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A Survey on Container Processing in Railway Yards: Decision Problems, Optimization Procedures and Research Challenges*

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Abstract

In spite of extraordinary support programs initiated by the European Union and other national authorities, the percentage of overall freight traffic moved by train is in steady decline. This development is driven by the fact that macro-economic benefits of rail traffic, such as relief of overloaded road networks and reduced environmental impacts, are counterbalanced by severe disadvantages from the perspective of the shipper, e.g., low average delivery speed and general lack of reliability. Attracting a higher share of freight traffic on rail requires a more efficient freight handling in railway yards, which includes technical

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innovations as well as the development of suited decision support systems. This paper reviews container processing in railway yards from an operational research perspective and analyzes basic decision problems for the two most important yard types, namely conventional rail-road and modern rail-rail transshipment yards. Existing literature is reviewed and open research challenges are identified.

Keywords: Railway System; Railway Yard; Container Processing; Decision Support; Survey

1 Introduction

From a macro-economic perspective shifting freight traffic from the road network to the railway system is certainly desirable for several reasons. An increased rail usage for mid-to long-distance freight can provide an opportunity to relieve the often congested roads of the big transit nations especially in the center of Europe. This objective is ever the more important, since Europe's freight traffic (and road freight in particular) is forecasted to considerably increase over the next decades (see, e.g., Prograns, 2007). Moreover, rail traffic is typically favored on the basis of its reduced environmental impact, for instance with regard to CO₂-emissions, which are estimated to being more than 4 times higher for road traffic (Allianz-pro-Schiene, 2008). In spite of extraordinary support programs of the European Union (see, e.g., Tsamboulas et al., 2007) and other national authorities, railway systems still face a considerable disadvantage compared to freight traffic by truck. Within the last 25 years the fraction of the overall freight traffic moved by train declined from 20% (1970) to 10% (2005) (EU, 2007a). This development is mainly due to the lack of investment in the railway infrastructure over the last decade. As a consequence the modest absolute increase of rail freight volume, led to an over utilization of critical resources and thus to severe competitive disadvantages of rail traffic when compared to road traffic from a shipper's perspective. According to recent studies only 53% of freight trains reach their destination with less than 30 minutes delay (EU, 2007b) and the average delivery speed of a freight train is estimated ranging merely between 10 km/h (VDA, 2006) and 20 km/h (EU, 2001), which is predominately caused by long waiting times in rail yards.

In addition to investments in the network infrastructure, another important starting point to increase the market share of rail freight is therefore to establish a more efficient freight handling in existing railway yards, e.g., by suited optimization approaches and decision support systems. This paper surveys rail yard operations in conventional rail-road and modern rail-rail terminals from an operational research perspective by characterizing important decision problems and solution approaches published in the scientific literature. On the basis of this analysis future research challenges are identified.

For this purpose the remainder of the paper is structured as follows. Section 2 defines the scope of this review by distinguishing different types of rail yards and briefly describing the associated decision problems. The two most important yard types – conventional rail-road terminals and modern rail-rail transshipment yards – are then studied individually in

dedicated sections with regard to the core decision problems, existing literature and future research challenges. Finally, Section 5 concludes the paper.

2 Scope of Review

A railway yard is a special transshipment node in a rail network where loads for trains are processed, i.e., collected, rearranged, unloaded, intermediately stored, loaded and/or picked up. Our survey exclusively treats railway yards where standardized load units are processed, whereas passenger railway systems (see, e.g., Freling et al., 2005; Kroon et al., 2008) and railway yards for bulk cargo, such as coal or tree trunks, are not considered. The load units processed in such yards are separable from railcars and comprise standardized containers, swap bodies, railroaders or trailers. The variety of containerized load units processed in rail yards is typically much higher than that of seaports, where only a handful of different container types is transshipped. For instance, the German rail network distinguishes between 23 different container types (Kombiverkehr, 2008) and a comparable number is reported for North America (Muller, 1999). In spite of the large variety, we will simply use the term 'container' throughout this paper for any load unit which is separable from its railcar, since the operational characteristics are for the most part identical.

Usually a freight yard serves at least one of two main purposes in a railway network:

- (i) On the one hand, a terminal may serve as an interface in intermodal transport, so that shipments can be interchanged between the rail system and an alternative mode of transportation, i.e., trucks or ships. Typically, in such a system either trucks pick-up shipments at and deliver them to customers on the last mile, while trains run the long-haul routes or an intermodal yard is located in direct vicinity to a seaport for moving freight to and from the hinterland.
- (ii) On the other hand, a transshipment yard might also serve as a hub node in a hub-and-spoke network, so that containers or even railcars themselves are exchanged between different trains. This allows a consolidation of several short trains with loads for multiple destinations to a reduced number of long trains, so that economies in transportation are generated. Without hub nodes, rail freight is predominantly executed as point-to-point traffic. As fixed cost for train traffic are high, point-to-point shipment is only profitable if full trains are moved over long distances. Different studies have calculated the break-even point between road and rail freight to range between 400 km (Williams and Hoel, 1998) and 500 km (van Klink and van den Berg, 1998). Thus, hub-and-spoke systems have been identified as one promising starting point to attract rail freight traffic for small freight flows over shorter distances (e.g., Trip and Bontekoning, 2002).

To fulfill these two tasks different types of yards have been established over the years, which, in accordance to the chronology of their appearance, can be grouped into three terminal generations (Boysen et al., 2010a):

- 1st generation: Traditional shunting (or classification) yards have several characteristics that help to explain some of the competitive disadvantages of rail transport. In these yards railcars of arriving trains are uncoupled, reshuffled via a system of classification tracks and shunting hills and newly coupled to outbound trains (see Figure 1). Such a reshuffling is very time-consuming, i.e., shunting operations may take 10-50% of trains' total transit time (Bontekoning and Priemus, 2004). Most of these yards are dedicated to function (ii) of rearranging railcars to outbound trains, however, also loading operations (function (i)), e.g., of bulk cargo, might be processed. Shunting yards have a long history which dates back to the beginnings of rail transport. Today, shunting yards have lost of their former importance and many of them have been put out of service during the last decades (see, e.g., Rhodes, 2003). However, there are still several operational shunting yards in different railway networks and in some areas (in particular in China) some are even newly constructed, mainly because of the comparatively low investment cost for technical equipment.

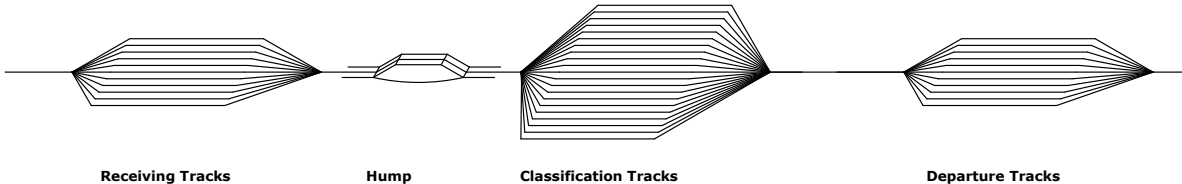


Figure 1: Outline of a shunting yard

- 2nd generation: In today's conventional rail-road terminals trains usually keep their railcars and only containers are actually transshipped typically by means of huge gantry cranes, which span over multiple parallel railway tracks. Such yards often accommodate additional elements, such as storage areas for an intermediate stacking of containers and adjacent truck lanes for an immediate transshipment from trains to trucks and vice versa. Rail-road terminals have become one of the cornerstones for intermodal freight, their main purpose being to function as an interface between different modes of transportation (function (i)). The German railway network for example, features 24 rail-road terminals spread all over the country (see DUSS, 2010). However, these yards are also applied as part of hub-and-spoke networks (function (ii)), for instance, between Germany (with hubs in Ludwigshafen, Munich-Riem and Port of Nurmberg) and Italy (with hubs in Bologna, Busto Arsizio, Milan and Verona) (see Kombiverkehr, 2009).
- The 3rd generation of modern rail-rail transshipment is dedicated to a rapid consolidation of trains (function (ii)). The layout of these yards is similar to that of 2nd generation terminals. However, for a further acceleration of container transfers, fully automated sorting systems are applied instead of conventional floor storage. Such a sorter consists of shuttle cars which take up containers close to their initial positions on inbound trains and move them alongside the yard to their target positions. Only then a gantry crane picks up these containers and transports them to their dedicated

outbound trains. Most of these terminals are still in the design phase, however, some of these novel hub yards have already been constructed in the EU (e.g., Port-Bou, see Martinez et al., 2004) and others are currently under development. For instance, the so called German Mega Hub in Hannover-Lehrte is expected to finally start construction in 2011 after a tedious design phase, which is documented in more detail by Aliche (2002) and Rotter (2004).

This study exclusively focuses on 2nd and 3rd generation terminals, since 1st generation shunting yards are fundamentally different in structure and operations. Therefore, they seem to be a suited subject for an exclusive treatment. They are moreover rarely part of modern intermodal transportation networks, which is expected to be the main driver of future rail freight and are therefore of minor relevance in the context of container transshipment. For an introduction to shunting yard processes see Gatto et al. (2009) or the valuable classification of Hansmann and Zimmermann (2008). Furthermore all freight terminals which are not explicitly designed to transship container units as well as innovative terminal concepts that have not yet overcome the purely conceptional phase are excluded from the scope of this survey. The former group includes, for instance, special terminals dedicated to automobile transshipment (see, e.g., Mattfeld and Kopfer, 2003; Fischer and Gehring, 2005) or company owned railway sidings (e.g., Lübbecke and Zimmermann, 2003), while the latter consists of concepts such as automated shunting terminals (Hansen, 2004) or moving train techniques (Ballis and Golias, 2004). Instead, it is the aim of this study to review scientific approaches which tackle the long- to mid-term decision problems of the design phase with regard to the layout and resource allocation of the terminal and short-term decision problems which are solved as part of the daily operations of conventional rail-road and modern rail-rail terminals. The problems are exclusively studied from the perspective of the terminal operator, so that macro-economic effects are not considered.

Due to the confinement on (isolated) terminal operations, decision problems with regard to the superordinate railway network are further excluded, which comprises location planning (e.g., see Klincewicz, 1998; Arnold et al., 2004), performance estimation of a railway network with respect to the capacity of nodes and connections (see, e.g., Ballis and Golias, 2002, 2004), distributing empty waggons within a network (see, e.g., Nozick and Morlok, 1997) as well as train time-tabling (e.g., see Newman and Yano, 2000). Moreover, the smallest load unit considered in this survey is the container (as a placeholder for any standardized load unit), so that stowage planning of containers (see, e.g., Geng and Li, 2001; Pisinger, 2002) is not covered. To conclude, Figure 2 schematically defines the scope of this review.

Yard operations have already been discussed in review papers with a wider scope, which cover rail transshipment yards as one segment of a broader topic. For instance, surveys on general railway optimization (Assad, 1980; Bussieck et al., 1997; Ferreira, 1997; Cordeau et al., 1998; Newman et al., 2002), intermodal transport (Macharis and Bontekoning, 2004; Bontekoning et al., 2004; Crainic and Kim, 2007; Caris et al., 2008), and seaport terminal operations (Vis and de Koster, 2003; Steenken et al., 2004; Stahlbock and Voß, 2008) also briefly elaborate on rail yards. However, the extended scope of these surveys prevented

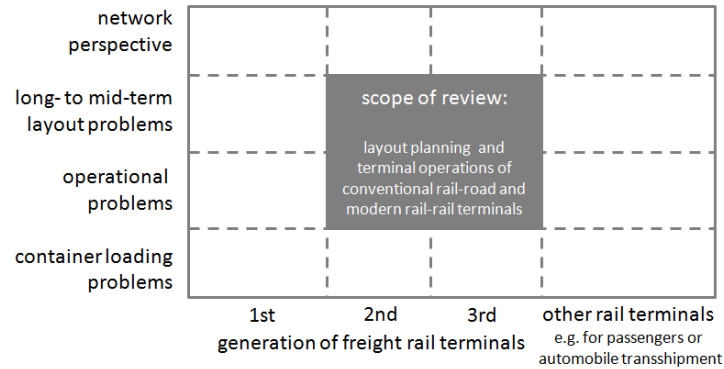


Figure 2: Scope of review

an in-depth discussion of decision problems, existing optimization approaches and future research challenges of rail yard operations.

3 Rail-Road Transshipment Yards

3.1 Yard layout, transshipment process and decision problems

Rail-road terminals mainly serve as interface nodes in intermodal transport, where gantry cranes transship containers between trains and trucks and vice versa. A schematic representation of a rail-road terminal is depicted in Figure 3.

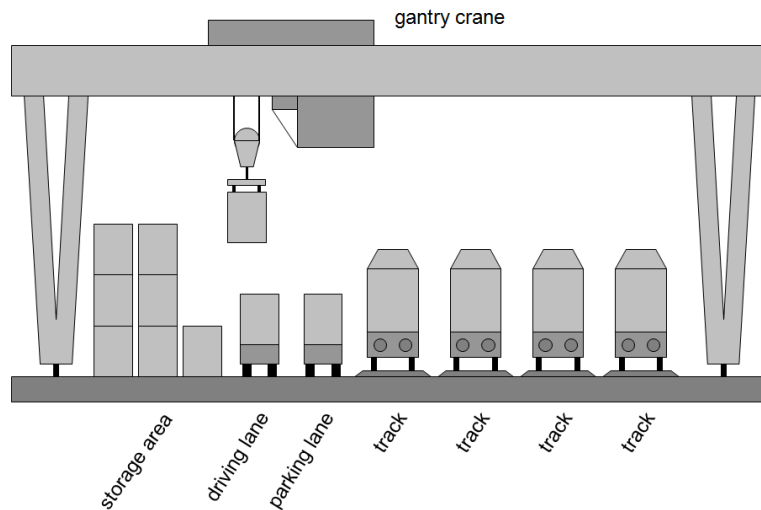


Figure 3: Schematic representation of a rail-road transshipment yard

Freight trains are parked on parallel transshipment tracks of the terminal. Typically, a terminal segment consists of between two and four parallel tracks while a maximum gantry

span of six tracks is possible (e.g., Steenken et al., 2004). As freight trains in Europe have a typical length of 600-750 m (Ballis and Golias, 2002) the track area accessible by cranes for container processing typically shows about the same length. Larger terminals, e.g., Köln-Eifeltor and Hamburg-Billwerder in Germany, consist of multiple parallel terminal segments. Trucks arrive on parallel truck lanes, which are usually separated into a driving and a parking lane. Furthermore, a floor storage area allows to intermediately stack containers, whenever a delivered container cannot be immediately shipped to the respective outbound truck or train. Typically, one or multiple gantry crane(s) span over all three elements, i.e., tracks, storage area and truck lanes, so that containers can be directly moved to their destinations in a single step. Up to four of these gantry cranes serve a terminal segment in parallel. The most widespread type of gantry cranes is rail-mounted, manually operated, has a maximum load capacity of 41 tonnes, processes between 20 and 25 container moves per hour (see Rotter, 2004) and is able to cross a maximum stacking height of three containers in the storage area (Ballis and Golias, 2002). However, there exist yards with alternative crane settings. Especially in smaller terminals, rubber tired gantries or reach stackers are applied (Ballis and Golias, 2002), so that resources can be more flexibly allocated to different segments of the yard. A yard terminal often features a holding lot for trucks, a gate and an office area for controlling and organizing access into and out of the terminal by truck. Additional rail tracks may be provided, e.g., for holding and shunting of trains or storing railcars (Ballis and Golias, 2002).

During the design phase of a terminal, critical decisions are taken in particular with regard to the number of tracks, the capacity of the storage area as well as the number and technology of gantry cranes, because these factors heavily influence yard performance and are not easily reversible. With regard to the remaining layout parameters there are only a few degrees of freedom left. For instance, the length of the yard is basically predetermined by the maximum length of trains to be processed. It is hence the job of the yard planner to carefully trade off investment cost of a specific layout against estimated operational performance. OR methods are especially suited to quantify the latter part of this trade-off, so that an accurate performance estimation of a specific yard layout is the essential task for supporting decisions of the design phase. Note that, albeit not in the scope of this review, the results on yard performance need to be further evaluated with respect to the yard's network integration, since an expansion of capacity in a non-bottleneck yard does not necessarily increase overall network performance. Existing approaches for performance estimation of rail-road terminals are reviewed in Section 3.2.

For a given yard layout, the operational process of container transshipment in a rail-road terminal is described in more detail in the following. On the basis of the superordinate timetable, container moves need to be processed periodically subject to arrival and departure times of trains. Typically, all trains arrive in the morning hours, are processed over the day and leave the terminal in the late evening. Due to the general right of way of passenger trains in many European countries and, e.g., Australia, freight trains are often bound to travel during night times exclusively. Once a train arrives at the transshipment

yard (after a potential interim stay at a holding track of the yard) it is first assigned to a vertical and horizontal parking position of the yard. While the vertical parking position relates to the actual track on which the train enters the yard, the notion of a horizontal parking position requires some additional explanations. Typically the yard area is subdivided horizontally into slots of equal size measured in the length of a standard railcar (or any other unit). The resulting grid is hence used to identify the coordinates of any given container on the yard, while the horizontal parking position of a train refers to the slot in which the traction vehicle is positioned. In the context of rail-road terminals the problem of assigning parking positions to trains has not been studied in detail thus far. The reason for this is that its impact on yard performance is usually considered to be rather low. Since trucks can be parked directly next to the respective container of the train, cranes need to move only vertically for the most part, which is often negligible in time compared to the time-consuming pick and drop operations of cranes. The horizontal parking positions do determine the accessibility of individual containers with respect to the different gantry cranes of the yard. Due to the immense fixed cost however, freight transport by train is often only profitable if full trains are moved. Therefore, train and yard lengths are about the same and the degree of freedom for varying horizontal parking positions is often not significant enough. In practice, parking positions are therefore typically assigned according to a simple first-come-first-serve policy (Kozan, 1997).

As soon as a train is parked, the unloading of all inbound containers can commence. In order to avoid double-handling, a container is preferably transshipped directly from the train to its dedicated truck. In the following, this form of container transfer is denoted as a direct move. Clearly, a direct move requires the simultaneous presence of a respective truck and train at the yard. The target truck is then called up from the holding area and is assigned a free parking position on the parking lane next to the respective railcar. If the target truck has not yet arrived and is therefore not directly available, the container is moved to the intermediate storage yard. This kind of double-handling is denoted as a split move (see Boysen et al., 2010c) where a storage location close to the respective railcar is sought, so that crane operating times are reduced. However, since containers are usually stacked on top of each other, split moves to and from the storage are subject to additional restrictions, e.g., with respect to weight, stability aspects and estimated departure times of containers to avoid a subsequent reshuffling. In analogy to stacking logistics in seaports (see Steenken et al., 2004), three interrelated decision problems are associated with split moves. First, a suited storage position is to be identified which minimizes the risk of container blockages. Secondly, stored containers might need to be pre-marshalled on the basis of updated information with regard to arrival times of trucks, which is especially reasonable during idle times of cranes. Finally, containers need to be efficiently retrieved from the storage area as soon as the respective truck arrives, which might in turn require additional handling of any blocking containers. Typically the frequencies of direct and container split moves vary over time (see Bose, 1983; Ballis and Golias, 2002). Shortly after a train's arrival, especially direct moves to trucks that already wait at the yard are processed. In the second phase, waggon-to-storage moves prevail, which are later on superseded by storage-to-truck moves.

In most terminals, outbound operations are executed only after inbound operations are completed. However, intermixed operations of inbound and outbound containers are certainly a possibility. The processing of outbound operations is carried out in analogy to those of inbound containers. Whenever trucks have deployed containers prior to the train's arrival, a split move occurs and containers are loaded on train from the storage yard, whereas deliveries that arrive during the loading process of the target train can be processed as direct moves. Therefore, prior to a train's arrival truck-to-storage moves prevail, which are then superseded by direct moves processed after a train's arrival. Finally, especially storage-to-waggon moves are executed. In some yard settings, outbound containers are moved by skeleton trailers rather than customers' trucks. The containers are then carried to a separate storage area where customer trucks pick-up trailers and vice versa. Clearly, this concept avoids double-handling of containers in the yard, at the price of an additional transshipment in the storage area and higher investment cost for many different skeleton trailers required for the wide range of possible containers. Nonetheless, this practice is often applied in North American yards (see Ferreira and Sigut, 1993; Kozan, 1997)).

During the loading operations of an outbound train, there exist some degrees of freedom with regard to the exact position of each container on a train. Therefore, a load plan is required which determines the loading pattern of containers on waggons. A typical terminal faces a high variety of container types and multiple different waggons, which vary in length between 40 and 104 feet (see Bruns and Knust, 2010). Given a specific setting of outbound containers and railcars, the loading problem has to consider several hard constraints, i.e., waggon length, separation of dangerous goods, weight restrictions and train height. Furthermore, the quality of a load plan can be determined by different conflicting objectives, e.g., the utilization of trains, setup time and/or cost for changing a railcar's pin configuration which fixes containers or processing times for moving a container from its current position to the respective waggon. Note that load planning is also heavily interdependent with the distribution of waggon types across yards from the overall network perspective, an aspect which is, for instance, investigated by Powell and Carvalho (1998).

Once the load plan is determined, the set of container moves is finally fixed and the planning can focus on determining transshipment schedules for each crane. Since gantry cranes principally work in parallel, it seems especially desirable to split the overall workload evenly among cranes, so that train processing is accelerated. However, in most yard settings the bulk size of gantry cranes prevents them to pass by one another, which results to hard obstruction constraints that limit a flexible container processing. Two distinct policies have been developed to avoid such crane interferences (see Boysen and Fliedner, 2010). On the one hand, the assignment of container moves to cranes can be static, which means that each crane receives a disjoint area of operations, where all container moves falling into the area are exclusively processed by the respective crane. On the other hand, containers can be assigned dynamically on the basis of the actual positions of cranes and the set of moves that need to be executed. Clearly, the latter policy offers more degrees of freedom for crane scheduling. However, the coordination of cranes becomes more complex and requires real-time crane scheduling procedures, in order to rule out any crane interferences. In real-world yards, a static crane split with equally sized yard areas is the most widespread

choice (see Boysen and Flidner, 2010). The sequence of moves falling into a crane's area is typically not computationally optimized but decided by the crane operator. The crane operator simply chooses among those moves currently being displayed on the monitor of the steeple cab on the basis of some nearest-neighbor decision rule (Boysen et al., 2010a).

To summarize, the operational process needs to address the following essential decision problems:

- (i) Decide on storage positions of containers handled by split moves.
- (ii) Assign each truck a parking position.
- (iii) Decide on the positions of outbound containers on trains.
- (iv) Assign container moves to cranes.
- (v) Decide on the sequence of container moves per crane.

In the following sections, literature on layout planning (Section 3.2) and operational container processing (Section 3.3) is summarized.

3.2 Literature on layout planning

Existing literature on layout planning exclusively consists of simulation studies. These simulations are applied to anticipate yard performance for different terminal layouts.

A discrete event simulation study including both a macro (network) and a micro (terminal) perspective is provided by Rizzoli et al. (2002). Here, different technologies and operational policies are compared with regard to their impact on terminal and network performance. A similar simulation model is described by Kondratowicz (1990). Lee et al. (2006) present a simulation study which is designed to support decisions on the number and locations of rail terminals in a Korean container port. Basic analytical equations are applied to calculate the number of tracks and cranes required for a specific number and location of rail terminals. The authors simulate different train and truck arrival patterns as well as container move settings by applying a simple crane scheduling rule, i.e., every crane processes containers successively while continuously traveling in a specified direction as long as a receiving truck is available (if not, the crane changes direction for the next container). The study is varied with regard to different numbers and locations of terminals.

Ferreira and Sigut (1993) and Ferreira and Sigut (1995) compare the resulting performance of container handling between a conventional rail-road terminal and a roadtrailer terminal. In the roadtrailer concept, load units are carried by special trailers, which are provided with a detachable bogie or a single rail axle, so that they are capable of being hauled on road and rail without requiring a waggon. Both concepts are compared as part of a simulation study of an Australian terminal. The results indicate a more efficient handling of containers instead of roadtrailers.

Another simulation tool dedicated to model a single terminal is introduced by Benna and Gronalt (2008). Terminal layout, arrival patterns of trains and trucks and container

settings are specified as part of the input data. Simple priority rule based approaches are applied to determine crane schedules and intermediate storage positions of containers. As quality measures the study evaluates lifting performance, system capacity and service level. A similar tool is described by Gronalt et al. (2007).

The results of a large EU research project, which aimed at increasing rail terminal performance, are presented by Ballis and Golias (2002, 2004) as well as Abacoumkin and Ballis (2004). The authors develop an extensive expert system consisting of a macro model which covers a complete railway network and a micro model simulating train processing in a single yard. A general overview on the macro and micro model is provided by Ballis and Golias (2004). They test the micro model for 17 different terminal layouts with varying numbers of tracks and cranes as well as lifting technologies. Ideal terminal layouts for a given transshipment volume are determined by calculating the total cost per container. The macro model is employed to anticipate the market share of rail freight over a longer planning horizon for a specific network structure and terminal configuration. A case study for the railway corridor from the large North-sea harbors to Switzerland is presented. A more detailed description of the micro model is presented by Ballis and Golias (2002) as well as Abacoumkin and Ballis (2004).

Kozan (2006) presents a simulation model for a terminal, where gantry cranes can be supported by additional lifting equipment (e.g., reach stackers and fork lifts). For joint loading and unloading operations over multiple days different crane settings are compared to identify a suitable crane configuration providing a reasonable trade-off between investment cost and operational performance. Sequencing of container moves for different arrival patterns of trucks and trains is guided by simple first-come-first-serve policies. By means of simulation Vis (2006) compares manned straddle carriers with automated stacking cranes. Total travel time required to handle all container moves is applied as a performance measure to determine the yard layout for the landside of a seaport terminal.

Although mainly dedicated to seaport container operations a helpful paper for generating representative simulation scenarios is provided by Hartmann (2004). The paper features a data generator for deriving diverse transshipment scenarios. It can be directly applied to simulate rail-road terminals by generating arrival patterns of trucks and respective container properties.

3.3 Literature on operational planning

Thus far, there exists no literature which explicitly treats the determination of storage positions in a rail-road yard. However, decision problem (i) is very closely related to the problems arising in stacking logistics of seaports. In this context, the problem has attracted lots of research, e.g., by de Castillo and Daganzo (1993), Kim (1997), Kim et al. (2000). The subproblem of pre-marshalling during idle time of cranes, has been investigated by, e.g., Lee and Hsu (2007), Choe et al. (2009), Lee and Chao (2009). Finally, for instance, Kim and Hong (2006) as well as Caserta et al. (2009) provide solution procedures for determining a suited sequence of crane moves to remove containers (in a predetermined sequence) from intermediate storage. In addition to these static problem settings, online

stacking rules are investigated, e.g., by Dekker et al. (2006) and Borgman et al. (2010). A more detailed review on these approaches is given by Steenken et al. (2004) and Stahlbock and Voß (2008). The extent to which these approaches are directly applicable to rail-road terminals remains to be studied, however.

A first basic version of the train loading problem (iii) is presented by Feo and González-Velarde (1995). Given a predetermined matrix defining which container can be assigned to which railcar on the basis of their pin configuration, the approach seeks to minimize the number of waggons per train. However, the model and solution approaches are restricted to at most two containers per waggon. For the solution of the basic train loading problem, a simple branch-and-bound approach relying on the LP-relaxation and a heuristic GRASP procedure are introduced, where initial solutions are locally improved by a 2-opt search. The procedures are shown to be efficient for real-world data from a North-American terminal. Corry and Kozan (2006) optimize the load planning with respect to handling times and the weight distribution within a train. Only one type of containers and no weight restrictions per waggon are modeled. Furthermore, it is assumed that each container can be loaded onto any wagon. The problem is formulated as an integer linear program and is solved with off-the-shelf solver CPLEX. In a subsequent paper Corry and Kozan (2008) aim to minimize the train length and the total handling time. Here, multiple container types are modeled. Load pattern restrictions are considered for the length of load units, but neither weight restrictions for the wagons nor for the whole train are integrated. The model is formulated as an integer linear program and solutions for real-world problem instances are generated by local search.

Recently, Bruns and Knust (2010) investigated another version of the loading problem (iii) of trains. They consider an optimization problem where weight and length restrictions of waggons are to be considered. In the objective function, three weighted objectives are considered: maximizing the utilization of trains, minimizing setup cost for changing the existing pin configuration and minimizing transportation cost from storage position to railcar. Two different mixed-integer programs are introduced for this problem setting, which are shown to be solvable even for real-world instances.

An additional aspect of the train loading problem (iii) has first been investigated by Lai and Barkan (2005). Intermodal trains often contain larger gaps of empty waggons, which leads to much worse aerodynamic characteristics than full trains carrying a close spacing, e.g. of hopper cars. Therefore, considerable savings in fuel cost can be achieved if train planning considers the additional objective of generating long chains of loaded railcars. Lai and Barkan (2005) quantified the aerodynamic and energy penalties of specific load and car combinations under idealized conditions by assuming that each waggon pair can be assigned to each other. Lai et al. (2007) describe a wayside machine vision system that automatically monitors the gap lengths between intermodal loads on passing trains, which allows an automatic evaluation of aerodynamic efficiency of loading patterns. In a subsequent paper Lai et al. (2008a) present a mixed-integer model for determining fuel efficient train loads while weight and length restrictions of waggons are considered. The model is solved with an off-the-shelf solver and the savings determined from real-world data allows Lai et al. (2008a) to estimate the potential of annual fuel savings to a remarkable 28 million US\$. The

joint optimization of multiple trains' load plans (with identical destination) and uncertain information on future trains and incoming loads is incorporated into the aforementioned mixed-integer model in another paper by Lai et al. (2008b). They iteratively solve the model in a rolling horizon scheme, where exponentially decreasing weights are assigned to the objective functions with regard to fuel efficiency of future trains.

Kozan (1997) provides a simple heuristic decision rule for determining the crane split (iv) and a simple dispatching rule for the assignment of trains to railway tracks. They employ some simple analytical measures for anticipating the processing times of current trains, in order to identify the track that enables the earliest expected departure of a current train. These simple heuristic rules are then applied in a simulations study, where the resulting throughput times of containers for different train arrival and loading patterns are compared for different yard layouts. Boysen and Fliedner (2010) also investigate decision problems (iv) and introduce a polynomial dynamic programming approach to determine static and disjoint crane areas, so that the workload is evenly shared among cranes. In a simulation of real-world yard operations they show that their approximate surrogate objective for determining the crane split is strongly positively correlated to actual processing times, while simple real-world policies are clearly outperformed.

Souffriau et al. (2009) propose a holistic approach, which jointly determines load plans (iii) and crane schedules (iv) and (v). In a decomposition approach they first determine follow-up destinations of trains, such that the number of resulting container moves is minimized. This problem is solved as a linear assignment problem. The load plan is hence determined by minimizing transportation cost of container moves in a mathematical model with an off-the-shelf solver. Only three different container types as well as length restrictions for the wagons are considered. Finally, the crane schedule, which distributes container moves among cranes and sequences moves per crane, is modeled as a sequential ordering like problem and solved by variable neighborhood search. Another holistic approach for train processing at the landside of a seaport is provided by Froyland et al. (2008). They treat an intermodal terminal in Australia where five successive gantry cranes transship containers between trains (two tracks), trucks (60 slots), straddle cranes (serving ships) and an intermediate storage area with a maximum capacity of 2100 TEU. They jointly investigate decision problems (i), (ii) and (v) and determine container positions in intermediate storage, parking positions of trucks and crane schedules, respectively. The problem is decomposed into three stages, where problems (i) and (ii) are determined by mixed-integer programming and cranes (v) are scheduled on the basis of simple priority rules. Finally, Montemanni et al. (2009) model the sequencing of a given set of container moves per crane (v) as a sequential ordering problem and provide local search and ant colony optimization as solution procedures.

Moreover, dynamic crane scheduling as defined by decision problems (iv) and (v) bears some similarities with quay crane scheduling in seaports, where a given number of quay cranes is employed to (un-)load container vessels. As in rail terminals, quay cranes may not interfere with nor cross each other during container operations. Typically, within quay crane scheduling a vessel is separated into holds (or bays), which are exclusively served by a dedicated crane, and non-crossing constraints need to be considered whenever cranes

change holds. If, analogously, a rail yard is separated into small horizontal areas, e.g., slots of container length comprising all containers of the parallel tracks ranging in the respective slot, then the solution procedures developed for quay crane scheduling could be directly applied for solving crane scheduling in a rail yard. The first optimization approaches for quay crane scheduling stem from Daganzo (1989) as well as Peterkofsky and Daganzo (1990). These studies, however, do not consider non-interference constraints of cranes. Kim and Park (2004) consider non-crossing constraints and present a model formulation along with exact and heuristic solution procedures. Alternative solution methods are presented by Lee et al. (2008), who also provide an NP-hardness proof. Related contributions stem from Lim et al. (2004), Zhu and Lim (2006), Lim et al. (2007) and Lee et al. (2008). A comprehensive review on quay crane scheduling is provided by Bierwirth and Meisel (2010). Of particular interest with regard to crane scheduling in rail-road yards are the results of Lim et al. (2007), who show that under given non-crossing constraints – and some additional simplifying assumptions – optimal crane schedules are unidirectional, in the sense that each train can move from left to right while processing container moves without ever changing direction. This finding is especially relevant for dynamic schedules since it reduces the real-time effort for collision detection to a minimum and thus might make static crane bounds expendable. However, this property only holds whenever container can be processed in an arbitrary sequence; an assumption which many other quay crane scheduling approaches equally make. This does not hold for the majority of rail-road terminals since dynamic arrival times of trucks need to be considered in the transshipment plans, so that these approaches would need to be extended accordingly.

3.4 Future research challenges

Although plenty of studies exist on conventional rail-road terminals, there are still many open questions for future research.

With regard to layout planning it can be stated that all existing simulation studies apply comparatively simple priority rules for solving the subordinate operational decision problems when estimating yard performance. This implies the risk of yard layouts being systematically underrated with regard to performance, since sophisticated scheduling procedures allow for a more efficient resource utilization than anticipated by simple rules of thumb. Consequently, existing studies bear the risk of choosing more efficient layouts accompanied by higher investment cost than required. Thus, simulation studies incorporating sophisticated scheduling procedures would be a valuable contribution for promoting the success of intermodal transport.

Furthermore, there exist potential layouts which have not yet been evaluated. For instance, cross-over cranes operating on different tracks could be applied and in intermediate block storage of modern seaports even triple cross-over gantry cranes are applied (Dorndorf and Schneider, 2010). Here, a pair of twin cranes running on the same tracks is supported by a large cross-over crane on its own rails. Evaluating the performance of these alternative crane layouts in comparison to existing layout configurations would be a valuable decision

support for future terminal projects.

An important decision heavily influencing the yard layout is the question whether the European policy of customer trucks directly entering the transshipment area or the North American policy of applying skeleton trailers which handover containers in the holding area is the better choice. While the latter policy reduces the load of gantry cranes by avoiding additional split moves and allows for a better (deterministic) planning of crane schedules, it extends delivery times for customers. A detailed comparison of both policies and their impact on yard layout is a challenging subject for future research.

Furthermore, additional research in the operational area is required with regard to each of the decision problems defined in Section 3.1:

- (i) Existing research on identifying appropriate stacking positions of containers in intermediate storage, so that additional effort for reshuffling is minimized, is dedicated to seaports. Although on the first glance existing procedures can be utilized in both fields of application, the dimensions of the storage areas in a rail terminal are much smaller. Actually, the mean stacking height in many rail yards is slightly above 1 up to 1.5 containers (Ballis and Golias, 2002). Therefore, it would be a valuable contribution to test whether applying the sophisticated procedures developed for seaports in fact accelerate container processing sufficiently, in order to justify the investment into a respective information system.
- (ii) The assignment of parking positions to trucks is a widely unexplored field of research. Only Froyland et al. (2008) integrate this problem into their holistic planning approach. Clearly, this problem is of minor importance if only a few trucks enter the yard simultaneously, since each truck can be parked directly next to its respective container location. However, directly after a train's arrival, when plenty trucks wait for container processing, trucks might compete for scarce parking places, so that a sophisticated planning approach avoiding truck congestions in the yard would be a valuable contribution.
- (iii) The train loading problem is the field which attracted most research contributions thus far. However, a versatile model integrating all real-world weight and loading constraints of waggons (as e.g. defined by Bruns and Knust, 2010) with aerodynamic aspects (e.g. Lai et al., 2008a) along with suited solution procedures are still missing. Furthermore, the degrees of freedom for train loading are diminished by the diversity of trailers and waggons to be processed. A further standardization of containers promises reduced effort for changing pin configurations of railcars and, thus, more efficient load plans. Therefore, quantifying the standardization effect could be a valuable contribution to further encourage standardization agreements for rail transport.
- (iv) With regard to the assignment of container moves to cranes, two basic policies are distinguished in this survey: static assignment where each crane operates in a distinct yard area and dynamic assignment where obstruction of cranes are to be avoided in

real-time. Clearly, the dynamic approach promises more efficient crane schedules but comes at the price of a suited information system. A comparison of both policies would be valuable decision support for the right policy choice in real-world yards.

- (v) Once all container moves are specified and assigned to cranes, the sequence of container moves per crane resembles a sequential ordering problem (Montemanni et al., 2009). However, in the real-world especially truck arrivals are bound to uncertainties, so that sequential ordering is to be executed in an online environment. It remains an open question how to integrate sequential ordering in a rolling planning horizon. Moreover, it should be tested whether such an approach is indeed able to considerably outperform the common policy of decentralized scheduling decisions of experienced crane operators.

Up to now, freight traffic is only profitable if full trains are moved over comparatively long distances (see Section 2), so that the degrees of freedom for parking trains in the transshipment area are limited. However, with hub-and-spoke systems being realized, also smaller trains might become profitable, which in turn affects the operational planning environment. For instance, horizontal parking positions might be used to evenly balance the workload among cranes as soon as the length of trains varies sufficiently, which gives rise to a parking problem (in analogy to the parking problem of rail-rail terminals, see Section 4.1). A careful examination of trends in intermodal transport might yield interesting insights with regard to upcoming challenges of yard planning.

Finally, in addition to an isolated investigation of the above decision problems, especially holistic approaches seem a promising field for future research. Currently, there exist some limited proposals for hierarchical procedures, e.g., by Froyland et al. (2008) and Souffriau et al. (2009). The high degree of interdependence and relatedness of the discussed decision problems makes determining the right sequence of decisions and a hierarchical integration of all or at least some decisions a challenging task.

4 Rail-Rail Transshipment Yards

4.1 Yard layout, transshipment process and decision problems

Modern rail-rail terminals mainly serve as hub nodes in a hub-and-spoke rail network. Containers are transshipped among trains without exchanging railcars, so that inbound trains are consolidated to a (reduced) set of full outbound trains. Note that in addition to their primary hub function, rail-road operations might be processed additionally in a rail-rail terminal. A schematic representation of a pure rail-rail terminal is depicted in Figure 4.

The main difference to conventional rail-road terminals – in addition to a potential lack of truck lanes – is that the simple floor storage area is replaced by a fully (or partially) automated sorting system. The sorter consists of moving and buffer lanes, where automated guided vehicles (Bostel and Dejax, 1998) or some rail-mounted shuttle cars (Alicke,

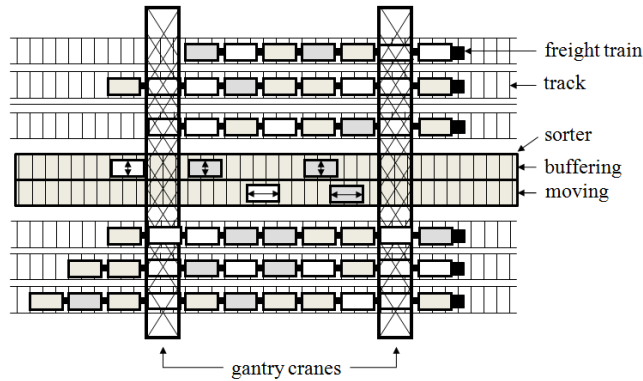


Figure 4: Schematic representation of a rail-rail transshipment yard

2002) take up a container from a gantry crane close to its initial position on the train and move it alongside the yard towards its dedicated container position on the outbound train. A fully automated system can, for instance, employ rail-mounted shuttle cars, which use a rotation mechanism for changing tracks (Franke, 2002) and are propelled by contact-free linear synchronous motors with an electronic position detection system that is able to direct shuttle cars with an accuracy of $\pm 3\text{mm}$ (Bauer, 1998). Simulation studies for the Megahub in Hannover-Lehrte indicate that such a sorting system increases container processing up to 45 container moves per hour and crane (Rotter, 2004).

The high performance impact of the sorting system also explains its critical importance during the design phase. The choice of an appropriate drive technology and the dimensioning of the system with regard to storage space and shuttle cars become some of the most important decisions in this context, in addition to the general yard layout determined by the number of tracks and cranes. In Section 4.2 OR tools which support the design phase of a rail-rail terminal are reviewed.

The operational process of container consolidation in a rail-rail terminal is similar in principle to a rail-road terminal. Since the hub visit constitutes a time-consuming additional step in the distribution process, some organizational changes are necessary in order to speed up transshipment and avoid a tedious stay for an extra day. Generally trains are required to exchange containers within merely a few hours, so that a rapid consolidation process is enabled and trains can depart to their next destinations the same day (or night). Therefore, a rail-rail terminal is operated in distinct so-called pulses (Bostel and Dejax, 1998) or bundles (Alicke, 2002; Rotter, 2004) of trains. This means that all tracks are occupied with trains, which are simultaneously served and jointly leave the system not before all container moves of the respective bundle are processed. Whenever the total number of incoming trains exceeds the number of tracks, a first decision problem constitutes of assigning each train to a bundle. This decision is subject to release dates and departure times of trains as given by the superordinate train schedule and might consider several in

parts conflicting objectives such as minimizing the number of containers dedicated to a train of an earlier bundle or maximizing the number of direct moves among trains of the same bundle. The former objective reduces the number of containers which do not arrive at their dedicated trains and thus need to be delayed until the next train which serves the respective destination, while the latter objective accelerates train processing by reducing the amount of double handling.

Once the pulses are determined, vertical and horizontal parking position need to be assigned to each train of a bundle. Trains which exchange a large number of containers should be assigned to neighboring tracks, so that distances of crane moves are reduced. As hub terminals tend to be also visited by shorter feeder trains, appropriate horizontal parking position of trains can positively influence yard performance, for instance, by evenly spreading container moves among cranes or by moving start and target positions of a container to the same area of operations, so that a single crane can process the job instead of relying on the sorting system.

The problem of determining an appropriate load pattern of containers on trains is quite similar to that arising in rail-road terminals. The impact of a load plan, which minimizes overall distances of container moves seems to have a somewhat smaller impact on the yard performance as long as the sorting system is not a bottleneck and, thus, able to preposition containers next to their intended target positions. However, whenever inbound and outbound loads are exchanged simultaneously, then for given parking positions of trains and operating areas of cranes, the load plan determines the target position of the outbound container and therefore split moves can be reduced by moving its target position closer to its starting position.

The assignment of container moves to cranes can once again be executed under a static or dynamic policy of distinct or variable crane areas, respectively. For given parking positions and load patterns of trains, static and dynamic areas can be determined, so that split moves are avoided and the given workload is evenly shared among cranes.

Finally, the schedule of container moves per crane is to be determined. The resulting problem constitutes an extension to crane scheduling in rail-road terminals and is similar in structure to a sequential ordering problem. One important aspect is that crane moves are asymmetric in distance, because executing move A before B results in another distance for connecting both loaded moves by an empty crane move than a reverted order. Furthermore, container moves are subject to precedence constraints, whenever a container is blocking another container's target position. In addition to that, split moves via the sorting system need to be considered. This leads to heavily interdependent crane schedules, because the release date of a container transported by the sorter, depends on the point in time at which another crane has fed this container into the sorting system. This problem becomes even more complex, if the sorter turns out to be a bottleneck, so that the availability of shuttle cars over time needs to be considered.

The basic decision problems of container processing in rail-rail yards can be summarized as follows:

- (i) Schedule the service slots of trains by assigning them to bundles.

- (ii) Assign each train a parking position.
- (iii) Decide on the positions of containers on trains.
- (iv) Assign container moves to cranes.
- (v) Schedule the shuttle cars in the sorter.
- (vi) Decide on the sequence of container moves per crane.

Existing literature on decision support with regard to these decision problems, is reviewed in Section 4.3.

4.2 Literature on layout planning

There exist only very few studies investigating a suited layout for modern rail-rail terminals.

Meyer (1999) investigates the layout problem of a rail-rail terminal, which successively processes bundles of six trains. In addition, the terminal is assumed to handle a limited volume of rail-road container exchanges. An animated computer simulation on the basis of Petri-nets was developed to determine the required capacity for cranes and internal transport systems and the most efficient arrival pattern of trains were identified. Results were obtained from simulation runs for a terminal planned to be constructed in Germany.

Wiegmans et al. (2007) compare shunting yards, conventional rail-road terminals and modern rail-rail yards with regard to their suitability of serving as a hub in a hub-and-spoke network under specific arrival patterns of trains and containers. The resulting crane and shunting operations are simulated for all three yard types and several terminal layouts. Layout and operational cost are evaluated in a separate cost module, so that suited application scenarios for all terminal types can be derived. It is established that a modern rail-rail terminal is beneficial only under high capacity utilization, non-predefined load positions of containers, synchronized train arrivals and synchronized crane operations. Suggesting a portfolio matrix Wiegmans et al. (2007) conclude that a modern rail-rail yard is the appropriate choice as a hub node, whenever fast operations take priority, while shunting yards and rail-road terminals are favorable for cost-efficient operations. The results presented are mainly based on the thesis of Bontekoning (2006).

4.3 Literature on operational planning

The assignment of trains to bundles (i) was first investigated by Boysen et al. (2010c). A basic transshipment yard scheduling problem (TYSP) is formulated which minimizes a weighted objective function considering split moves between those trains that are assigned to different bundles and the number of revisits by trains that could not take up containers during their first visit in the yard. The problem is shown to be NP-hard in the strong sense and different heuristic and exact solution procedures are presented. The study of Boysen et al. (2010b) builds up on this research. TYSP is modified to consider an additional

objective function which minimizes the number of containers that could not be transshipped to their target trains in time. Additional complexity results are presented and a more efficient exact branch-and-bound procedure as well as a very efficient heuristic ejection chain approach are provided.

Kellner et al. (2010) present a solution approach for solving decision problem (ii). In their approach, the assignment of a given bundle of trains to tracks (vertical position) and horizontal parking positions along the spread of the yard aims to minimize the makespan of train processing. Furthermore, split moves via the sorting system are considered between cranes operating in disjoint crane areas. They present a genetic algorithm for solving the resulting problem and test their approach in a simulation study. An even simpler approach for determining parking positions (ii), is presented by Aliche and Arnold (1998). They merely model the track assignment of trains (vertical position) in a very basic fashion without, e.g., considering horizontal parking positions, sorter operations and multiple cranes. Instead they develop a simple priority value weighting the number of container moves with their total horizontal distance to approximate the resulting workload between two trains. These weights are then applied in a quadratic assignment problem to determine the track assignment.

Bostel and Dejax (1998) treat problem (iii) and aim to jointly determine load plans for inbound and outbound containers. Start and target positions of a container move on its inbound and outbound train are to be brought close together, so that the resulting costs of trains processing are minimized due to reduced crane distances. However, with regard to load planning the underlying assumptions are rather limiting. It is assumed that each container can be separately stored on each waggon and weight restrictions are not considered. Four different models for this problem are derived by additionally considering container transfer by shuttle cars and storage constraints in the sorting system. Each model requires different solution approaches, so that several procedures based on the linear assignment problem, the minimum flow problem and different start and improvement heuristics are developed. A computational study using real-world data from a French railway company shows a huge potential for accelerating train processing by simultaneously optimized load plans.

Boysen et al. (2010a) assign static and disjoint crane areas (iv) to a bundle of trains with given parking positions in order to minimize the makespan of train processing. The sorting system is assumed to be activated, whenever start and target position of a container move fall into the different crane areas. They present a polynomial dynamic programming procedure for solving the resulting problem and test the solutions against typical real-world policies in a simulation of yard operations.

Aliche (2002) jointly treats decision problems (iv), (v) and (vi). A given set of crane moves is assigned to cranes with overlapping areas of operation, which are blocked whenever a crane enters an area. Whenever a start or target position falls in an overlapping area, the procedure dynamically decides which of two neighboring cranes processes the move. This decision also influences whether or not a container move uses the sorting system in a split move. The model takes the movement speed and availability of shuttle cars into account. The overall problem is modeled as a constraint satisfaction problem and tested

on data sets of the German MegaHub in Hannover-Lehrte. Different heuristic rules for fixing variables of the constraint satisfaction problem are compared.

At the border between two countries and railway systems, rail-rail terminals are also used to bridge different track gauges. This requires a special yard setting where complete train loads are transshipped by cranes onto a train with the gauge width of the destination railway system. Martinez et al. (2004) investigate two simple rules for crane scheduling (vi) at a terminal at the border between France and Spain. Both rules are compared by means of a simulation study. The same terminal is investigated by Gonzalez (2008). They provide a mixed integer model for jointly determining the load plan of outbound trains (iii) and crane schedules (vi). Their objective is to minimize crane distances while observing weight and length restrictions of waggons. The model is implemented in an off-the-shelf solver and shown to be suitable for real-world instances of small size.

4.4 Future research challenges

As consolidating containers in a rail-rail terminal is still an emerging technology in railway systems (Bontekoning et al., 2004), there remain a lot of open fields for future research.

Similar to the situation for rail-road terminals, the few existing simulation studies merely apply very simple myopic decision rules when evaluating the performance of terminal layouts. However, the threat of underestimating the performance of rail-rail terminals seems even more imminent, since many terminals are currently in the conceptual evaluation phase. If poor scheduling rules lead to a poor forecast of yard performance, it is to be expected that some projects (including new hub-and-spoke systems) are not realized which, in turn, might further deteriorate the market share of rail freight traffic.

With regard to operational planning the following open research challenges can be stated:

- (i) The existing procedures for assigning trains to bundles only consider a static and deterministic problem. Since time tables are often unreliable and bound to changes due to canceled or additional trains, it might be reasonable to model transshipment yard scheduling as an online problem, where the set of trains to be scheduled continuously changes and forces updates to an active plan. If an already scheduled train fails to appear or additional unplanned trains arrive, these changes need to be considered appropriately, for instance, in a rolling planning horizon.
- (ii) Currently, there exist only two approaches for determining parking positions of trains (Alicke and Arnold, 1998; Boysen et al., 2010a) which are both heuristic in nature. An exact solution procedure is still missing.
- (iii) Bostel and Dejax (1998) introduce a simultaneous load planning for inbound and outbound trains, so that distances for crane moves can be minimized. However, they assume that only one container can be loaded per waggon and all containers can be assigned to any car. Real-world weight constraints and length restrictions are not

considered. Furthermore, split moves resulting from container positions in different crane areas are also omitted. Therefore, future research should seek to integrate more of the diverse real-world constraints of train planning, which have already been widely explored for conventional rail-road terminals (see Section 3.1).

- (iv) In analogy to rail-road terminals, studies on the performance impact of static versus dynamic crane areas have not yet been undertaken (see Section 3.1).
- (v) Existing research mostly assumes that the sorting system is not a bottleneck. However, whenever the availability of shuttle cars is not guaranteed, crane scheduling needs to be complemented by a sophisticated scheduling of shuttle cars. An interesting yet unexplored problem in this context is further the real-time control of sorting vehicles in order to generate deadlock-free travel routes.
- (vi) Analogously to rail-road terminals, the scheduling of crane moves can be modeled as a sequential ordering problem as soon as all crane moves have been specified and assigned to cranes. However, the problem becomes somewhat more complicated in rail-rail yards since split moves processed by the sorting system need to be considered. Some containers become available only after they have been fed into the sorter by another crane, so that crane schedules cannot be decomposed. Suited crane scheduling procedures have not yet been developed.

A further field for future research is to integrate the above decision problems into a holistic procedure. For instance, parking positions of trains and load plans of inbound and outbound trains both influence crane moves and decide whether or not a container needs to use the sorting system. Integrating both problems in a simultaneous planning procedure or determining the better sequence of both decisions in a successive approach would be a valuable contribution.

5 Conclusion

This paper provides a survey on layout planning and operational decision problems arising in rail freight yards. The core decision problems of rail-road terminals and modern rail-rail transshipment yards are characterized and existing research is reviewed. In order to provide a more concise overview on existing research, Table 1 lists the literature of the field along with the problem treated and the methodology applied. By contrasting the structure of decision problems with the scope of existing research, several avenues for future research are identified.

Clearly, future research challenges exist not only with regard to each single terminal type but also in relation to their superordinate integration into an existing railway network. Each terminal type varies in investment cost and operational performance, so that choosing the right terminal type with a proper layout and efficient operational transshipment processes is a challenging task. In particular because the individual performance

assessment needs to be complemented by a network analysis which takes the relations to all other nodes of the rail network into account. A concerted research effort is required in order to successfully promote an efficient use of rail freight in the future.

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source	terminal	decision problem	method
Abacoumkin and Ballis (2004)	rail/road	layout	simulation
Alicke and Arnold (1998)	rail/rail	(ii)	mixed-integer programming
Alicke (2002)	rail/rail	(iv), (v), (vi)	constraint satisfaction
Ballis and Golias (2002)	rail/road	layout	simulation
Ballis and Golias (2004)	rail/road	layout	simulation
Benna and Gronalt (2008)	rail/road	layout	simulation
Bontekoning (2006)	rail/road, rail/rail	layout	simulation
Bostel and Dejax (1998)	rail/rail	(iii)	linear assignment, network flow, mixed-integer programming
Boysen and Fliedner (2010)	rail/road	(iv)	dynamic programming
Boysen et al. (2010c)	rail/rail	(i)	dynamic programming, beam search
Boysen et al. (2010b)	rail/rail	(i)	branch&bound, ejection chain
Boysen et al. (2010a)	rail/rail	(iv)	dynamic programming
Bruns and Knust (2010)	rail/road	(iii)	mixed-integer programming
Corry and Kozan (2006)	rail/road	(iii)	mixed-integer programming
Corry and Kozan (2008)	rail/road	(iii)	mixed-integer programming, local search
Feo and González-Velarde (1995)	rail/road	(iii)	branch&bound, GRASP
Ferreira and Sigut (1993)	rail/road	layout	simulation
Ferreira and Sigut (1995)	rail/road	layout	simulation
Froyland et al. (2008)	rail/road	(i), (ii), (v)	mixed-integer programming, priority rules
Gonzalez (2008)	rail/rail	(iii), (vi)	mixed-integer programming
Gronalt et al. (2007)	rail/road	layout	simulation
Kellner et al. (2010)	rail/rail	(ii)	genetic algorithm
Kondratowicz (1990)	rail/road	layout	simulation
Kozan (1997)	rail/road	(iv)	priority rules
Kozan (2006)	rail/road	layout	simulation
Lai and Barkan (2005)	rail/road	(iii)	mixed-integer programming
Lai et al. (2008b)	rail/road	(iii)	mixed-integer programming
Lai et al. (2008a)	rail/road	(iii)	mixed-integer programming
Lee et al. (2006)	rail/road	layout	simulation
Martinez et al. (2004)	rail/rail	(vi)	simulation
Meyer (1999)	rail/rail	layout	simulation
Montemanni et al. (2009)	rail/road	(v)	local search, ant colony optimization
Rizzoli et al. (2002)	rail/road	layout	simulation
Souffriau et al. (2009)	rail/road	(iii), (iv), (v)	linear assignment, mixed-integer programming, variable neighborhood search
Vis (2006)	rail/road	layout	simulation
Wiegmans et al. (2007)	rail/road, rail/rail	layout	simulation

Table 1: Summary of literature