropriate number of loaded cars given the assigned containers, and train and block capacities are enforced through linking constraints.

4 SOLUTION APPROACH

To address real-world instances from our railroad company partner, we propose an exact iterative variable fixing scheme to obtain high-quality warm-start solutions before fully solving the problem with a general-purpose solver. This approach consists in imposing integrality constraints on only specific sets of variables in an iterative fashion. The process first begins by relaxing all variables.

Then, we force integrality on the *Extra train selection* variables followed by the *Block selection*, *Railcar distribution* and finally the *Container flow distribution* variables. The resulting solution from these steps then serves as a warm start for solving the full model and constitutes a valid upper bound.

5 RESULTS AND CONCLUSION

Experiments on the model above were conducted using data from a North American class I railroad. Two sets of realistic instances were solved and analyzed: a realistic large-scale one with 169 origin-destination (OD) pairs and a smaller case with 44 OD pairs focused on the highest-volume routes. Additionally, four variations of each instance were generated by introducing some randomness to the demands needing to be transported. The model was solved on seven different railcar fleet scenarios with the number of allowed resource types varying from 1 to 6. In total, 70 problem instances were used: (5 small + 5 large instances) x (7 railcar scenarios).

Furthermore, the model was evaluated using two distinct train schedule configurations. In the first, the given train schedule remained fixed, while in the second, the model was allowed to introduce extra trains by duplicating any existing train in the schedule. Two different solution approaches for solving the problem were compared: the use of CPLEX 22.1.1 to solve the full model from scratch (referred to as FILP) and our iterative variable fixing scheme (phases P1 to P8). This resulted in a total of 280 problems being solved (4 problems) x (70 instances).

In the following we highlight a few key insights:

- The iterative variable fixing approach (P1-P8) outperforms the general-purpose solver when solving the full ILP model (FILP) across all scenarios. For the model with extra trains, it takes 12 hours on average for the FILP compared to 2 hours for the variable fixing approach. For the model without extra trains, it takes 5 hours on average for the FILP compared to less than 8 minutes for the variable fixing approach.

- The first seven phases of the iterative variable fixing are fast to compute. A warm start solution is obtained across all railcar scenarios in under 2 minutes on average for the model without extra trains, and in 15 minutes on average for the model with extra trains.

- Allowing extra trains in the schedule reduces substantially unsatisfied demands, with only a minimal increase in the number of trains.

- Optimal fleet compositions favour railcars from two specific types: railcars made of 5 platforms of 40 feet and 5 platforms of 53 feet. This mix of resources makes better use of available capacity for certain mixes of container types (determined through the load planning constraints). When considering all types of railcars, the fleet composition is composed, on average, of 94% of those two railcar types.

These findings highlight that a relatively simple solution approach allows to solve intermodal railroad blocking and railcar fleet management problems of realistic sizes.

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