Quantitative Decision Support for the Layout Design of Container Terminals

Dipl.-Wirt.-Inform. Jörg Wiese

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Gutachter:
1. Prof. Dr. Leena Suhl
2. Prof. Dr. Hans-Otto Günther

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Contents

1. Introduction

In times of a globalized world and interlinked markets a cheap and efficient international transportation network becomes more and more important. Container terminals are one essential part in the current worldwide transportation network (see Saanen 2004, p. 1f). Nearly all important ports have dedicated container terminals in which almost only containers are handled. The advantage of these specialized terminals is that the shipment of goods in standardized boxes (containers) allows the use of highly adjusted equipment, which in turn allows an efficient and quick turnover of containers and the goods therein. Levinson summarizes the advantage of the container as follows: "The container is at the core of a highly automated system for moving goods from anywhere, to anywhere, with a minimum of cost and complication on the way" (Levinson 2006, p. 2). The importance of container traffic is clear from the ongoing growth in the worldwide container turnover in the last years. Following UNCTAD (2008) the container trade (measured in twenty-foot equivalent units) increased by a factor five between 1990 and 2007. In this period the container business underwent several developments to handle the increasing volume of containers. As a consequence container terminal operators have expanded their capacity, e.g. UNCTAD (2008) presents a brief overview of some 30 planned or just finished port expansion projects.

In the case of a port expansion project, the new or expanded terminal has to be designed. One important step in the design of a terminal is the determination of its layout, as an efficient terminal layout allows a smooth operation of the container terminal (see Günther and Kim 2006). An inefficient layout can lead to costly movements of the terminal equipment which reduce the overall terminal performance and hence its efficiency. Efficient terminal operation, however, is vital for container terminal operators to be competitive, as there is a strong competition among container terminals in a single region (see Meisel 2009, p. 1).

To achieve an efficient design of a container terminal layout, methods which support the terminal planners during the design process can be an important factor. The aim of this thesis is to provide quantitative models and methods for decision support during the design of a container terminal layout. The science which is connected to quantitative models and methods for decision support is called

Operations Research (OR) (see e.g., Winston 1991, Taha 2003, Suhl and Mellouli 2009). The Institute for Operations Research and the Management Sciences (INFORMS) defines OR as follows: "In a nutshell, operations research is the discipline of applying advanced analytical methods to help make better decisions" (INFORMS 2004). In this thesis we thus focus on OR methods. In particular we focus on decision support based either on simulation (see e.g., Law 2007, Taha 2003) or analytical models (see e.g., Winston 1991, Law 2007). We do not aim to provide a complete procedure model to plan the layout of a container terminal, which covers all aspects of terminal layout planning ranging from the technical design to organizational problems. We focus rather on container terminal layout problems to which the OR methods provide useful help to container terminal planners.

We assume that the reader is familiar with the methods of OR. For an introduction to the field of OR and its methods we refer to Winston (1991), Taha (2003), Suhl and Mellouli (2009) and Domschke and Drexl (2005). More detailed introductions to specific methods like integer and linear programming can be found in Schrijver (1986), Chvátal (1983), Wolsey (1998) and Nemhauser and Wolsey (1999); and an introduction to simulation and statistics can be found in Law (2007).

This thesis is structured as follows: Chapter 2 gives the foundations of container terminal operations and terminal layout planning. The history and the recent development of the container sector is briefly described. The processes within a container terminal and the different equipment types are also discussed. Logistics needed to coordinate the processes of a container terminal are described. In the end, the layout planning problem of container terminals is explained.

Chapter 3 reviews literature which is related to the layout planning of container terminals and proposes a classification for the approaches in the literature. With the help of this classification we identify gaps in the literature concerning container terminal layout planning.

In Chapter 4 we propose a mixed-integer program based on facility layout planning models for the positioning of storage blocks in the yard as well as for the positioning of the gate and rail tracks. To evaluate the influence of the positions on the overall terminal performance a simulation model has been developed. This simulation model is able to simulate different layout solutions and thus allows us to measure the effect of different block positions on the terminal performance.

In this thesis we distinguish the following yard categories: yard layouts with transfer lanes, yard layouts with transfer points, and yard layouts with direct transfer. The next three chapters deal each with a yard layout problem considering a given layout category.

Chapter 5 discusses the problem of designing yard layouts with transfer lanes, for which we propose two new approaches: the first approach considers different numbers of driving lanes and positions of driving lanes in the yard and the second considers variable span widths of the cranes in the yard. For the former approach a new mathematical model is proposed which can be solved as a linear programm. In addition, a variable neighborhood descent heuristic is proposed for non-rectangular shaped storage yards as the objective of the model is in this case non-linear. The latter approach uses statistical estimates for the expected cycle times of the cranes in the yard to compare layouts with different possible crane span widths.

Chapter 6 deals with the problem of designing storage yards with transfer points. We propose a model for the design of the storage yard considering costs and the performance of the storage blocks in the yard. To measure the block performance approximately we propose estimates for the cycle times of the yard cranes.

Chapter 7 examines the problem of designing storage yards with direct transfer. Again a model is proposed which uses estimates for the cycle times of the transport and yard equipment. The model identifies an optimal number of horizontal or vertical driving lanes in the layout.

Chapter 8 analyzes the suitability of different layout categories for certain scenarios. We consider RTG-based layouts with transfer lanes and RMG-based layouts with transfer points, and analyze their suitability for different transhipment scenarios. For the performance evaluation of different layouts we develop a simulation model which is able to simulate different layout configurations for different scenarios.

Chapter 9 summarizes the approaches and results of this thesis. Further possible research issues in the context of container terminal layout planning are proposed.

2. Container Terminals - Nodes in the Global Transportation Network

This chapter covers general topics concerning container terminals and questions of layout design of container terminals. General topics are the history and the current developments of the container sector, which we briefly describe in Section 2.1. Section 2.2 introduces the different processes at a container terminal. In addition to these processes the possible equipment types are depicted which can be used to fulfil different tasks at a container terminal. Section 2.3 outlines the main planning and logistic problems of a container terminal. Finally, Section 2.4 discusses in detail the layout planning problem for container terminals. Parts of this chapter are based on Wiese et al. (2011b).

2.1. Development of the Worldwide Container Sector

The passage of the vessel Ideal-X with fifty-eight metal boxes from Newark, New Jersey, to Houston, Texas, in 1956 is considered to mark the starting point of the history of the maritime container sector (see Levinson 2006, p. 1). Nowadays, containers are ISO[1] standardized boxes used to transport diverse goods. Containers are eight foot wide and most twenty or forty-foot long. A twenty-foot container is denoted as a twenty-foot equivalent unit (TEU). Correspondingly, a forty-foot container corresponds to two TEUs. The TEU measure is used to quantify the turnover of container terminals or the capacity of container ships (see Brinkmann 2005, p. 66).

The use of the standardized boxes creates the opportunity to introduce an efficient, low-cost automated system for global transport of goods (see Levinson 2006, p. 2). This leads to an expansion of the container sector with new container

[1]ISO stands for International Standardization Organization

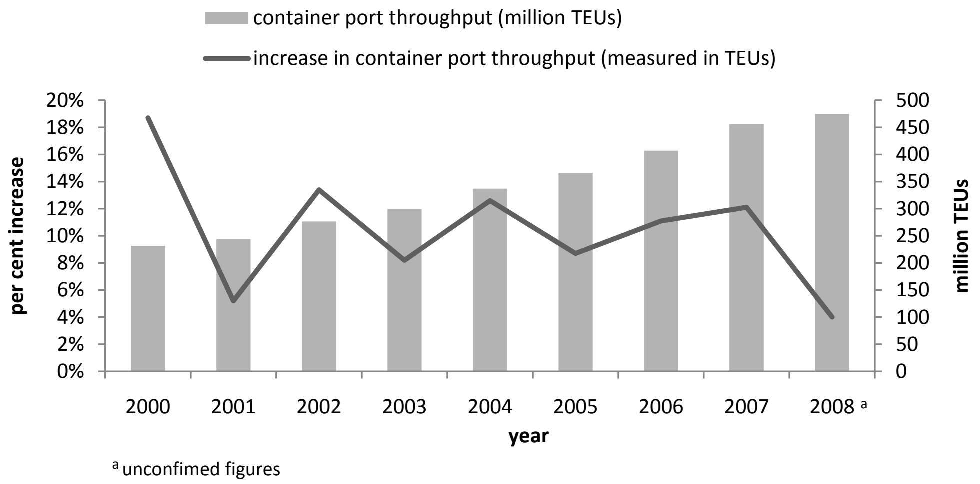


Figure 2.1.: Development of the worldwide container port throughput based on data available in the UNCTAD reports from 2003-2009

terminals all around the world. From its first days container traffic grew rapidly, e.g. the container trade (measured in TEUs) has increased from 1990 to 2007 by a factor five. This corresponds to an annual increase of 9.8%, leading to a container trade of 143 million TEUs in 2007 (see UNCTAD 2008). Figure 2.1 shows the development of the worldwide container throughput in million TEUs and the corresponding percentage increase based on the data available in UNCTAD (2003; 2004; 2005; 2006; 2007; 2008; 2009)[2]. The data in Figure 2.1 show that from 2000 to 2008 the container throughput increased continuously, albeit at changing growth rates. For instance, the high growth of about 19% in 2000 fell to 6% in 2001.

Along with the growth of the container trade there has been an increase in the size and capacity of container vessels. Table 2.1 illustrates the development of the container vessel dimensions. The first container vessels built in the late sixties had a capacity of about 1000 TEUs and a length of about 190 m. The continuous increase led to vessels of a beam wider than the maximal beam of ships that can pass through the Panama Canal (32.25 m). These are called Post-Panamax-Ships and can carry above 5000 TEUs (see Brinkmann 2005, p. 67). Nowadays, the biggest container vessels like the Emma Maersk can carry more than 14000 TEUs and have an overall length of 397 m (see Maersk Line 2010).

Recently, the continuous increase in container traffic has been interrupted due to the financial crisis. As shown in Figure 2.1 the rate of port turnover increase

[2]Please note that there are some inconsistencies between the per cent value of increase and the actual value of port throughput in million TEUs starting from 2004. Hence we calculated the port throughput in million TEUs using the per cent increase based on the actual port throughput value of 2003.

Table 2.1.: Container vessel dimensions (Source: Brinkmann 2005, p. 67)

Year of construction	Capacity (TEU)	Ship length (m)	Ship width (m)
1965/1970	760 - 1000	120 - 190	16.0 - 28.0
1970	2000 - 2800	210 - 240	28.0
1980	3000 - 4000	260 - 290	32.2
1990	4000 - 5000	280 - 295	32.2
1992	5000 - 6000	285 - 318	39.2 - 40.8
1994	6000 - 6400	295 - 318	40.0 - 42.8
1996	6400 - 7500	318 - 348	42.8 - 45.0
2002	7500 - 8400	348 - 365	48.0

reduced to estimated 4% in 2008. Preliminary figures for 2009 show that the downturn of the worldwide economy leads to a decrease in the port container turnover. For example, the container throughput of the Hamburger Hafen und Logistik AG, a major container terminal operator in Hamburg, reduced in 2009 by 32.9% (see Hamburger Hafen und Logistik AG 2010a). Another indicator is that the total turnover of China's main container ports reduced by 11% in the first quarter of 2009 (see UNCTAD 2009, p. 113f). Summing up, 2009 might be the first year after a long period of continuous growth in which the worldwide container turnover went down. However, the current worldwide economic recovery seems to be leading to a recovery in container turnover. For instance, the container throughput of the just-mentioned Hamburger Hafen und Logistik AG increased by 8.9% in the first half of 2010 over the same period of 2009 (see Hamburger Hafen und Logistik AG 2010b).

2.2. Processes on a Container Terminal and Used Equipment

A sample structure of a container terminal is shown in Figure 2.2. We distinguish three parts of a terminal: the seaside, the storage yard and the landside. The seaside consists of a quay wall, of quay cranes (QCs) which operate on rail tracks along the quay wall, and of the manoeuvring area, the so-called apron, which is the area between the quay and the storage yard. The apron is needed to provide, e.g. space for parking slots for vehicles and for driving lanes. The quay wall is divided into several berths, at which the vessels moor in order to be loaded or unloaded. In most container terminals quay cranes are used to (un)load containers (from)onto a vessel (see Brinkmann 2005, p. 254).

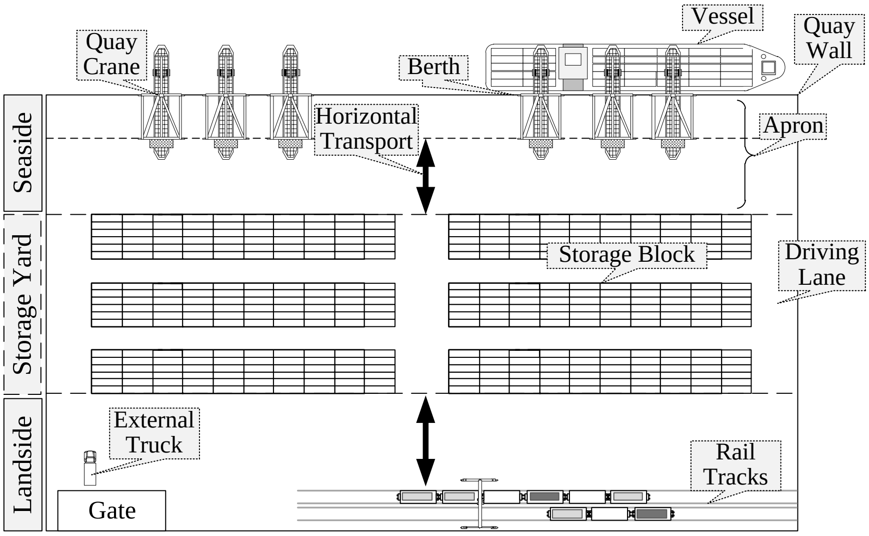


Figure 2.2.: Schematic structure of a typical container terminal

The storage yard consists of several storage blocks (or stacks) in which the containers are temporarily stacked (see Figure 2.2). The containers remain in storage blocks until they are picked up by the designated mode of transport. The storage blocks are separated by driving lanes, which provide access for transport to the storage blocks. The landside part of a terminal shows the intermodal character of the terminal as facilities exist which connect the terminal to the hinterland[3]. At most terminals there is a gate through which trucks enter the terminal to deliver or collect containers. These are called external trucks. Some terminals have several rail tracks on which trains enter the terminal to deliver or collect containers. Hence container terminals are intermodal nodes connecting the maritime transport with landside modes of transport (see Saanen 2004, p. 1f.).

Three types of container flow through a terminal (see Figure 2.3): evidently import containers arrive on the seaside and leave the terminal via a landside mode of transport (truck or train). Export containers arrive on the landside and depart over the seaside. Containers arriving and departing by seaside are called transhipment containers. The corresponding stages at a container terminal which are passed by import, export, and transhipment containers are as follows: An import container is first unloaded from a vessel by a QC. The QC passes the container to a vehicle. The vehicle conveys the container into the yard, where

[3]The hinterland is the region from which export containers originate and is the destination for import containers (see Meisel 2009).

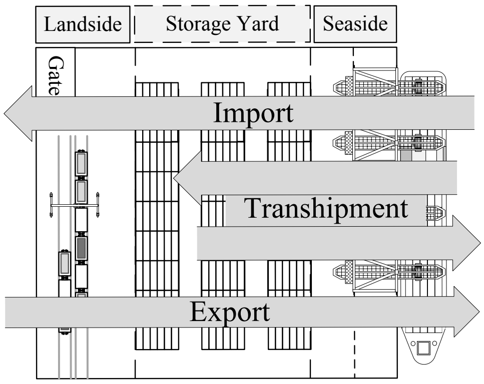


Figure 2.3.: Three different ways containers pass through a container terminal

the container is taken by a crane and stacked in a storage block. The container remains in the storage block until a truck or train arrives which collects the container. At the arrival of a truck or train the container is retrieved from the block and if necessary transported to the rail tracks. Export containers pass through the terminal in the opposite direction. Transhipment containers are also unloaded from a vessel and are conveyed into the storage yard. In the yard the transhipment containers are stacked into blocks until the vessel arrives which collects the containers. The containers are retrieved from the blocks and transported back to the seaside. At the seaside the containers are picked up by QCs which load them onto the designated vessel. In consequence, two QC moves are needed at a container terminal to handle a transhipment container, in contrast to a single move needed for an import or export container.

Terminals that mostly handle transhipment containers (about 80% of the containers are transhipped) are called transhipment terminals. For example, the container terminal Singapore has a ratio of transhipment containers of about 80% (see Petering and Murty 2009, Saanen 2004). In the case of a pure transhipment terminal (where only transhipment containers are handled at the terminal) no landside facilities are needed. The ratio of transhipment containers arriving via the seaside is defined as transhipment rate. In other words the transhipment rate denotes the percentage of containers that arrive via the seaside and depart via the seaside. Containers destined for the hinterland and handled by barges via seaside are sometimes not regarded as transhipment containers (see Saanen 2004, p. 38). In this thesis, however, this distinction is not made.

Besides the distinction between import, export and transhipment containers, containers may also be categorized by their suitability for storage of special goods. Standard containers (twenty or forty-foot) are those with no special characteristics. These standard containers usually constitute the largest proportion of containers handled at a terminal. Reefer containers are those which can refrigerate theirs contents, thus allowing transport of perishable goods. Containers with dangerous goods are called dangerous goods containers. Other typical special containers include empty or oversize. Most of these containers have to be handled specially unlike standard containers. Reefer containers, for instance, need a power supply and have to be stored in specially prepared parts of the storage yard that provide these power supplies. More details about different container types can be found in Brinkmann (2005).

The remainder of this section discusses the processes occurring in the various parts of the terminal. The seaside processes are described in Section 2.2.1. Section 2.2.2 treats of the horizontal transport of containers within a container terminal. The storage of containers is considered in Section 2.2.3. Section 2.2.4 deals with the landside processes. Finally, Section 2.2.5 summarizes the main processes at a container terminal.

2.2.1. Handling of Containers at the Seaside

The main process at the seaside is the loading and unloading of vessels. On arrival, a vessel docks at a free berth. As mentioned above, most container terminals use QCs also called ship-to-shore cranes for the (un)loading operations of containers (from)onto vessels (see Koppe and Brinkmann 2008). A schematic view of a QC is given by Figure 2.4. Some smaller terminals employ mobile cranes for the (un)loading operations, which are more flexible but have a lower performance (see Brinkmann 2005). QCs are equipped with a spreader, which enables them to dock on containers and lift them. The trolley of the QCs is used to move the containers from ship to shore (see Figure 2.4). Once a container is ashore, the QC sets the container down on a vehicle or on the apron. QCs may be categorized according to the ability of the quay crane spreader to lift more than one container at once. Conventional QCs can only lift a single container. Quay cranes with twin or tandem lift ability can simultaneously lift up to four adjacent twenty-foot containers (see Brinkmann 2005, Stahlbock and Voß 2008, p. 254). Double trolley QCs use two trolleys in (un)loading operations. In such a system a temporary storage is used between the first and the second trolley. The use of a second trolley decouples the process of (un)loading a container (from)onto a vessel from the transfer processes between QC and horizontal means of transport or the apron (see Brinkmann 2005, Stahlbock and Voß 2008).

These possible characteristics of a QC determine its performance. A common parameter to measure the performance of QCs is the quay crane rate (QCR) (see Petering et al. 2008, Saanen 2004) which denotes the number of container

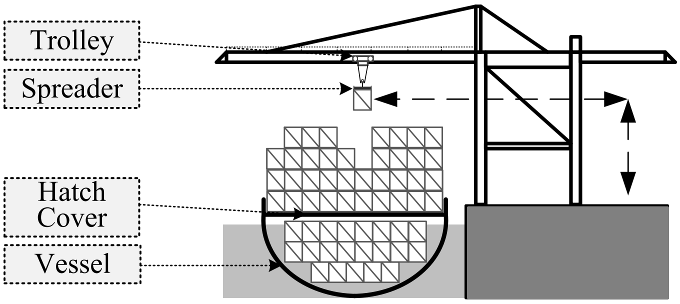


Figure 2.4.: A schematic view of a quay crane (ship-to-shore crane) with a single trolley serving a moored vessel

moves performed by a quay crane per working hour. Following Saanen (2004) and Brinkmann (2005) the QCR is in practice about 30 container moves per hour for a standard quay crane. Brinkmann (2005) and Koppe and Brinkmann (2008) state that double trolley quay cranes are able to achieve a QCR of about 45 container moves. However, the theoretical performance of quay cranes is higher (depending on the QCs characteristics, e.g. 60 moves for a standard QC) as for the QCR additional times have to be considered, e.g. waiting times for vehicles or the times needed to move vessel hatch covers (see Saanen 2004, p. 46). The waiting times for vehicles are avoidable and therefore offer opportunity to close parts of the gap between theoretical and operative QC performance. An overview of technical data on quay cranes can be found in Stahlbock and Voß (2008). A more technical description of quay cranes is given, e.g. by Brinkmann (2005).

2.2.2. Horizontal Transport of Containers

The horizontal transport of containers is needed to convey containers from the seaside area into the storage yard and vice versa. Containers have also to be transported between the landside facilities (such as rail tracks) and the storage yard (see Figure 2.2). Several transport technologies can be used for terminal operations. We distinguish active and passive transport technologies. The former are able to lift containers by themselves and do not have to be served by a crane. Active transport technologies include straddle carriers, fork lift trucks and reach-stackers. A current new development is the automated straddle carrier (see Annala 2007, Koppe and Brinkmann 2008). A similar design of automated straddle carrier is considered in the literature under automated lifting vehicles (ALVs) (see Vis and Harika 2004, Yang et al. 2004). Passive transport technologies are automated guided vehicles (AGVs), trucks and multi trailers. Several new developed transport technologies are considered for operation in container terminals. For example, the following new technologies are considered for terminal operations: linear motor-based transfer technology (LMTT) also called linear motor conveyance system (see Spasovic et al. 2004, Ioannou et al. 2001, Franke 2001), grid rail system (see Ioannou et al. 2001), “CargoRail”, “CargoMover”, “TransRapid for cargo”, and “Auto Go” (see Spasovic et al. 2004). As far as we know, these equipment types are still in a prototypic state and so far not used in productive container terminal environments.

Trucks are a common form of passive transport technology. They are called yard trucks (YTs), terminal trucks or internal trucks. Trucks pull a trailer on which either maximal two twenty-foot containers or one forty foot container can be transported. A multi trailer system is a system in which a truck pulls more than one trailer (Brinkmann 2005, p. 265). A truck system or more generally a passive transport technology is not able to lift containers. In this case the terminal operator has carefully to synchronize the movements of the horizontal means of transport and the cranes. For example, if a QC has unloaded a container and no transport vehicle is available to take the container, unproductive waiting time occurs for the QC. These waiting times lead to a decrease in the above mentioned QCR and should thus be avoided.

Straddle carriers (SCs) are a common form of active transport technology. They are able to drive over a container and lift it autonomously. Using an active transport technology enables the operator to decouple the handshake processes between horizontal means of transport and QCs. The QCs can just deposit an unloaded container on the ground of the terminal and do not have to wait for arriving means of transport. Thus waiting times for a QC occur during the unloading process only if no additional space is available under the QC to depose an additional container. A disadvantage of SCs is their relative high investment costs compared with that of trucks (see Saanen 2004, p. 49).

2.2.3. Storage of Containers in the Yard

The yard is used for the temporary storage of containers. In most terminals containers are stacked upon each other within so-called storage blocks (see Figure 2.2). After a QC has transferred a container to a horizontal means of transport, the container will be transported into the yard, where the container is stacked into a block. The container remains in the block until it is collected by another carrier (vessel, truck or train). In this case the container will be retrieved from the block and passed to a means of transport which conveys the container to its destination at the quay or the landside (depending on the mode of transport requesting the container). The main processes in the yard are thus the loading and unloading of means of transport, the stacking of containers and the retrieval of containers.

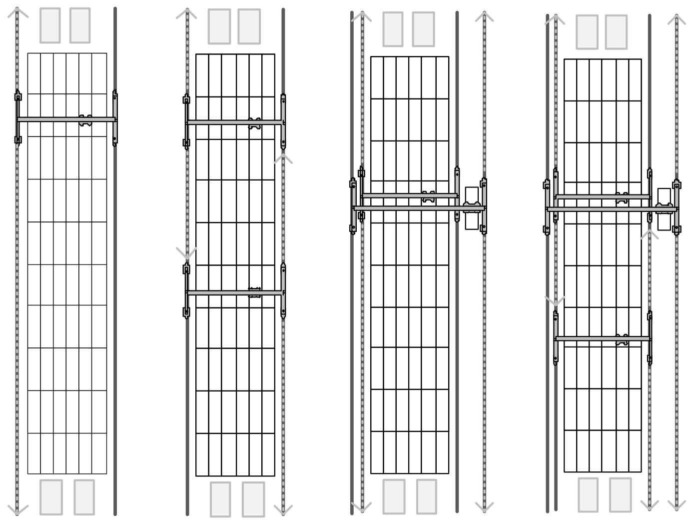
Additionally, in the case of low workload, the containers in a stack may be reordered, e.g. to prepare the stack for a specific retrieval sequence of containers. This process is called housekeeping, reorganization or remarshalling (see Saanen and Dekker 2007a, Dekker et al. 2006). A specific retrieval sequence of containers from a stack occurs as containers have to be loaded in a specific sequence onto a vessel in order to ensure that restrictions proclaimed by the shipping companies are satisfied[4]. However, even in the case that housekeeping processes are executed at a terminal, a container might be requested from a stack in which other containers are stored upon the requested container. In this case the containers on top of the requested container have to be repositioned within the block. The repositioning moves of containers within a block to retrieve another container are called rehandles (reshuffles). These rehandle moves should be avoided as they are unproductive and slow down the retrieval of the requested container. Rehandles, however, cannot be fully avoided due to the lack of available data on the exact time when a container is retrieved, especially for import containers that are collected by external trucks (see Dekker et al. 2006).

Stacking Equipment

Several equipment types can be used for stacking operations in the yard. One option is to use the straddle carriers or automated straddle carriers described in Section 2.2.2. Besides SCs several types of crane can be used as yard equipment. These include rubber-tired gantry cranes (RTGs), rail-mounted gantry cranes (RMGs), and overhead bridge cranes (OHBC) (see Brinkmann 2005, 275f). In addition, some terminals use an automated version of RMG: the automated rail-mounted gantry crane (A-RMG). Gantry cranes are equipped with a trolley and a spreader. The trolley is used for the sideward movements of containers. The spreader is used to dock on containers and to lift them. The forward and backward travel of the gantry crane itself is called gantry travel. These cranes which are used for stacking operations in the yard are often called yard cranes (YCs).

As mentioned above, most terminals stack their containers upon each other. A few terminals, however, use a so-called wheeled storage in which the containers are stored on trailers (chassis) in the yard. In this case no stacking is needed as

[4]For instance, stability restrictions for the vessels have to be considered (see e.g. Imai et al. 2006)



(a) (b) (c) (d)

Figure 2.5.: Different RMG Systems: (a) a single RMG per block, (b) two RMGs per block, (c) two RMGs of different size, and (d) three RMGs per block

the trailers can be easily picked up by a truck. An obvious disadvantage of such a system is the inefficient use of storage space (see Brinkmann 2005, p. 273).

A variation of the (A-)RMG system is the use of more than a single crane per storage block. Possible configurations are two cranes of the same size (twin RMGs), two cranes of different sizes per block (cross-over RMGs), and three cranes (triple cross-over RMGs) with two of the same size (see Saanen and Valkengoed 2005, Dorndorf and Schneider 2010). These different (A-)RMG systems are illustrated in Figure 2.5. Two cranes of the same size operate on the same rail tracks, whereas the two cranes of a cross-over RMG system operate consequently on different rail tracks. Cranes of different size have the advantage that they can cross each other (see Saanen and Valkengoed 2005, Steenken et al. 2004) in which case the larger crane has to move its trolley to the rightmost position (see Figure 2.5 (c)). Therefore, in a cross-over system both cranes can reach each end of the storage block. In contrast, cranes of the same size can only reach their corresponding end of the block. The disadvantage of cranes of different size is that additional space is needed as illustrated by Figure 2.5.

In addition to the use of A-RMGs, a future development could be the use of automated storage and retrieval systems (AS/RS) for the storage of containers. AS/RS are warehousing systems usually consisting of racks for the storage of items and cranes operating between those racks (see Roodbergen and Vis 2009). Asef-Vaziri et al. (2008), for instance, examine the potential use of such a system for container terminals in a simulation study. Hu et al. (2005) propose a modification

Table 2.2.: Statistics of yard equipment used in terminals worldwide (Source: Wiese et al. 2009a)

Yard Equipment	Frequency	%	Main region	Frequency in region
RTG	72	63.2%	Asia	40
SC	23	20.2%	Europe	15
A-RMG	7	6.1%	Europe	6
Wheeled	2	1.8%	America	2
RTG / SC	2	1.8%	Asia	2
Reach Stackers	2	1.8%	Europe	1
RTG / RMG	2	1.8%	Europe	1
automated SC	1	0.9%	Australia Pacific	1
RMG	1	0.9%	Asia	1
RTG / A-RMG	1	0.9%	Asia	1
OHBC	1	0.9%	Asia	1
$\sum$	114			

of a standard AS/RS (called split-platform AS/RS) which is appropriate for heavy loads and thus could be used in the storage yard of a container terminal.

In summary, various types of equipment can be used for the stacking of containers within the yard. A global survey of terminals with the focus on large seaside container terminals published by Wiese et al. (2009a) analyzes the proportions of the different types of equipment used in operations within the yard. In total 114 terminals were examined. The results show that an RTG system is used in 63.2% of terminals and is consequently the most common yard equipment. The second most common equipment is the straddle carrier system with a ratio of about 20%. Table 2.2 gives an overview of yard equipment used in container terminals. The region where most yard equipment installations of the corresponding type can be found is indicated by the column "Main Region". The column "Frequency in region" shows the number of terminals in the main region using the corresponding equipment type. The main region where RTG systems are implemented is Asia. Automated terminals using an A-RMG systems can be mainly found in Europe. An explanation for this might be the high labor costs in Europe, which make the use of automated equipment more attractive (see Saanen 2004, Böse 2008). For more details of the survey we refer to Wiese et al. (2009a).

Structure of Storage Blocks

The above-described types of equipment useable for stacking affect the structure of a storage block. In the following these effects are described. Figure 2.6 shows the different block structures for the most common equipment types: RTG, SC

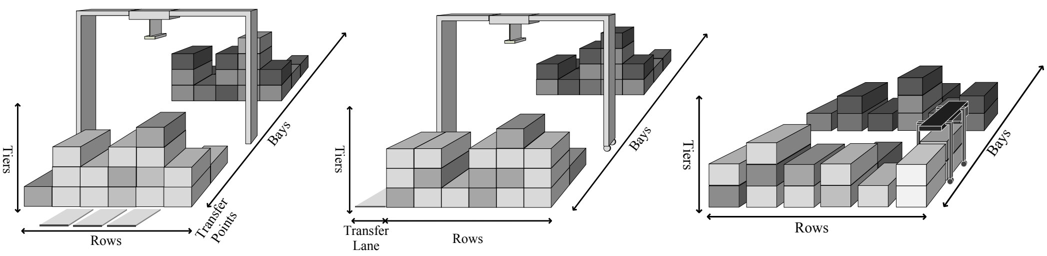


Figure 2.6.: Structures of blocks for an (A-)RMG with transfer points, for an RTG with transfer lane and for an (automated) SC

and (A-)RMG. A block is defined by the number of rows in which containers are stacked parallel to each other, by the number of bays, by the number of tiers in which containers are stacked on each other and by the space needed between bays and rows. A bay of a block (see Figure 2.6) is one column (one container in length) of the block. A slot (ground slot) of a block is the ground space on which a pile of containers is stacked. The number of twenty-foot ground slots (TGS) of a block can thus be calculated by multiplying the number of rows by the number of bays. Gantry cranes span several container rows in which containers are stacked in several tiers. (A-)RMGs are mounted on rails and therefore achieve higher gantry travel speeds than RTGs (see Stahlbock and Voß 2008). By contrast RTGs are more flexible as they are not fixed to rail tracks. In consequence RTGs can move from one storage block to another block even if the blocks are not at the same level of the terminal. A move of an RTG from one block to another at a different level is referred to as cross gantry move (see Petering et al. 2008).

RTGs can not efficiently perform a gantry travel while carrying a container, unlike (A-)RMGs which can simultaneously travel while carrying a container (see Petering and Murty 2009). This leads to different possibilities for the transfer of containers between a crane and a horizontal means of transport: RTGs can only perform a trolley travel once they have lifted a container. Accordingly, a lane parallel to the container rows is used for the transfer of containers to the vehicles (see Figure 2.6). This lane is called transfer lane. The RTG spans the container rows as well as the transfer lane, in which transport waits to collect or deliver a container. By contrast, at a block operated by (A-)RMGs transfer points could be used for the transfer. Transfer points are positioned at the start and end of the rows of a block (see Figure 2.6). Means of transport wait at the transfer points to retrieve (deliver) a container from (to) an (A-)RMG. (A-)RMGs can, however, also use a transfer lane option or combine both, transfer lane and transfer points.

When SCs are used for the stacking operations as well as for horizontal transport no transfer between stacking equipment and horizontal transport is needed as

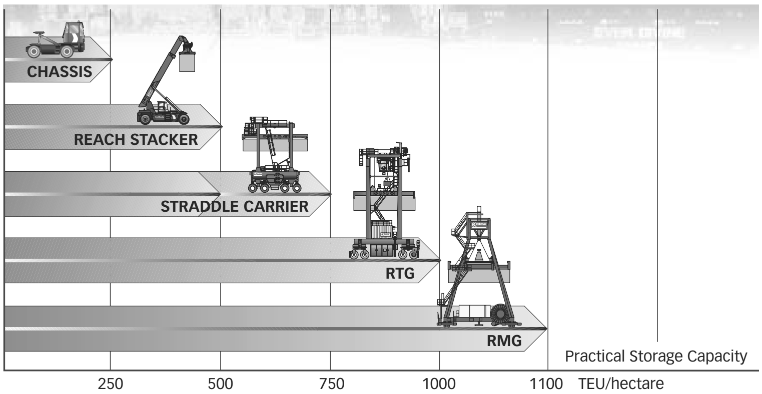


Figure 2.7.: Stacking densities of different equipment types (Source: Kalmar 2008b)

both operations are performed by SCs. Nevertheless, SCs might be used in a "straddle-carrier-relay" system (see Günther and Kim 2005, Vis and Roodbergen 2009). The SC relay system is a SC-based system with no direct transfer. Thus SCs are only used for stacking, and trucks e.g., are used for the horizontal transport. In such a system transfer points at each end of the rows are needed. In summary, there are three transfer options: indirect transfer either with transfer points (e.g., in the case of (A–)RMGs) or with transfer lanes and direct transfer. In the following we define the block structure by the transfer option together with the equipment type used for stacking operations. The actual number of rows and bays of a block considering a given block structure is defined by the block design.

Another difference between SC and gantry crane systems is the stacking abilities of the equipment. Blocks operated by SCs have wider space between the rows of a block (see Figure 2.6). By contrast, gantry cranes can stack container closer to each other. Moreover, SCs are currently restricted to four tiers (see Kalmar 2008a), whereas RTG and RMG systems currently available can stack containers up to seven tiers high (see Shanghai Zhenhua Heavy Industry 2009). Given different stacking capabilities and other characteristics of the equipment, different stacking densities (yard densities) can be achieved by each of the above-described systems. Stacking densities might be expressed by the number of TEU stored per hectare yard (see Saanen 2004, p. 47). Figure 2.7 illustrates different stacking densities. Stacking densities can be used to limit the possible equipment types. For instance, when space is limited in a terminal some equipment types might be impractical. Expecting a high annual capacity and having less space available for the yard, the use of an SC system could be impossible.

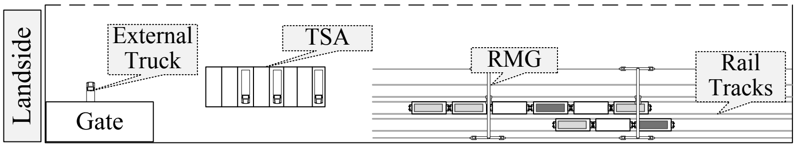


Figure 2.8.: Scheme of the landside part of a container terminal with a truck service area

2.2.4. Handling of Containers at the Landside

The landside is the remaining functional part of a terminal. As mentioned above the landside connects the terminal to its hinterland via road and rail connections as shown in Figure 2.8. Trains and trucks arrive at the landside to pick up import containers which have arrived via the seaside or deliver export containers due to depart via the seaside. External trucks have to enter the terminal through a gate where containers and corresponding transport documents are checked (see Meisel 2009, p. 15). Where gantry cranes are used for the stacking operations, external trucks can be handled at the blocks by the cranes. Where SCs are used for stacking, an additional truck service area (sometimes called truck lanes) is needed (see Figure 2.8). Such a truck service area (TSA) is mostly located in the landside area of the terminal. External trucks wait at the TSA after they have entered the terminal through the gate. SCs travel to the TSA and serve the waiting trucks either by delivering an import container from a storage block to the truck or by collecting an export container from the truck.

Additional to a road connection via a gate some terminals have several rail tracks. For the service of trains special types of RMG are commonly used. At some terminals SCs also undertake the task of (un)loading trains (see Brinkmann 2005, p. 260). In Froyland et al. (2008) a new concept of train and truck service area is proposed in which RMGs span the rails, truck lanes, and in addition an "Intermediate Stacking Area", where containers are temporarily stored for landside operations. In this configuration the landside RMGs serve trucks in addition to trains. This new approach is implemented at the Port Botany terminal in Sydney.

2.2.5. Summary of the Main Processes

Above the main processes and the equipment used are described. Figure 2.9 summarizes the main processes at a container terminal. At the seaside the vessels are loaded and unloaded. This is mainly done by quay cranes (ship-to-shore cranes). In the yard the containers are temporarily stored. The main operations in the yard are the stacking and retrieval of containers and the service of means

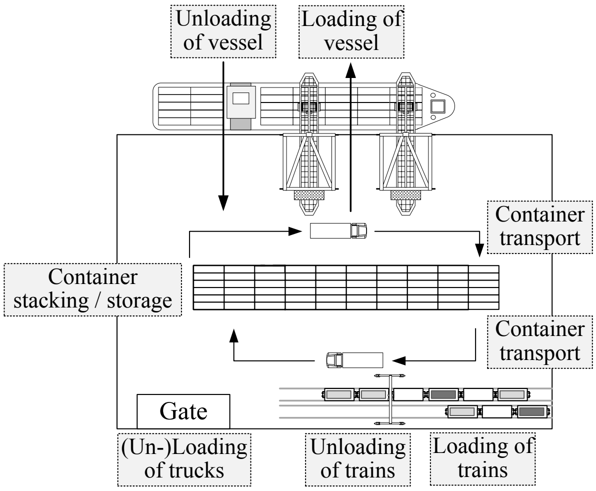


Figure 2.9.: Main processes at a container terminal

of transport. Some terminals additionally perform housekeeping operations to improve the loading process of the vessels. Important equipment types for the yard operations are RTGs, (A-)RMGs, SCs and OHBCs. At the landside trucks and trains are served. For the landside operations similar equipment types are used as for the yard operations. The three parts of the terminal, the landside, the storage yard and the seaside are linked by the horizontal transport of containers.

2.3. Planning and Logistic Problems at Container Terminals

In Section 2.2 the different processes and equipment used at a container terminal are described. To coordinate these processes several logistic problems have to be solved. Moreover, there are several planning problems for container terminals. In this section some of the logistic and planning problems are briefly described to give an overview of the decision processes at container terminals. More details about logistic problems concerning container terminal operations and solution approaches can be found in the extensive surveys of Vis and de Koster (2003), Steenken et al. (2004), Stahlbock and Voß (2008) and Vacca et al. (2008). Günther and Kim (2005; 2006) give an introduction to the field of container terminal operations and Crainic and Kim (2007) describe several problems and solution approaches.

Figure 2.10 gives an overview of problems occurring at container terminals. Problems can be differentiated by planning level, i.e. by the real-time, operational, tactical and strategic level (see Vis and Harika 2004, Meisel 2009). Günther and

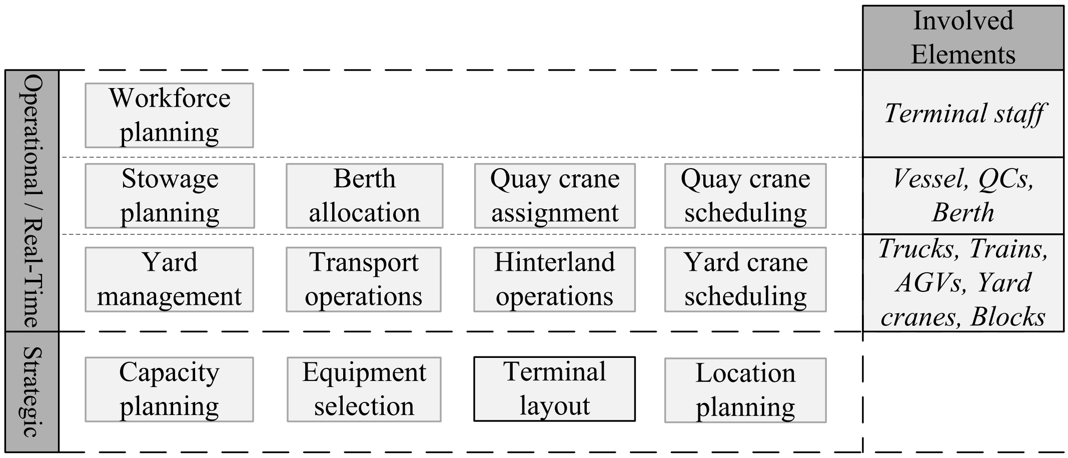


Figure 2.10.: Planning and logistic problems at container terminals (Sources: Günther and Kim 2006, Bierwirth and Meisel 2010)

Kim (2006) differentiate between terminal design problems, operational problems, and real-time problems. The different planning levels can be distinguished by the time horizon which covers the decision made at a planning level. Strategic decisions last for the longest time, followed by tactical decisions and operational decisions. Real-time decisions last only for a very short period of time. The exact definition of the time horizons for which the decisions last are defined differently in the literature. Following Meisel (2009) strategic problems lead to decisions which last for a time horizon of years. Tactical decisions cover a time horizon ranging from weeks to several months. Operational problems cover a time horizon from a day to months (see Vis and Harika 2004). Real-time decisions are those which are connected to the operation of terminal equipment, i.e. the assignment of jobs to transport vehicles. Thus real-time decisions are made every minute (see Vis and Harika 2004, Günther and Kim 2006) which leads to very short planning horizons for real-time problems (see Meisel 2009). Therefore a quick generation of decisions is needed for real-time problems. Following Günther and Kim (2006) we do not distinguish between tactical and strategic problems. Thus Figure 2.10 divides the problems in two categories of strategic problem and operational or real-time problem.

As mentioned above we focus in this thesis on the terminal layout planning problem. This is a strategic problem in the field of terminal design. In the following Section 2.3.1 we first briefly describe several operational problems to help the reader to understand the complex system of a container terminal. Moreover, when building a simulation model, several of the following operational problems described have to be considered. Finally, we discuss strategic problems in Section 2.3.2.

2.3.1. Operational Problems

In the following, operational problems at container terminals are described. Workforce planning is the task of scheduling workers for different tasks on a terminal. Hartmann (2004a), for instance, proposes a general framework which, besides other problems, is applied to the problem of scheduling workers who handle reefer containers. Operational problems which are connected to arriving vessels, QCs and berths are those of stowage planning, berth allocation, quay crane assignment and quay crane scheduling (see Figure 2.10). The stowage planning problem generates a plan in which each departing export container is assigned to a loading position in a vessel. For the creation of the stowage plan the shipping company provides data to the terminal operator which proclaims for each slot of the vessel container characteristics like container weight, destination port etc. (see Steenken et al. 2001). The assignment of containers to loading positions in the vessel defines a sequence in which QCs have to load containers onto a vessel. Variations of the loading sequence may be possible for containers having the same characteristics (weight, destination port etc.) as these containers might be interchangeable (see Dekker et al. 2006). Solution approaches are presented, for instance, by Steenken et al. (2001) and Imai et al. (2006). The berth allocation problem is that of assigning berths and service times to vessels arriving at the terminal (see Bierwirth and Meisel 2010). After a berth is assigned to a vessel, the available QCs, which are needed for the (un)loading operation of the vessel, have to be assigned in addition. This problem is called quay crane assignment. The scheduling of the quay cranes to sections of the vessels is done in the quay crane scheduling. Bierwirth and Meisel (2010) describe these three problems in more detail and give an overview of existing literature concerning these topics.

Problems associated with the yard and the landside are those of yard management, yard crane scheduling and hinterland operations (see Figure 2.10). Yard management deals with storage processes in the yard. For instance, arriving containers have to be assigned to a specific storage block and a slot therein. For the assignment of containers to storage blocks and slots so-called stacking policies can be applied (see Dekker et al. 2006, Saanen and Dekker 2007b;a). These stacking policies are rules on how to allocate containers to a specific slot within a block. Optimization models for the yard management of transhipment terminals have been proposed by Lee et al. (2006) and Han et al. (2008). They consider the assignment of storage space in the yard to containers arriving by vessels. These approaches, however, do not consider the assignment of concrete containers to specific storage positions but the assignment of ranges in the yard to containers unloaded from a specific vessel. The assignment of storage space in the yard is also discussed for instance by Zhang et al. (2003).

Transport operations (see Figure 2.10) are concerned with problems arising from the horizontal transport of containers between the quay and the storage yard and between the storage yard and the landside. For example, Briskorn et al. (2007), Grunow et al. (2005) and Kim and Bae (2004) treat the dispatching of AGVs to transport jobs. Böse et al. (2000) and Steenken et al. (1993) deal with the routing and dispatching of SCs in container terminals.

For hinterland operations the processing of trucks and trains has to be coordinated. An example of a problem concerning hinterland operations is described in Froyland et al. (2008) where RMGs serving trucks and trains are scheduled.

For yard cranes, several storage or retrieval jobs have to be scheduled. For instance, Petering et al. (2008), Ng and Mak (2005), Ng (2005) and Li et al. (2009) examine the YC scheduling problem. The scheduling of SCs (in a relay system) performing storages and retrievals is considered in Vis and Roodbergen (2009).

We have above briefly described operational problems at container terminals. These individual problems, however, are interrelated and mutually influential. The berth allocation problem, for instance, is influenced by the quay crane assignment problem because QC assignment strongly affects the handling time of vessels (see Bierwirth and Meisel 2010). Integrated approaches that consider the interrelations of different problems are becoming increasingly vital (see Steenken et al. 2004). The approaches of Meisel and Bierwirth (2009) and Imai et al. (2008) are examples of integrated consideration of berth allocation and QC assignment problem.

2.3.2. Strategic Problems

In planning a container terminal an appropriate location has first to be selected. In a subsequent step its capacity has to be planned (see Figure 2.10). Thus terminal planners determine the seaside capacity in a first step. This can be defined by the length of the berth and the number of allocated QCs. The basis for the calculation of the seaside capacity usually forms a forecast schedule of vessel arrivals (so-called vessel call pattern) and a (minimum) throughput target per QC claimed for the considered planning horizon. The forecast vessel arrivals includes specifications of ship characteristics like length and capacity. From these data the berth length and the number of QCs needed to handle the assumed numbers of vessels can be determined. These values can, for instance, be used in a simulation study to determine seaside capacity (see Ficke and Schütt 2008, Brinkmann 2005).

The seaside capacity forms the basis of further steps in the design process. Estimates of the arrival rates of trucks and trains can be derived from the planned seaside turnover (capacity) considering a forecast transhipment rate. From the estimated arrivals, the capacity of the landside facilities like gate and rail tracks can be calculated. Therefore the number of lanes and rail tracks should be determined, which itself determines the size of these facilities. In addition, the yard capacity, i.e. the storage capacity of the yard, is derived from the seaside capacity. The yard capacity can be estimated from an envisaged seaside container turnover, the dwell time of the containers in the yard, and a peak factor. Brinkmann (2005) and Chu and Huang (2005), for example, examine the problem of determining the yard capacity. In summary, the seaside, landside and yard capacity are defined via the capacity planning process of a terminal.

Another strategic problem is the selection of equipment for terminal operations. In Section 2.2 the different possible equipment types are described. In the equipment selection problem appropriate equipment has to be selected for the different tasks of a terminal. To select appropriate equipment the prior estimated capacities have to be considered. For instance, the yard capacity and the space available for the yard might restrict possible equipment types for the stacking operations (see Section 2.2.3). Where several equipment types are suitable for the planned terminal an equipment type has to be selected. Costs, performance aspects and technical restrictions are among considerations for the selection of equipment. During the equipment selection process it is important to take into account that the combination of equipment for the different tasks of a terminal (e.g., stacking and horizontal transport) have to work together smoothly. In Brinkmann (2005) the following common terminal systems (combinations of equipment) are described:

– Straddle-Carrier-System (direct): All tasks are performed by SCs. A modification of this system is the use of gantry cranes for landside operations instead of SCs.

– RTGs with yard trucks: The yard trucks are used for the horizontal transfer of containers and RTGs for the operations in the yard. A possible modification of the systems is the use of other horizontal transport equipment such as multi-trailers.

– RMGs with yard trucks/AGVs: RMGs are used for the stacking operations in the yard, and yard trucks/AGVs are used for horizontal transport.

- OHBC with yard trucks/AGVs: OHBCs are used for the stacking operations in the yard, and yard trucks/AGVs are used for horizontal transport.
- Reach-Stacker with yard trucks: Reach-Stackers are used for the yard operations and yard trucks for the horizontal transport.

The costs of different terminal equipment can be found in Saanen (2004) and Stahlbock and Voß (2008). Simulation is widely used in the comparison of performance of different equipment or to compare the performance of different complete terminal systems. More details of the steps in the container terminal planning process can be found in Saanen (2004). In this thesis we consider the strategic problem of planning the layout of container terminals, which is described in detail in the next section.

2.4. The Layout Planning Problem of Container Terminals

In the previous section the different operational and strategic problems occurring at a container terminal were briefly described. In this section the strategic layout planning problem of container terminals is explained in detail. We also discuss other strategic problems mentioned above and their influence on the layout planning problem. Finally, the problem of designing yard layouts is illustrated. In this section we do not describe in detail each possible subproblem arising from the container terminal layout problem. The detailed descriptions follow in the corresponding later chapters which explicitly cover a subproblem.

The remainder of this section is structured as follows: Section 2.4.1 deals with the general layout planning problem of container terminals and its aims. In Section 2.4.2 the impact of the other strategic problems on the characteristics and conditions layout planning problem are discussed. Finally, in Section 2.4.3 we focus on the layout of the main part of a terminal, the yard layout.

2.4.1. Container Terminal Layout Planning

In accordance with the three parts of a terminal, the layout planning problem can be subdivided into yard, seaside and landside layout planning. The yard layout planning itself has the subproblem of designing storage blocks. The seaside layout (see Figure 2.2) is defined by berth length, the number of quay cranes and the distance between quay and storage yard (size of apron). These elements have to be designed in a proper way. The apron, for instance, has to provide a sufficient number of driving lanes and of waiting or parking positions for transport vehicles. The landside layout (see Figure 2.8) may consist of a gate, truck service areas and rail tracks. The elements of the landside layout are optional because pure transhipment terminals for instance do not need a gate or rail connections. To define a landside layout the dimensions of the needed elements have to be specified (e.g., the number of truck lanes of the gate) as well as their positions.

The major part of a terminal and hence of its layout is made up by the yard layout. The yard layout (see Figure 2.2) is composed of storage blocks, the structure, orientation and design of these blocks, and the driving lanes separating blocks. Consequently the yard layout problem is concerned with the organization of the elements of a yard: the storage blocks and the driving lanes considering a given block structure. The block structure is determined by equipment type used and, more importantly, by the options for transferring a container between a storage block and a horizontal means of transport (see also Section 2.2.3). During the block design the configurations of the blocks are determined considering different block widths (number of rows) and different block lengths (number of bays). These characteristics of a block might be restricted by the block structure.

An aim of the layout planning is to design a terminal which allows a smooth operation achieving an envisaged annual terminal throughput, quay performance (QCR) and performance levels for landside modes of transport. For instance, the apron area of the seaside layout has to be defined in a way that avoids obstruction between transport equipment units which leads to waiting times of the QCs. Moreover, during the layout planning, costs and restrictions (organizational, technical) have to be considered. Organizational restrictions might occur when automated equipment is used as special security issues might have to be considered, such as the fact that in some cases no staff are allowed to access the area where automated equipment is operating. Technical restrictions flow from equipment selected. For instance, the required width of the driving lanes depends on the technical characteristics of the transport technology used.

2.4.2. Layout Planning and External Impacts

The layout planning problem and its subproblems have been described above. We have thus already mentioned that the block structure is influenced by the stacking equipment selected and that the estimated capacities have to be taken into consideration in the planning of a container terminal. In the following we describe in detail the different influences of both other strategic problems on the layout planning problem. Figure 2.11 illustrates the tasks layout planning and equipment selection as well as seaside, yard and landside capacity planning

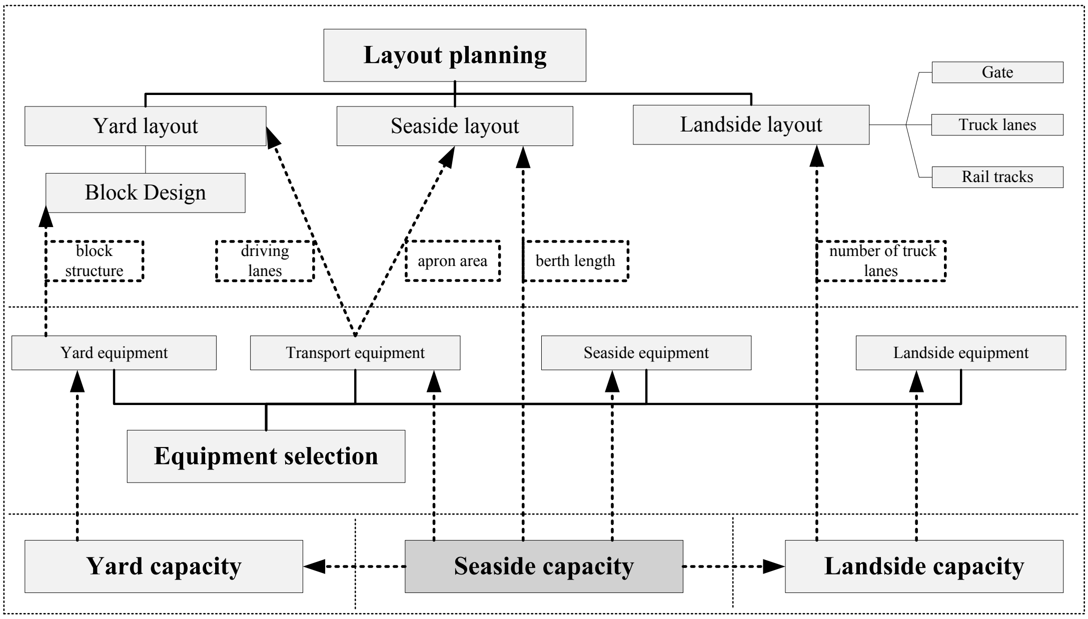


Figure 2.11.: Relationships between the different planning tasks: layout planning, equipment selection as well as yard, landside and seaside capacity planning

and their mutual influences. As mentioned above, the first step of the terminal planning process is to determine the seaside capacity. The needed landside and yard capacities are subsequently derived from the prior calculated seaside capacity. Thus both capacities have to be designed for the handling of the container flow derived from the seaside capacity. The different capacities influence the corresponding equipment selection problems, which in turn influence the layout planning problem. For instance, the block design problem and therefore the yard layout problem are influenced by the yard equipment selected. The yard equipment itself is restricted by the yard capacity. The structure of the driving lanes is influenced by the transport equipment selected. The seaside layout is influenced by the transport equipment (required size of apron area) and by the seaside capacity which specifies the berth length. The landside layout is influenced by the required landside capacity which specifies, e.g. the needed number of truck lanes or rail tracks.

In consequence the planning tasks of equipment selection, of determining the seaside, yard and landside capacity have to be carried out before the layout planning. When these tasks are finished, the information gained is used for the layout planning: One part of the seaside layout can be defined using the berth length resulting from the seaside capacity as well as considering the restrictions of the selected QC technology. The remaining part of the seaside layout, the apron area, can be defined using the information on the chosen transport equipment

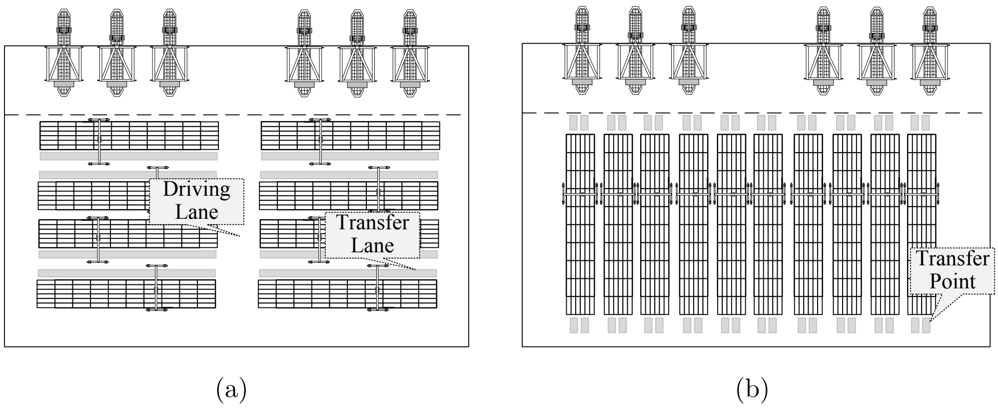


Figure 2.12.: Parallel layout with transfer lanes (a) and perpendicular layout with transfer points (b) operated by gantry cranes

and the seaside capacity. The chosen transport equipment and seaside capacity are used to determine the required number of driving lanes and parking positions which compose the apron area. This, however, is not a trivial task as the apron has to be designed in a way that allows smooth traffic without disturbance, but it still should not waste valuable space.

To define the landside layout the gate, truck lanes and rail tracks have to be positioned. As the landside connection of rail tracks and streets have to be considered, the possible placement positions could be limited. The remaining problem is to determine the yard layout. The characteristics of the driving lanes are defined by the transport equipment selected and thus the equipment selection again influences the terminal layout planning (see Figure 2.11). The problems occurring during the planning of yard layouts are described in the next section.

2.4.3. The Yard Layout

The storage yard layout is defined by the organization of the driving lanes, by the number of driving lanes, by the orientation of the storage blocks, the block structure and the design of the storage blocks. The orientation of the storage blocks can either be perpendicular or parallel to the quay (in the case of a single straight quay wall). Figure 2.12 shows two typical layouts of differing block orientation. The layout in Figure 2.12 (a) displays a layout with blocks parallel to the quay and a transfer lane at each block. This is a common layout when RTGs are used for stacking operations. The study of Wiese et al. (2009a) shows that in about 90% of cases where RTGs are used for stacking a parallel layout with transfer lanes is used. The layout in Figure 2.12 (b) is a perpendicular layout of blocks where transfer points are used at both ends of the blocks. This layout is

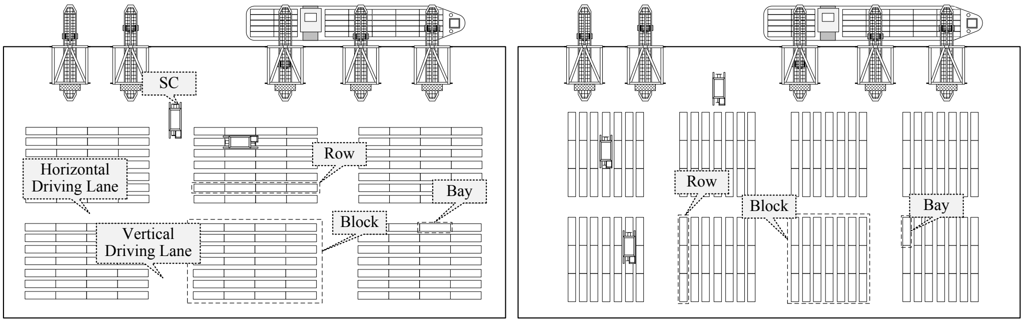


Figure 2.13.: Parallel layout and perpendicular layout with direct transfer

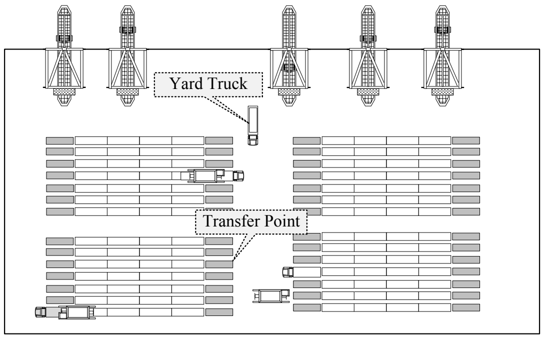
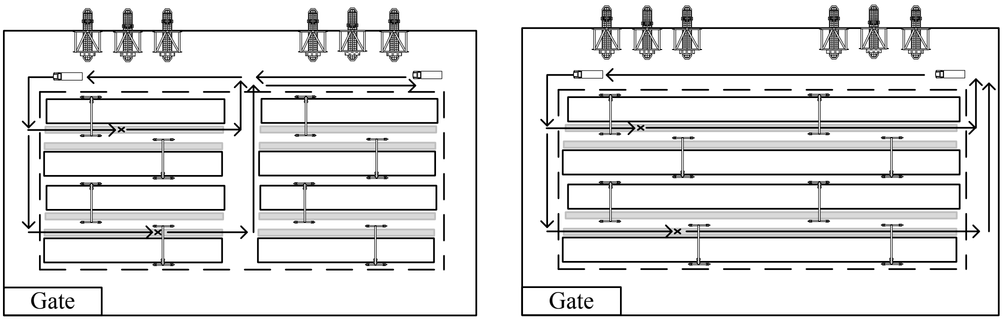


Figure 2.14.: A SC operated terminal with indirect transfer ("straddle-carrier-relay" system)

frequently used in combination with RMGs or A-RMGs for stacking operations (see Wiese et al. 2009a). As mentioned in Section 2.2.3 the transfer lane and transfer point option can be combined when using for instance A-RMGs.

When using active transport technologies for stacking as well as for horizontal transport no transfer points or lanes are needed. Nevertheless, the rows in which the containers are stored, can either be arranged in parallel or perpendicularly to the quay. Figure 2.13 shows the possible orientation options of a direct transfer-based layout. As mentioned above, SCs can also be used in a relay system without direct transfer. Figure 2.14 illustrates such a SC-relay system. As illustrated by Figure 2.14 and Figure 2.12 (b) there are still differences between a SC system and an RMG system with transfer points, even though both use transfer points. For instance, in an RMG system the width of a block is restricted by the maximal span width of an RMG, whereas the width of a SC operated block is not limited in theory (only by the width of the whole yard). Moreover, the movement capabilities of the two equipment types are quite different. Consequently, both options, the equipment and transfer option, have to be considered when defining a block structure. According to the block structure, container terminal layouts



(a) (b)

Figure 2.15.: Parallel RTG-based layout with transfer lanes (a) with one additional vertical driving lane and (b) with no additional driving lane

can be categorized. In this thesis we consider the categories which are illustrated in Figure 2.12 and Figure 2.13. These are (RTG-based) yard layouts with transfer lanes, (RMG-based) yard layouts with transfer points and (SC-based) yard layouts with direct transfer.

As mentioned in the previous section, the tasks equipment selection and capacity planning precede the layout planning of a terminal. In consequence, the block structure (used equipment and transfer option) are known before the layout is planned. This allows us to consider different yard layout problems for each layout category. For instance, the yard layout of an RTG-based layout with transfer lanes, as shown in Figure 2.12, can be considered as a yard layout problem. Other problems are the design of yard layouts with transfer points or the design of yard layouts with direct transfer. For all problems similar aspects such as block length and width (block design) have to be determined. In the following we discuss the different trade-offs that arise when a yard of a container terminal is planned. Thus we use the example of RTG-based layouts with transfer lanes. As mentioned before, detailed description of the problems considered in this thesis is given in the corresponding chapter that focuses on the problem.

For the design of a yard layout with transfer lanes the orientation of the blocks (either parallel or perpendicular), the length and width of blocks can be considered as variables. The block length in a transfer lane layout depends directly on the number of driving lanes in the layout. For the width, however, several restrictions concerning the maximal span width of RTGs have to be considered. Figure 2.15 shows two possible layout configurations for a parallel RTG-based layout with transfer lanes. The layout in Figure 2.15 (a) has an additional driving lane in contrast to the layout in Figure 2.15 (b). One obvious advantage of layout (a) is that it allows shorter travel distances for internal yard trucks. The additional driving lane in the middle of the yard is used by the yard trucks to get back to the seaside, whereas the trucks in layout (b) have to travel the whole distance of the yard to get back to the seaside. The additional driving lane, however, has a drawback as additional land is needed for the installation of the driving lane. Terminal operators have two options in providing this additional land: either to decrease the space for stacking and to use the available space for the driving lane, or to increase the width of the terminal by the space required for a driving lane (see Petering and Murty 2009). The disadvantage of the first option is the reduced availability of stacking space (lower number of TGS) which leads to an increased average stacking height when the same amount of containers is stacked at a lower number of TGS (see Kim et al. 2008). This increases the probability that rehandles occur. The second option has the disadvantage of an increased terminal area, which on the one hand leads to higher costs for land and on the other increases the possible maximal distances of the YTs and of the YCs. An advantage of this option is that YCs are distributed over a greater area and that in consequence the probability of interference between YCs decreases (see Petering and Murty 2009).

The two options for providing additional land can be distinguished by assumptions about the terminal area: if the terminal area is changeable, the increase in the terminal land is possible, whereas a fixed terminal area excludes this option and only allows the increase of the average stacking height. In summary, there are several trade-offs in designing an RTG-based layout. There is a trade-off between shorter truck distances and higher average stacking heights (higher probabilities of rehandles) if a fixed terminal area is assumed. Assuming a flexible terminal area and a constant stacking height there are trade-offs between possible shorter truck distances, a lower probability of YC interference on one side and higher possible maximal distances of trucks and YCs as well as a higher use of land on the other side. In addition, if a flexible terminal area is assumed without a restriction on the stacking height, all the above-mentioned trade-offs have to be considered to find a satisfying layout configuration.

Another matter connected with the layout design of a storage yard is the determination of a distribution of special container storage areas. This problem arises since some container types have to be stored in special areas in the yard. For instance, reefer containers need a power supply which is provided by so-called reefer racks (see Section 2.2). Another example is that of dangerous goods containers which have to be stored in specially prepared areas to satisfy safety requirements (see Brinkmann 2005). Thus there is the problem of how to distribute these special areas (e.g., the reefer racks) over the available storage yard. The chosen positions or the distribution of the special container areas influence the travel distances of the horizontal means of transport for the transport of containers. Moreover, the workload balance of the YCs is influenced by the distribution of the special storage areas as only these blocks can handle the corresponding special containers. An intensive concentration of special storage areas on a few blocks can lead to a high workload for these blocks especially in situations where the traffic of the corresponding special containers makes up a great proportion of the overall container traffic.

3. State of the Art: Layout Planning of Container Terminals and Related Problems

In the previous chapter several operational and strategic problems concerning container terminal logistics were described and at the end the layout planning problem for container terminals was introduced in detail. This chapter discusses the literature on topics of container terminal layout planning. As mentioned above, we concentrate on the layout planning problem or on subproblems of the layout planning problem (e.g., the yard layout planning problem) and try to provide OR-based methods for these problems. We therefore focus in this chapter on methods related to OR which deal with aspects of container terminal layout planning. For a survey of approaches to general logistic problems at container terminals we refer again to Vis and de Koster (2003), Steenken et al. (2004), Stahlbock and Voß (2008) and Vacca et al. (2008).

The remainder of this chapter is structured as follows: in Section 3.1 problems related to the layout planning of container terminals and general approaches for the facility planning of terminals are described. Besides these related and general approaches, we focus on approaches which are explicitly related to container terminal layout planning. In the following we distinguish between simulation models and analytical approaches[1] when discussing the literature on planning of container terminals. The simulation models are described in Section 3.2 and analytical approaches in Section 3.3.

3.1. Related Problems and General Approaches

In this section problems from other fields are described that are related to the layout planning of container terminals as well as general approaches which focus on the overall planning of container terminals and not on specific OR-based

[1]For a detailed discussion of the terms simulation, simulation model and analytical solution we refer to Law (2007) p. 4f.

methods. The former problems are described in Section 3.1.1 and the latter in Section 3.1.2.

3.1.1. Related Problems

Related to the planning of layouts of container terminals is the planning of facility layouts or the design of warehouses. Planning the layouts of facilities is a well-studied OR problem in the literature. Meller et al. (1999) define the facility layout problem as follows: "In the facility layout problem (FLP) we are to find a non-overlapping planar orthogonal arrangement of n rectangular departments within a given rectangular facility of size $L^x \times L^y$ so as to minimize the distance based measure $\sum_{j>i} f_{ij} d_{ij}$, where f_{ij} is the amount of flow between departments i and j and variable d_{ij} is the rectilinear distance between their centroids." There are several special cases of the facility layout problem each having its own specific restrictions. Nearchou considers e.g. a loop layout where objects are "arranged in a closed ring-like network" (Nearchou 2006). Other examples are single or multi-row layouts (see Drira et al. 2007).

Interesting models for the FLP are the current mixed integer formulations for the facility layout problem by Meller et al. (2007), Xie and Sahinidis (2008), which adopt the sequence pair concept introduced by Murata et al. (1996) for a related problem. These models for the FLP can be used as a basis for the positioning of elements in a terminal. For instance, they can be used to find an optimal position of the gate or to find positions for special storage areas. For the general design of a terminal layout, however, the FLP cannot be used as most FLP models assume a given number of objects which have to be arranged. The focus of the yard layout planning of container terminals, however, is the determination of the number of driving lanes in the yard or the design of the blocks which both define the number of objects in the yard. In consequence, the number of objects is not given in advance as assumed by the FLP models. As we focus on the yard design of container terminals we refer for more detail on the facility layout problem to the surveys of Meller and Gau (1996), Domschke and Krispin (1997), Singh and Sharma (2006), and Drira et al. (2007).

Another related problem is the development of travel-time models for AS/R systems. On designing a layout of a container terminal several estimates for movements of terminal equipment can be used. Similarly, the travel-time models for AS/R systems use estimates for the movements of an AS/RS. Bozer and White (1984), for instance, propose a travel-time model for a standard AS/R system. As mentioned above, Hu et al. (2005) propose a modification of a standard AS/RS for the storage yard of container terminals and they also develop a travel-time model for the proposed kind of AS/R system. Nevertheless, the travel-time models cannot be simply adapted to a container terminal system without an AS/RS due to the different characteristics and restrictions of the movement of AS/R systems compared with the movements of other container terminal equipment (see Kim et al. 2008). Terminal estimates depend, for instance, on the number of driving lanes in the yard, whereas no corresponding element exists for an AS/RS.

Other related problems occur for the design of manual order picking areas in warehouses. Hall (1993), Roodbergen and Vis (2006), and Roodbergen et al. (2008) study the design of layouts of order picking areas in warehouses. They derive estimates for the expected distances of order pickers for their movements through a warehouse. This distance is influenced by the number of aisles in the warehouse layout. However, the estimates cannot be adapted to the movements of container terminal equipment, as the movement characteristics are different. For example, manual order pickers pick up several items during one movement, whereas internal trucks mostly collect a single container (or a maximum of two 20-foot containers) from the yard. In consequence the movements of the pickers within a warehouse differ from those of horizontal means of transport in terminals. The estimates in Roodbergen et al. (2008) for the movements of the order pickers are based on a complex routing heuristic of order pickers (S-Shape heuristic, see Roodbergen and Koster 2001).

3.1.2. General Approaches

General approaches concerning the planning of the whole facility of a container terminal can be found in Brinkmann (2005) and Watanabe (2006). Brinkmann (2005) focuses on the planning of general seaports and in this context on planning aspects for container terminals. Brinkmann (2005) describes several possible equipment systems for a container terminal and their advantages and disadvantages. She also presents the results of a study in which the seaside capacity for a new container terminal is determined via simulation. In a following step, the required area sizes of different equipment systems are compared.

General container terminal and technical topics are described in Watanabe (2006). The design of the seaside layout including the apron is described considering different traffic lane widths for equipment like SCs. Possible layout configurations (parallel and perpendicular layout) are also described, focusing on straddle carrier systems or on systems with RTGs and yard trucks. These layout descriptions contain information on different space restrictions. However, no specific OR-based methods are proposed to design the layout of a container yard. Another topic in Watanabe (2006) which is related to the layout planning is the use of queueing theory to calculate the required number of lanes for the gate and methods to determine the storage capacity of the yard.

3.2. Simulation Models for Container Terminals

Several studies which use simulation to analyze various aspects concerning container terminal logistics have been published. Some of these studies use simulation to analyze operational or even real-time decisions during the terminal operations. Legato and Mazza (2001), for instance, model the berth processes of a container terminal as a queuing network model. For several reasons (e.g., complex resource allocation policies) they are not able to solve the model analytically. Accordingly they use discrete-event simulation for their analysis. Another example is Dekker et al. (2006) who use simulation to study different stacking policies (see also Section 2.3). However, these simulation models are used for operational considerations and not for layout planning. In the following we focus on simulation models that are related to layout planning topics. For an overview of simulation studies we again refer to the above-mentioned surveys and to the summary of simulation studies in Petering and Murty (2009).

As described in Section 2.3 an issue related to the layout problem is that of equipment selection. One important factor in the choice of a suitable equipment is its performance. To compare the performances of container terminal equipment, several simulation studies have been undertaken. Vis (2006) and Saanen and Valkengoed (2005) analyze the use of different stacking equipment in simulation studies. Vis (2006) compares the performance of a SC system and an A-RMG system considering a single block. Both systems are assumed to have pickup and delivery points (transfer points) at the landside and seaside ends of the block. Thus a straddle-carrier-relay system is examined. The average total travel time of the SC or A-RMG is considered for the comparison. Saanen and Valkengoed (2005) compare the performance of three A-RMG systems, namely single RMG, twin RMG and cross-over RMG. For the comparison of these A-RMG systems they simulate a system with a single block as well as the whole terminal operations (in a perpendicular layout with transfer points). For the single block simulation the performance measure considered for the comparison is the number of boxes per hour moved by the respective A-RMG configuration and the delays occurring in the case of a twin RMG or cross-over RMG. Additionally, they consider truck service times and a seaside performance measured for the whole terminal simulation.

Simulation studies have been published which mainly compare the performance of different equipment types for the horizontal transport of containers: In Liu et al. (2000) a manually operated container terminal is compared with an AGV and an LMTT system by means of simulation. For this purpose they consider a parallel yard layout where a YC operates at each block. Liu et al. (2002) carry out simulation studies to evaluate automated container terminals considering the following systems: an AGV, a LMTT, a grid rail and an AS/R system. For each a fixed layout is specified. Buffer areas are implemented at the gate and train facilities. The former is used to decouple the manual and automated operation as well as for intermediate storage of containers. The latter is used for the service of trains. The layouts for the AGV and LMTT-based systems are parallel layouts with transfer lanes (see Liu et al. 2002). For the AS/RS and the grid rail system equipment-specific layouts are proposed. Several performance measures are tracked during the simulation, e.g. the QCR, the truck turnaround time and different idle rates of equipment. The average costs per container are also calculated. More details of the cost calculation can be found in Ioannou et al. (2001).

Another comparison of transport systems can be found in Duinkerken et al. (2006), who compare different systems for inter-terminal transfer, i.e. the transport of containers between adjacent terminals. They consider a scenario which is based on container terminals in the Maasvlakte in the Netherlands. In a simulation study they compare the performance of multi-trailer, AGV and ALV systems.

Two simulation studies compare the performance of an AGV system with the performance of an ALV system for the horizontal transport of containers. Both studies, Yang et al. (2004) and Vis and Harika (2004), assume a perpendicular layout with transfer points where A-RMGs operate at the storage blocks. Yang et al. (2004) track several performance measures as waiting times and the QCR. They use the simulation study to determine the required number of vehicles to achieve a given QCR. The simulation study shows that an ALV configuration is superior to an AGV configuration. Vis and Harika (2004) also track several performance measures like the unloading time of a ship and waiting times of QCs and AGVs. Again, the number of vehicles needed is determined. Their results are similar to those of Yang et al. (2004).

The above-described studies focus on the comparison of the performance of different types of terminal equipment. Some studies also consider aspects relevant to the design of a terminal layout: Vis and Harika (2004) consider layout options for the seaside as they simulate different buffer sizes for the ALVs at the QCs and at the storage blocks (number of transfer points). The buffer areas at the QCs are used by the QCs to store unloaded containers. The result shows that increasing the buffer size at the QCs allows for a reduction in the number of

ALVs needed. In contrast, the buffer size at the stacking block has no impact on the required number of ALVs. Liu et al. (2002) consider aspects related to the landside layout of a terminal. They use a $M(\lambda)/M(\mu)/n$ queuing system to determine the number of truck lanes of a gate, where λ denotes the mean arrival rate and μ the mean service rate of trucks and n the number of truck lanes (see also Watanabe 2006).

Besides the different equipment, Vis (2006) also compares different stack configurations. In other words Vis (2006) evaluates the block design of a single block with transfer points either operated by a single A-RMG or by a SC. The initial block design with six rows and 42 bays is compared with designs where the block has three rows and 84 bays, four rows and 63 bays, five rows and 51 bays, seven rows and 36 bays, eight rows and 32 bays, and nine rows with 28 bays. The results show that considering a single block a wider block width leads to a reduced average total travel time for both types of equipment. This is due to the shorter length and thus shorter travel distances of the SC or A-RMGs (see Vis 2006).

Vis and Bakker (2005) simulate an automated container terminal in which they analyze different real-time dispatching rules of AGVs and real-time assignment rules of containers to storage blocks. Beside these operational investigations they consider the design of the storage blocks assuming a perpendicular yard layout with A-RMGs used for stacking. In their approach they simulate the unloading of 2500 containers from a single container ship assuming a layout with seven blocks. To examine different designs of the storage blocks they simulate different block configurations each having a storage capacity of 720 containers. They vary the numbers of tiers and rows of the blocks which together determine the number of bays. They do not consider that different block widths lead to different total yard widths and that this may exceed the available land. Therefore the number of blocks remain constant for different block widths. The results show only small variations in the total cycle time taken to unload the 2500 containers on the different block configurations.

A paper that clearly focuses on layout planning aspects of container terminals is that of Liu et al. (2004). They consider an automated container terminal where AGVs are used for the horizontal transport of containers. In a simulation study they compare two yard layouts. The first is a parallel and the second a perpendicular layout. For both layouts transfer lanes (called working roads) are used to transfer containers between the AGVs and the YC. These working roads are assumed to be unidirectional for the parallel layout and bi-directional for the perpendicular layout. In consequence the AGVs can use the working roads to return to the seaside for the perpendicular layout. To avoid two AGVs traveling in opposite directions on the same path Liu et al. (2004) assume that only one AGVs is allowed to enter a working road at a time. Three scenarios are simulated for both layout options: in the first only containers are loaded onto a ship, in the second containers only are unloaded from a ship, and in the third scenario containers are loaded onto and simultaneously unloaded from a ship. For both layout options a different number of YCs is deployed as a different number of blocks exists in the layout. For the parallel layout a maximum of 18 YCs is deployed, whereas a maximum of 15 YCs is deployed in the perpendicular layout. Using the same number of AGVs for both layouts the perpendicular layout achieves a higher QCR than the parallel layout.

Petering (2007) introduces a comprehensive simulation model for transhipment container terminals. The papers of Petering (2008), Petering and Murty (2009), Petering (2009) described below are based on this simulation model and analyze various aspects concerning layout planning of container terminals. The first, Petering (2008) compares the two orientation options (parallel or perpendicular) for yard layouts with transfer lanes similar to Liu et al. (2004). A combination of YCs and YTs is considered as equipment system. Several performance measures are tracked, e.g. the QCR, YC productivity, and productivity of YTs over a long term of three weeks. Petering (2008) assumes that besides the transfer lane an additional traveling lane exists which can be used by the YTs to return to the seaside. In contrast to Liu et al. (2004), Petering simulates for both layouts different terminal layouts and equipment scenarios, i.e. scenarios with more or less equipment (number of YCs, YTs), different lengths and widths of terminal, and different block designs (lengths and widths of blocks). The results differ from those of Liu et al. (2004) as for most combinations of terminal layout and equipment scenario the parallel layout outperforms the perpendicular layout with respect to the QCR. For two scenarios, however, the perpendicular layout is superior to the parallel.

In Petering and Murty (2009) a real-time control aspect and a layout aspect are considered using a similar simulation model. The real-time control aspect analyzed is the influence of several yard crane deployment rules, i.e. the assignment of YCs to blocks. The layout aspect considered is the influence of the block design (the block length) on the terminal performance. To identify a promising layout several yard layout configurations with different block lengths are simulated. As layout category a parallel layout with transfer lanes is considered. They assume for all configurations an identical number of TGS. When the block length decreases an additional driving lane is installed in the yard. To provide the same number of TGS for each configuration the terminal length is increased by the width of the additional driving lane. All different combinations of yard layout and YC deployment systems are simulated for different scenarios. These scenarios include a different quantity of equipment deployed and different terminal settings, e.g. a different number of berths. The simulation results are used to identify a promising YC deployment system in combination with a promising block length.

In Petering (2009) the simulation model of the transhipment container terminal is used to evaluate the influence of different block widths on the terminal performance. Again, a parallel layout with transfer lanes is considered for the analysis. The capacity of TGS provided by each block width is assumed to be constant, which leads to varying terminal depths for different block widths. Moreover, different scenarios are considered for which each different block width is simulated. These scenarios differ in the quantity of equipment deployed and in the terminal settings, e.g. the block length and number of berths. Hence, each combination of scenario and block width is simulated and promising block widths are identified.

To sum up, there are several simulation models that consider different aspects of terminal layout planning. The papers that focus on layout aspects are those of Liu et al. (2004), Vis and Bakker (2005), Vis (2006), Petering (2008), Petering and Murty (2009), and Petering (2009). The other approaches described are concerned with the related problem of equipment selection by comparing different types of equipment. Most of the papers on aspects of container terminal layout planning focus on the design of yard layouts with transfer lanes and they consider in each study a different aspect of the container terminal layout planning problem. For instance, Petering and Murty (2009) analyze the influence of the block length on the terminal performance, whereas Liu et al. (2004) consider the orientation options.

3.3. Analytical Approaches to Yard Layout Planning

Beside the simulation approaches which are concerned with topics related to layout planning, there are some analytical approaches. These analytical approaches to planning yard layouts are discussed in this section.

Kim et al. (2008) propose a procedure for the design of storage yards with transfer lanes. They consider the orientation of the blocks to the quay (either parallel or perpendicular) and the number of driving lanes in the yard. Estimates are derived for the expected distances of trucks and the expected number of rehandles, both depending on the number of driving lanes in the layout. In their approach the number of bays is the same for all blocks in the storage yard. For their study they assume a rectangular terminal and storage yard with a gate located in the middle of the landside border. They also assume a fixed terminal area, unlike Petering and Murty (2009) and Petering (2009). Thus installing an additional driving lane leads to a decrease of available storage space. In consequence, the installation of driving lanes leads to a higher probability of rehandles. The trade-off between the expected distances of trucks and number of rehandles is analyzed. To calculate layouts they enumerate different numbers of driving lanes and calculate the resulting expected number of rehandles and travel distances for trucks. This trade-off is evaluated using the corresponding cost factors of the equipment involved, i.e. costs of yard trucks and yard cranes. The total cost is used to calculate the optimal block length and to compare perpendicular with parallel layouts. For this comparison Kim et al. (2008) assume that between the blocks there are only unidirectional transfer lanes. Thus YTs are not able to use driving lanes between the blocks to get back to the seaside. In consequence the YTs have to go long distances using the available horizontal driving lanes to get back to the seaside (see Petering 2008, Kim et al. 2008). This is in contrast to the assumption in the simulation studies of Petering (2008) and Liu et al. (2004) in which driving lanes exist that allow YTs to get back to the seaside more easily. The numerical results in Kim et al. (2008) show that the parallel layout achieves lower costs than the perpendicular layout based on the assumption that the transfer lanes between blocks are unidirectional.

The block design is considered in Lee and Kim (2010). They analayze the layout of a single block for two different block structures: a block with a transfer lane and a block with transfer points at both ends of the block. For both block structures expected cycle times of the YCs are derived distinguishing operation types like the receiving operation, loading operation, discharging operation, and delivery operation. The receiving and delivery operations are connected to landside operations and the discharging and loading operations are connected to the seaside operations. They also assume that a block is dedicated either solely to inbound (import) or to outbound (export) containers and that a YC performs only one of the four operation types for a relatively long time. This leads to the assigning of two YCs to a block with transfer points. Lee and Kim (2010) derive estimates for cycle times of YCs and truck waiting times of YTs at a YC. These estimates distinguish between the four operation types and both block structures. Four models are suggested that uses these estimates: “minimizing the expected YC cycle time subject to a minimum block storage capacity, maximizing the block storage capacity subject to a maximum expected YC cycle time, minimizing the expected truck waiting time subject to a minimum block storage capacity, and maximizing the block storage capacity subject to a maximum truck waiting time” (Lee and Kim 2010). The variables are the block length, stacking height and block width. Results are generated by enumerating different possible values for these variables.

A decision support system is proposed by van Hee and Wijbrands (1988), which can be used for the capacity planning of container terminals. They assume a terminal system with transfer lanes, where internal and external trucks are separated by the yard. This leads to a configuration in which a block has two transfer lanes, one at each side of the block. They use queuing models to develop a decision support system which supports decisions for the capacity planning. However, they also derive estimates for the cycle time of a single yard crane at a storage block. As do Lee and Kim (2010) they distinguish blocks that are dedicated either to import or export containers. For an import container block they derive cycle times. The cycle time of different import block configurations are compared using different widths and heights of a storage block.

3.4. Overview of Approaches to Container Terminal Layout Planning

In the sections above the approaches in the literature have been summarized which consider topics related to the planning of container terminal layouts. In this section these approaches are categorized and an overview is given. We focus on papers that consider aspects of container terminal layout planning topics. In consequence, we do not include related simulation approaches that solely compare the performance of equipment in the overview.

Table 3.1 gives an overview of quantitative approaches concerning container terminal layout planning topics. The approaches are structured by the following layout categories: RTG-based layouts with transfer lanes, (A-)RMG-based layouts with transfer points, and SC-based layouts with indirect or direct transfer. We divide the literature into approaches that are based on simulation models and analytical approaches. Some of the papers only consider the design of a single block and not of a whole yard. For each layout category we indicate which of the following variables are considered: the orientation of the storage blocks, different block lengths or different block widths. A bullet (•) in Table 3.1 indicates whether the approach considers either the design of a whole container terminal yard or of a single block; whether the approach is simulation-based or analytical, and which of the variables are considered.

The overview of Table 3.1 shows that most approaches so far focus on RTG-based systems with transfer lanes. Apart from Vis (2006) who considers aspects of the design of a single SC-based block in an indirect transfer system, we are

Table 3.1.: Overview of quantitative approaches for yard layout planning of container terminals

					RTG			(A-)RMG			SC (ALV)					
					Transfer Lane			Transfer Points			Indirect -			Direct Transfer		
	Single Block	Whole Yard	Simulation	Analytic	Block Width	Block Length	Orientation	Block Width	Block Length	Orientation	Block Width	Block Length	Orientation	Block Width	Block Length	Orientation
van Hee and Wijbrands (1988)	•			•	•	•										
Liu et al. (2004)		•	•				•									
Vis and Bakker (2005)		•	•					•	•							
Vis (2006)	•		•					•	•		•	•				
Petering (2008)		•	•				•									
Kim et al. (2008)		•		•		•	•									
Petering and Murty (2009)		•	•			•										
Petering (2009)		•	•		•											
Lee and Kim (2010)	•			•	•	•		•	•							

not aware of any publication that deals with the layout design of a SC-based container terminal. Thus it appears that no approach has been suggested, that can be used for the design of a SC-based layout using direct transfer. Moreover, only Vis and Bakker (2005), Vis (2006), and Lee and Kim (2010) consider a layout with transfer points. Vis (2006) and Lee and Kim (2010) consider the design of a single block, not of a whole storage yard. By contrast, Vis and Bakker (2005) consider a whole storage yard, but they do not consider limitations of the available space (see Section 3.2).

Table 3.1 shows that most approaches, i.e. those of Liu et al. (2004), Vis and Bakker (2005), Vis (2006), Petering (2008), Petering and Murty (2009), and Petering (2009) use simulation. Only van Hee and Wijbrands (1988), Kim et al. (2008), and Lee and Kim (2010) propose analytical approaches. The approaches of van Hee and Wijbrands (1988) and Lee and Kim (2010) focus on the design of a single storage block and not on the design of a whole storage yard. Kim et al. (2008) focus on the design of RTG-based yard layouts for rectangular terminals.

3.5. Required Work

The general objective of this thesis is to provide OR-based methods for decision support during the layout design of terminals. The overview of the actual quantitative approaches in the section above shows that there are already several OR-based approaches that consider the layout planning of container terminals. These approaches can be used for decision support by terminal planners during the design of a terminal layout. For instance, the approaches and results in the studies of Liu et al. (2004), Kim et al. (2008), and Petering (2008) are useful to terminal planners when they have to decide on the orientation of an RTG-based yard layout. Nevertheless, the overview also shows that there is still a need for additional or extended approaches that support terminal planners in designing a terminal layout, mainly in situations in which the current approaches cannot be used.

There is no approach in the literature that supports the terminal planner in finding a terminal layout, when a terminal planner decides to use SCs (or ALVs) in a direct transfer system. The approaches so far present mainly simulation models; just a few approaches are analytical. Terminal planners who want to compare several alternative layout configurations in a rough planning phase could use an approach which allows quick evaluation and comparison of all possible configurations. Obviously simulation can be used in such a situation, but simulation models often need time-consuming computations. Analytical approaches, however, can sometimes allow a quick computation and comparison of alternative configurations (e.g., that of Kim et al. 2008). As most analytical approaches need a higher level of abstraction than simulation models, the analytical approaches can be used to limit the number of possible alternative configurations and to gain a deeper understanding of the problem and its impact factors. Simulation models with a lower level of abstraction of the terminal system can then be used to compare the remaining alternatives in more detail or to validate the accuracy of the analytical approach. Accordingly, we aim to extend the set of analytical approaches for the layout design of container terminals.

As the overview shows, there are still topics for the design of RTG-based layouts which are not yet treated and which would provide additional help for terminal planners. For instance, all approaches for RTG-based layouts assume a rectangular yard or terminal. In practice, several terminals are not rectangular. Thus another goal of this thesis is to develop a new approach to the design of an RTG-based layout.

None of the approaches to (A-)RMG-based layouts with transfer points consider limitations of the yard. In addition, two of the three approaches focus on the design of a single block rather than the whole yard. Thus another objective of this thesis is to develop an approach to the layout design of (A-)RMG-based layouts with transfer points. It is obvious that there is no approach to design of the storage yard of a SC-based layout with direct transfer (see Table 3.1). A goal of this thesis is to fill this gap.

Topics that are not related to a special layout category are also important to the design of a terminal layout. The position of storage areas for non-standard containers (e.g., reefer racks) in the terminal layout and the resulting influences on the design of storage blocks or the movements of the horizontal means of transport (see also Section 2.4.3) merit investigation. We are not aware of any study that analyzes such effects. The distribution of the reefer racks, however, might be an important factor in an efficient layout.

A more general topic is the adequacy of different layout categories for different scenarios. Investigation could determine whether a yard layout category can provide an adequate layout for a transhipment terminal. The results of such a study could be used to reduce the number of possible layout configurations during the design of a specific terminal.

The following are the research objectives of this thesis. Each of the following objectives is related to a special layout category:

- to develop a new analytical approaches for RTG-based layouts with transfer lanes.
- to develop a new analytical approach for the design of RMG-based layouts with transfer points.
- to develop a new analytical approach for the design of SC (or ALV) based layouts with direct transfer.

The following research objectives are general and not related to a special layout category:

- to develop a new approach which analyzes the influence of the positions of storage areas for non-standard containers on the terminal performance.
- to analyze the adequacy of different yard layout categories for different scenarios.

The objectives of the thesis are tackled in the following way: Firstly, the influence of the positions of storage areas for non-standard containers on the terminal performance is addressed in Chapter 4. Accordingly, a mixed-integer model is used to find the position of storage blocks and other elements of a terminal within a given area. The model, however, does not consider flexible block dimensions or a flexible number of blocks. These degrees of freedom are considered in the approaches for the three layout categories. Novel approaches for the yard categories connected to the use of gantry cranes are presented in the following two chapters, where Chapter 5 deals with RTG-based layouts with transfer lanes and Chapter 6 with RMG-based layouts with transfer points. The layout category which is not connected to the use of gantry cranes is covered in Chapter 7, where a new approach to the design of SC-based layouts with direct transfer is proposed. The adequacy of the previously examined layout categories for certain scenarios is analyzed in Chapter 8.

4. The Influence of Block Positions on the Terminal Performance

As described in Chapter 3, there are several approaches to planning the layout of facilities. These problems are known as facility layout problems, which are used to arrange objects within a given area. In this chapter we propose a model based on FLP models which can be used to define positions for the landside facilities like gate and rail tracks as well as for determining positions for blocks storing non-standard containers. We also present a simulation model which allows us to compare different layout solutions. The simulation model allows the influence of the positions on the terminal performance to be evaluated. This chapter is based on Wiese et al. (2009b).

The remainder of this chapter is structured as follows: In Section 4.1 we propose a mixed integer model to plan container layouts and we describe the basic assumptions. At the end of the section we present computational results for instances generated considering two scenarios. The scenarios on which the instances are based are also described. In Section 4.2 the simulation model is proposed which can be used to simulate different layout solutions. The layout solutions generated for the instances are simulated and the results discussed. Section 4.3 summarizes the results of this chapter.

4.1. A FLP Based Approach to Layout Planning of Container Terminals

The problem in facility layout design is to find an efficient arrangement of objects in a given area, given the material flow between these objects. In general, the aim is to minimize the cost for transporting material. Transferring this concept to container terminal layout planning, we have items to arrange on a container terminal and a flow of containers between these items. The aim of this approach is to arrange these objects in a way that minimizes the travel distances for the horizontal means of transport.

Items of a container terminal are quay cranes and in the yard the storage blocks. In the landside area of a terminal there might be a gate, rail tracks and TSAs. Besides these items driving lanes for horizontal means of transport have to be considered in determining a feasible layout. Regarding the list of items just mentioned we have to consider that not all of them have full flexibility to be positioned on the terminal area: The quay cranes are bound to the quay and, furthermore, they are moveable during daily operation. In addition the land side connections to external roads and train tracks necessitate that the gate and tracks are restricted to subsections of the available terminal area. As a result a model for container terminal layout design needs the ability to restrict elements to a subset of possible positions.

The most important remaining flexible items are storage blocks. Here several observations may be made concerning layout design. For the approach in this chapter we assume that the storage capacity of the terminal for different types of container such as empty and reefer is predetermined and the equipment for the terminal operation has been selected. Thus the capacity planning and the equipment selection problem has been handled beforehand (see also Section 2.4.2). As described in Section 2.4.3, the dimensions of storage blocks can vary. We nevertheless assume for the approach in this chapter that the block dimensions are fixed due to the inherent complexity of the problem when considering variable dimensions.

As mentioned in Section 2.2 different types of container are handled at a container terminal. With respect to the storage of these container types different conditions have to be considered. The most frequent containers are standard containers, for which no special attributes addressing storage conditions have to be considered. By contrast, for reefer containers, containers for dangerous goods and empty containers special storage conditions exist. Empty containers are normally stored separately and can be stacked higher. Containers of dangerous goods have to be stored in sections of the yard which are specially prepared. Reefer containers need a power supply and thus cannot be stored in a section for standard containers. In designing a layout of a terminal, these conditions have to be considered on building blocks and in particular on defining a container flow among items. For instance, considering a block that solely stores reefer containers, a less intensive flow of containers to this block can be assumed than to a block storing standard containers. In most cases a lower ratio of reefer containers to standard containers is handled at a terminal.

For the horizontal means of transport, such as yard trucks or straddle carriers, driving lanes need to be considered in planning a terminal layout. We assume that we are able to consider them by introducing minimal distances between blocks and between all other items.

To sum up, we make the following assumptions for the model introduced in the chapter:

– The equipment decision has been made in advance and therefore the block structure is given.

– The number of quay cranes is given, each with a fixed position at the quay.

– The area of the container terminal is rectangular and its dimensions are given.

– The required storage capacity is given and the number as well as each dimension of a storage block is predetermined.

– The gate can be positioned at a predetermined border of the terminal area.

– The container flow is given and considers the ratio of container types.

To consider non-rectangular terminal areas in the model it is possible to introduce virtual items with a fixed position on the non-usable segments of the area. Quay cranes operate flexibly on the quay and thus their position changes during daily operation. For the strategic decision on the layout we spread the quay cranes equally along the quay giving each crane a fixed position.

We assume that the flow of containers is given as well as that the flow takes into consideration the ratio of different container types. The flow of containers at a terminal in short-term daily operations depends on operational decisions of the yard management (see Section 2.3.1). For example, the decision on assigned storage space for export containers of a specific vessel influences the flow of containers during the loading of the vessel. We assume, however, that for the strategic layout design these operational planning decisions are not crucial. For instance, regarding two blocks storing the same type of container and having the same dimensions, it is of no relevance which of the blocks is next to a specific berth. Hence we model the flow for equal container types by equally distributing the containers between the blocks of the same size. In contrast, the flows of different container types have to be considered. That is, containers of a special type can only be routed to storage blocks meant for this type. In consequence, different flow intensities are considered with respect to the different container types.

The assumption of fixed block dimensions restricts a possibly important degree of freedom. With respect to fixed block dimensions one can state that in knowing this information it is easily possible to manually construct an at least feasible solution. The remaining degrees of freedom are:

- The placement of gate, truck service lanes and rail tracks.
- The orientation of the blocks; either perpendicular or parallel to the quay.
- The placement of blocks which store non-standard containers.

Nevertheless, it is important to analyze whether those degrees of freedom have an impact on the overall terminal performance. The model determines, e.g. where to place blocks storing reefer containers or blocks storing standard containers considering the different flow intensities described above. As noted, the exact placement of the gate on a border of the terminal is determined. The influence of those decisions on the terminal performance is analyzed using simulation.

4.1.1. Model Formulation

On these assumptions we are able to formulate a mixed integer model. To reduce the model complexity we use the sequence pair representation introduced by Murata et al. (1996). Meller et al. (2007) and Xie and Sahinidis (2008) successfully adopted this representation for the facility layout problem. For the sake of brevity we only describe the used variable representation and refer for a more detail description to the above-mentioned publications. We introduce binary variables n^a_{ij} and n^b_{ij}, where a and b define two sequences of binary variables. The variables n^a_{ij} and n^b_{ij} are used to define a relation of item i to item j with respect to their relative location in the layout:

- If $n^a_{ij} = 1$ and $n^b_{ij} = 1$, then item i must follow item j in the x-direction.
- If $n^a_{ij} = 0$ and $n^b_{ij} = 0$, then item j must follow item i in the x-direction.
- If $n^a_{ij} = 0$ and $n^b_{ij} = 1$, then item i must follow item j in the y-direction.
- If $n^a_{ij} = 1$ and $n^b_{ij} = 0$, then item j must follow item i in the y-direction.

The term “item” means all elements on a terminal, e.g. quay cranes, blocks or the gate.

Using this representation we formulate a mixed integer model to find a layout for a container terminal considering minimal distances between items as well as a subset of items having a fixed positions - the quay cranes. To model the problem we introduce the following parameters:

s	direction indices ($s = \{x, y\}$)
v	sequence pair variable indices ($v = \{a, b\}$)
w_i	width of item i

l_i	length of item i
lb_i^s	lower bound of s-position of item i
ub_i^s	upper bound of s-position of item i
L^s	length of container terminal in s-direction
pos_i^s	s-position of item i
a_{ij}^s	minimum distance in s-direction between items i and j
f_{ij}	container flow between i and j
M_{ij}^s	$M^s = L^s + a_{ij}^s$
I	set of all items
Q	set of quay cranes ($Q \subset I$)

In sum the following variables are defined:

d_{ij}^s	Manhattan distance in s-direction between the centres of item i and item j
x_i	x-coordinate of upper left corner of item i
y_i	y-coordinate of upper left corner of item i
p_i	binary variable for the orientation of item i
n_{ij}^v	binary variable denotes the relative location to each other of item i and item j

Using these parameter and variables we define the following model which we refer to as fix block model (FBM):

$$\min \sum_{i,j \in I, i \neq j} (d_{ij}^x + d_{ij}^y) f_{ij} \tag{4.1}$$

s.t.

$$x_i \geq x_j + p_j l_j + (1 - p_j) w_j + a_{ij}^x - M_{ij}^x (2 - n_{ij}^a - n_{ij}^b) \quad \forall i \neq j \in I \tag{4.2}$$

$$y_i \geq y_j + (1 - p_j) l_j + p_j w_j + a_{ij}^y - M_{ij}^y (1 + n_{ij}^a - n_{ij}^b) \quad \forall i \neq j \in I \tag{4.3}$$

$$L^x \geq x_i + p_i l_i + (1 - p_i) w_i \quad \forall i \in I \tag{4.4}$$

$$L^y \geq y_i + (1 - p_i) l_i + p_i w_i \quad \forall i \in I \tag{4.5}$$

$$y_i = pos_i^y, x_i = pos_i^x, p_i = 0 \quad \forall i \in Q \tag{4.6}$$

$$1 = n_{ij}^v + n_{ji}^v \quad \forall i < j \in I, v \tag{4.7}$$

$$n_{ik}^v \geq n_{ij}^v + n_{jk}^v - 1 \quad \forall i \neq j \neq k \in I, v \tag{4.8}$$

$$d_{ij}^x \geq \left(x_i + p_i \frac{l_i}{2} + (1 - p_i) \frac{w_i}{2} \right) - \left(x_j + p_j \frac{l_j}{2} + (1 - p_j) \frac{w_j}{2} \right) \quad \forall i \neq j \in I \tag{4.9}$$

$$d^x_{ij} \geq \left(x_j + p_j\frac{l_j}{2} + (1-p_j)\frac{w_j}{2}\right) - \left(x_i + p_i\frac{l_i}{2} + (1-p_i)\frac{w_i}{2}\right) \qquad \forall i \neq j \in I \quad (4.10)$$

$$d^y_{ij} \geq \left(y_i + (1-p_i)\frac{l_i}{2} + p_i\frac{w_i}{2}\right) - \left(y_j + (1-p_j)\frac{l_j}{2} + p_j\frac{w_j}{2}\right) \qquad \forall i \neq j \in I \quad (4.11)$$

$$d^y_{ij} \geq \left(y_j + (1-p_j)\frac{l_j}{2} + p_j\frac{w_j}{2}\right) - \left(y_i + (1-p_i)\frac{l_i}{2} + p_i\frac{w_i}{2}\right) \qquad \forall i \neq j \in I \quad (4.12)$$

$$lb^x_i \leq x_i \leq ub^x_i \qquad \forall i \in I \quad (4.13)$$

$$lb^y_i \leq y_i \leq ub^y_i \qquad \forall i \in I \quad (4.14)$$

$$x_i, y_i \in \mathbb{R}^+, p_i \in \{0,1\} \qquad \forall i \in I \quad (4.15)$$

$$n^v_{ij} \in \{0,1\} \qquad \forall i,j \in I, v \quad (4.16)$$

The objective function (4.1) minimizes the overall travel distances needed to transport the given container flows. Constraints (4.2) and (4.3) in conjunction with constraints (4.7) and (4.8) prevent the overlapping of items and in addition secure a minimum distance between items. Constraints (4.4) and (4.5) guarantee the limitation of item positions to the dimension of the terminal area ($L^x \times L^y$). The quay cranes are fixed to given positions with a fixed orientation (4.6). Constraints (4.9)-(4.12) are used to calculate the rectangular distances between the items. Finally, constraints (4.13) and (4.14) define an upper and lower bound on the possible positions of the items' upper left corner.

Additionally, we adopt valid inequalities presented in Meller et al. (2007) to our formulation:

$$d^x_{ij} \geq \min\left(\frac{l_i}{2}, \frac{w_i}{2}\right) + \min\left(\frac{l_j}{2}, \frac{w_j}{2}\right) + a^x_{ij} - L^x(2 - n^a_{ij} - n^b_{ij}) \qquad i,j \in I, i \neq j \quad (4.17)$$

$$d^y_{ij} \geq \min\left(\frac{l_i}{2}, \frac{w_i}{2}\right) + \min\left(\frac{l_j}{2}, \frac{w_j}{2}\right) + a^y_{ij} - L^y(1 + n^a_{ij} - n^b_{ij}) \qquad i,j \in I, i \neq j \quad (4.18)$$

These valid inequalities force the distances between items i and j to be at least as great as the sum of the following values: the minimum of the half length and width of item i, the minimum of the half length and width of item j plus the minimum distance a^s_{ij} depending on the relative location denoted by the n^v_{ij} variables.

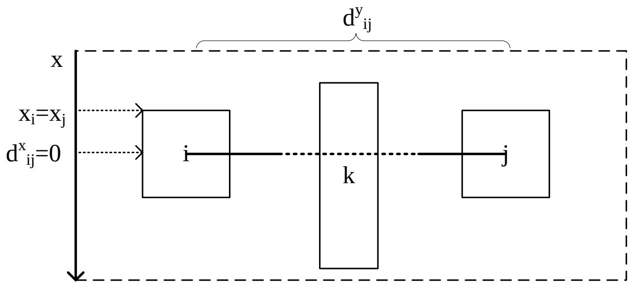


Figure 4.1.: Manhattan distance

4.1.2. Distance Correction

To model the distances between two items we choose the rectangular distance also known as Manhattan distance. This measure is suitable for use in a mixed integer formulation. Nevertheless, it is an approximation of the actual distance needed for horizontal means of transport to travel between, e.g. a block and a QC. The real distance between these items, however, is hard to calculate within our model. Nevertheless, after a solution is computed using the FBM we correct the distances to gain accuracy in the following way: for example, having two items i and j with $x_i = x_j$ the distance $d^x_{ij} = 0$ as depicted in Figure 4.1, even if an item k exits with $y_i < y_k < y_j$ and $x_j - p_k\frac{l_k}{2} + (1-p_k)\frac{w_k}{2} < x_k < x_j$. We refer to item k as blocking item because in reality a horizontal means of transport from item i to item j has to detour round the blocking item k.

To consider these detours we implement a procedure which takes solutions of the FBM and searches for pairs of elements for which the distance has to be corrected. For those pairs we update their distances and calculate a new objective value z^c. For the above constellation of items i, j and k, d^x_{ij} is updated by adding:

$$\begin{aligned} d^x_{ij} += 2 \times \min\Bigg(\Big|x_j + p_j\frac{l_j}{2} + (1-p_j)\frac{w_j}{2} - x_k\Big|, \Big|x_j \\ + p_j\frac{l_j}{2} + (1-p_j)\frac{w_j}{2} - (x_k + p_k l_k + (1-p_k)w_k)\Big|\Bigg) \end{aligned} \tag{4.19}$$

Figure 4.2 illustrates the updated distance d^x_{ij}.

4.1.3. Problem Instances

We develop two scenarios based on typical yard and equipment configurations of container terminals. On these two scenarios we build instances of different size. We consider one terminal configuration using a straddle carrier system with

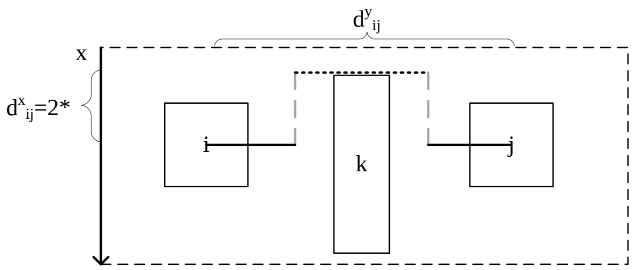


Figure 4.2.: Corrected distance

direct transfer (see Figure 2.13) and a terminal based on a truck and yard crane system with transfer lanes (see Figure 2.12 (a)).

For the straddle carrier scenario with direct transfer we use the available data described in Brinkmann (2005) to build realistic instances: The container terminal has a quay length of 1750 m with four berths and a terminal depth of 650 m. The containers are stored in 22 blocks in the yard. They are divided into 15 blocks for storing standard containers (l=117 m, w=150 m), three blocks for storing reefer containers (l=76 m, w=175 m), one storage block for container containing dangerous goods (l=117 m, w=150 m), and one block for empty containers (l=139 m, w=117 m). The external trucks enter the terminal through a gate (l=30 m, w=30 m) and are serviced at a truck service area (l=30 m, w=79 m). Tracks 1430 m long and 45 m wide are available for the service of trains, and 16 quay cranes are used to service vessels. On the instance with four berths we build smaller instances with one, two and three berth(s). These instances are built by scaling the values respectively to the number of berths. For example, the scenario with three berths consists of 12 quay cranes. To determine the correct number of storage blocks needed, we do not directly scale the number of blocks but the storage capacity needed. From the storage capacity the actual number of blocks is calculated. In particular, considering the block for storage of containers of dangerous goods, we scale the dimensions to avoid an unrealistic high storage capacity for this type of container (B_14_8: l=59 m, w=122 m; B_12_4: l=46 m, w=105 m). Table 4.1 displays information about the instances.

For the layout instances based on a yard crane system we build instances in orientation to the terminal HIT 9 in Hong Kong having two berths with an overall quay length of 700 m. Due to a lack of available data we assume the following values: we use a typical block length for blocks operated by RTGs of 170 m (see Kim et al. 2008). We assume a width of a block for reefer and standard containers of 24 m. The block width for empty container is set to 29 m. Storage of dangerous containers is not considered. The depth of the terminal is assumed to be 450 m. For the instance having two berths eight quay cranes operate at the

Table 4.1.: Instances for the straddle carrier scenario

	Number of blocks						
Instance	Standard	Reefer	Dangerous	Empty	L^x	L^y	l^{train}
B25_16	15	3	1	3	1750	650	1430
B19_12	11	2	1	2	1470	600	1073
B14_8	8	1	1	1	980	600	715
B12_4	6	1	1	1	784	600	572

Table 4.2.: Instances for the yard crane scenario

	Number of blocks				
Instance	Standard	Reefer	Empty	L^x	L^y
A34_12	28	3	2	1050	450
A23_8	19	2	1	700	450
A12_4	9	1	1	350	450

quay. In the container yard 22 blocks are used for the storage of containers. The landside connection consists of a gate, with additional waiting slots for trucks, 170 m long and 45 m wide. There is no railway connection. From this instance with two berths we build additional instances considering one or three berth(s). The instances for the yard crane scenario are displayed in Table 4.2.

As discussed in Section 4.1, the flow of the instances is generated by an equal distribution of the flow to storage blocks of the same size. Different flow intensities hold for different type of container as well as for blocks of different size. This method of building the flow matrix f_{ij} is called equal distribution. To show the complexity of the FBM with an unequally distributed flow matrix we introduce a second method which adopts the equal distribution and randomly intensifies or reduces the flow between blocks. To ensure a steady overall flow a decrease is only allowed when the sum of decreases is less than the sum of increases and vice versa. In addition, a ratio r is given, which bounds the maximal possible increase or decrease of the flow f_{ij} value to a value lower than rf_{ij}. For each of the described instances in this section we model one flow with an equally distribution and one with a random adjustment using a ratio of $r = 0.3$.

4.1.4. Ordering of Items

As mentioned in previous sections it can be observed that pairs of identical items exist which have the same flow to all other items. With respect to a layout the positions of those items can be interchanged without a change of the solution value. To avoid the enumeration of identical solutions we add a constraint to the FBM which orders those items in advance. Let ID be the set of identical items pairs:

$$\begin{aligned} ID := \{(k,m) | f_{ki} = f_{mi} \wedge f_{ik} = f_{im} \wedge w_k = w_m \wedge \\ l_k = l_m \ \forall i \in I, i \neq k, i \neq m, k < m\} \end{aligned} \tag{4.20}$$

We add the following constraint to FBM:

$$n^a_{km} = 1 \qquad \forall (k,m) \in ID \tag{4.21}$$

This constraint forces an order for item k and item m on the layout either in the x- or y-direction.

4.1.5. Computational Results

The resulting mixed integer instances are solved using Cplex 11 (see ILOG 2007) on an Intel Pentium 4 CPU 3.40GHz with 4 GB RAM. Table 4.3 shows results for the instances using the standard flow of containers. The described valid inequalities (4.17)-(4.18) and constraint (4.21) are added to the FBM. The column "#-Nodes"" describes the number of nodes examined in the branch and bound process and "Time" gives the time in minutes needed to solve the instances. We set a time limit of 12 hours to solve the instances. For instances with a gap higher than zero no optimal solution could be found due to restriction of time or memory. The column z^c shows the results by adjusting the distances as described in Section 4.1.2. Values in columns z^c and z are divided by 1000. The last column "Gap" shows the gap between the current lower bound and the current best solution.

Table 4.3 shows that about 40 hours are needed to solve all instances. The instances of the straddle carrier-based scenario can be solved optimally until two berths. For the scenario based on yard cranes there is a higher number of blocks per berth. Thus an optimal solution has been found solely for the instance with one berth. Updating the distances by considering blocking elements increases the sum of the solution values by about 2.18%.

Table 4.4 shows results for the instances with a randomly adjusted flow using a ratio of $r = 0.3$. For these instances the constraint (4.21) is not used because of an empty set ID. The results show that none of the instances can be optimally solved when using a randomized flow matrix. In summary, the above results show

Table 4.3.: Results with $r = 0$

Instance	#-Nodes	Time	z	z^c	Gap
B25_16	2989	721.4	7827.60	7911.21	25.4
B19_12	84389	378.8	4879.47	4995.13	12.6
B14_8	565711	76.7	2507.92	2533.11	0
B12_4	200645	11.0	1737.77	1749.97	0
A34_12	661	720.0	4284.83	4352.54	38.0
A23_8	49361	484.7	2062.01	2188.10	23.9
A12_4	58312	4.5	788.96	883.95	0
$\sum$	962068	2397.0	24088.56	24614.03	

Table 4.4.: Results with $r = 0.3$

Instance	#-Nodes	Time	z	z^c	Gap
B25_16	2046	720.0	7359.27	7634.2	30.7
B19_12	61501	177.87	4828.72	5050.1	26.8
B14_8	1523117	720.0	2469.63	2527.6	23.2
B12_4	4263591	718.53	1691.8	1780.1	12.5
A34_12	16	720.0	3829.9	3928.2	37.9
A23_8	21595	720.0	2039.0	2155.1	31.2
A12_4	3676232	720.0	762.6	858.6	20.6
$\sum$	9548098	4496.42	23161.1	23933.9	

that even without considering variable block dimensions instances of the model are hard to solve.

The objective of this chapter is to evaluate the influence of block positions for non-standard containers and the positions of the landside facilities on the terminal performance. To evaluate the influence of solutions found by the FBM on the terminal performance we developed a simulation model. This simulation model is used to evaluate the resulting layouts. To compare the solutions generated by the FBM with manual planning we additionally construct layout solutions manually. These manually constructed solutions are additionally evaluated in the simulation study.

4.2. Simulation of Different Terminal Layouts

A modular configurable discrete event-based simulation model has been designed in Plant Simulation 8.1 (see UGS Tecnomatix 2007) to evaluate the performance of the layout configurations generated by the solution method described above.

As we have to cope with scenarios where different types of equipment are used for the terminal operation, we use a level of abstraction that allows us to manage various types of equipment. Moreover, it is essential for the evaluation of the performance of a container terminal to simulate the whole terminal operation.

4.2.1. Simulation Design

We structure our simulation model in modules for each vital part of the terminal. Beginning at the seaside the first module consists of a berth and a fixed number of assigned quay cranes. The quay cranes at one berth are all either in discharging mode or (when all containers are unloaded) in charging mode. The sequence of the containers assigned to unloading and loading a vessel is defined in advance. The time needed to handle a single container by a quay crane is modeled using a triangular distribution with parameters (1.0, 1.5, 2.0) minutes (see Petering and Murty 2009) allowing a maximal performance of 40 quay crane moves per hour.

For transporting containers between the seaside and storage blocks as well as between storage blocks and landside facilities we use an abstract class horizontal means of transport. Depending on the ability of the horizontal means of transport to hoist a container the process of unloading a container from a vessel is decoupled from the availability of horizontal means of transport at the corresponding apron. The container can be temporarily stored on the apron until horizontal transport arrives that is able to hoist the container. The transport times needed are calculated on a distance matrix gained from the results of the layout solutions and using an average travel speed of six meter per second for the horizontal means of transport.

The stacking module either consists of a yard crane system or is, in the case of the straddle carrier system, just a memory of stored containers. To determine the time needed to handle a single container at a storage block triangular distributions are used. The handling time for a standard container in the straddle scenario is defined by (25, 35, 60) seconds. The handling time of containers using yard crane is modeled using a triangularly distributed random variable with parameters (80, 120, 240) seconds for the loading and unloading of containers (see Petering and Murty 2009). The gantry of the crane between to jobs is modeled using a triangularly distributed random variable with parameters (0, 10, 60) seconds. We do not model the explicit stacking of containers in a pile, so rehandles are not explicitly considered. However, all compared layout solutions have the same stacking capacity in the yard.

The landside connections are modeled by a module for tracks using two stacking cranes to manage the loading and unloading operations of trains. As with the operations at the vessels, the sequence of containers to discharge and charge is given. The operation of external trucks on the terminal is modeled similarly to the horizontal means of transport using a distance matrix to calculate the required travel times. In the case of external trucks the gate is either the start or destination of each move of an external truck in the yard. For the straddle carrier system truck service lanes exist, where straddle carriers load or unload arriving external trucks. The load or unload time is defined by a uniform distribution with values between 20 and 40 seconds.

For the generation of data we use a scenario generator based on the work of Hartmann (2004b). For a detailed description of the generation process and the configurable parameters we refer to Hartmann (2004b). The scenario generator computes information on vessel, truck and train arrivals. In addition the number of containers delivered by each arriving carrier and container type is generated. Upon a dwell time distribution the containers are assigned to a carrier which picks them up. Thus the flow of containers through the terminal via the landside or the seaside is modeled in advance using the scenario generator. For instance, the following data are given for a container: the arrival time of a vessel that delivers the container, the container type (standard, reefer, etc.), the assigned carrier which picks up the container and the arrival time of the carrier.

The assignment of ships to berths (the berth allocation problem, see Section 2.3) is managed by a first-come, first-served procedure using the vessel arrival information of the scenario. The actual arrival time of vessels and the assigned berth are not changed during the simulation. The choice of a block to stack a container is made by one of the following two procedures: The first (random) randomly assigns a container to a storage block. The second (min-heading) distinguishes between export and import containers. For import containers the procedure searches for all blocks which are able to store the corresponding type of container. Using this set of blocks, the block is assigned which has the lowest number of horizontal means of transport heading for or waiting at the block (see Petering and Murty 2009). Where more than one block has the same number of approaching horizontal means of transport, the block is chosen which has the shortest travel distance. For export containers, it might be advantageous that the containers are stored in blocks which are next to the berth where the collecting vessel is about to moor. Therefore we define for each berth a set of blocks containing blocks which have the shortest distance from this berth. Among these blocks the export containers are distributed similarly to import containers.

The horizontal means of transport dispatching system works similarly to the system proposed in Petering and Murty (2009). The system used in our simulation model has additional queues for landside facilities. The jobs for the horizontal means of transport are stored in several queues: a queue for each quay crane, one for the truck service lanes and one for each crane operating at the rail tracks. When a horizontal means of transport becomes idle the “most starved queue” is first serviced by the horizontal means of transport (see Petering and Murty 2009). The most starved queue is that with the longest waiting time for the assignment of a horizontal means of transport to a job in the queue.

The events vessel, truck and train arrival are triggered by the data of the scenarios. These are the basic events that trigger the following ones. After an arrival of a ship (vessel or feeder), the ship waits until its assigned berth becomes free. When it is available, the ship moors at the berth and the process of unloading containers starts. Once a container is unloaded by a quay crane, the transport job is added to the corresponding queue. This triggers the transport events of the horizontal means of transport. The arrival of a horizontal means of transport at a block triggers events that correspond to the operations at the block. At a block where yard cranes operate, the gantry event of the yard crane is triggered, followed by the unloading of the horizontal means of transport. When the unloading of a vessel is finished, the loading process starts. As mentioned above, the containers that are picked up by a vessel are given by the scenario. Transport jobs for the transport of the required containers from a storage block to the quay crane are added to the queues. This triggers a transport process similar to that for unloading. The train arrival releases a process similar to that after the mooring of a vessel. Thus the unloading and subsequent loading process of the train is started. The arrival of external trucks triggers an event in the case of the straddle carrier scenario as a SC has to serve the external truck. In the case of the yard crane scenario external trucks are directly handled at the blocks.

4.2.2. Simulation Scenarios

For the simulation we assume a layout configuration with two berths. Thus the layout solutions for the instances B14_8 and A23_8 are considered for the simulation. Arrival data are generated by the scenario generator based on the work of Hartmann (2004b) for a horizon of seven days. We assume that 6500 containers arrive by vessels, 4367 containers arrive by feeders, 225 containers arrive by truck and 490 containers arrive by train. For the scenario based on yard cranes we assume the same values except that no container arrives by train. The number of containers arriving by train is assumed also to arrive by truck. Table 4.5 shows the average number of carriers arriving in the given horizon. The average dwell time of containers is 4.6 days. The ratios of the different container types (reefer, standard, etc.) are set to the same values as assumed on generating

Table 4.5.: Average carrier arrivals

Scenario	Trucks	Feeders	Vessels	Trains
straddle carrier-based scenario	651.5	39.4	4.6	8.5
yard crane-based scenario	1564.8	39.4	4.6	0

Table 4.6.: Simulated layout solutions for the straddle carrier-based scenario

Layout Solution	z	$\frac{z}{\max(z)}$	Layout Solution	z	$\frac{z}{\max(z)}$
B_z1	2507.9	0.78	B_z1_C	2533.1	0.79
B_z2	2752.7	0.85	B_z2_C	2757.8	0.86
B_z3	3208.7	1.00	B_z3_C	3221.4	1.00
B_Man	2635.3	0.82	B_Man_C	2650.3	0.82

the flow intensities (f_{ij}) for the FBM instances. Using different seed values we generate ten datasets with different arrival data for each scenario. To achieve a high workload in the terminal for the last two days we let up to two vessels arrive on day two and the remaining three vessels on day six of the horizon. The collection of statistical data is started at the beginning of day six. For the scenario based on yard cranes 48 trucks and for the scenario based on straddle carriers 78 straddle carriers are used as horizontal means of transport.

For both scenarios we simulate different layout solutions found during the branch and bound process (denoted by z1-z3) and manually constructed layout solutions (denoted by Man). In addition solutions with corrected distances are simulated. The manual layout solutions are constructed by positioning the blocks perpendicular to the quay in the case of the straddle carrier-based scenario and parallel in the case of the yard crane-based scenario (see Figure 2.13 and Figure 2.12). The manual solutions also consider the minimal distance constraints. The blocks for non-standard containers are positioned in the back of the yard as well as the truck service area and the tracks. The block storing standard containers are positioned next to the quay wall.

The layout solutions simulated for the straddle carrier-based scenario are displayed in Table 4.6. The columns z depict the corresponding solution value and columns $\frac{z}{\max(z)}$ the percentage of the solution value compared with the worst solution value. B_Man is a manually constructed solution. The solutions in the fourth column are computed on the corresponding solution in the first column by using the distance correction method.

Table 4.7 shows the layout solutions for the yard crane-based scenario. A_Man is a manually constructed solution. In total 10 layout solutions are simulated for

Table 4.7.: Simulated layout solutions for the yard crane-based scenario

Layout Solution	z	$\frac{z}{\max(z)}$	Layout Solution	z	$\frac{z}{\max(z)}$
A_z1	2062.2	0.91	A_z1_C	2188.1	0.96
A_z2	2117.6	0.93	A_z2_C	2221.7	0.98
A_z3	2151.6	0.95	A_z3_C	2248.8	0.99
A_Man	2154.3	0.95	A_Man_C	2267.6	1.0

the yard crane-based scenario with a different of 9% of the best solution value (A_z1) compared with the worst solution value (A_Man_C). Each layout solution is simulated using the random or the min-heading procedure for the assignment of containers to storage blocks. Thus two different ways of organizing the transport moves are simulated. This leads to different container flows through the container terminal for both methods.

4.2.3. Simulation Results

To quantify the efficiency of the terminal layout we use the following performance measures:

- Average of the sums of turnaround times in hours of trucks and trains.
- Average quay crane moves per hour (QCR) when a ship is moored at the corresponding berth.
- Average of the sums of travel distances (Distances) of horizontal means of transport (HMT).

The results of the simulation runs for the yard crane-based scenario are depicted in Table 4.8. The results are shown grouped by the layout solution simulated as well as by the procedure used for the dispatching of the horizontal means of transport. Table 4.9 shows the results for the straddle carrier-based scenario. Figure 4.3 shows the average quay crane moves per hour for each layout solution using both procedures for the storage block assignment. In most cases the min-heading procedure outperforms the random procedure with respect to the average QCR. In every case the random procedure results in a higher average distance to be traveled by the HMT. The min-heading procedure achieves on average about 12.8% lower distances.

The layout solutions for the straddle carrier-based scenario achieve higher QCRs than solutions of the yard crane-based scenario. A possible explanation is the decoupled process at the seaside (quay crane and horizontal means of transport)

Table 4.8.: Simulation results for yard crane-based scenarios

Layout Solution	Block assignment	QCR	Distances	Turnaround time of Trucks
A_z1	random	31.32	5972.2	306.55
	min-heading	31.38	4848.2	307.59
A_z2	random	31.21	6225.5	306.06
	min-heading	31.33	5059.4	307.03
A_z3	random	31.12	6133.8	306.87
	min-heading	31.30	5081.9	307.04
A_Man	random	30.95	6312.9	306.02
	min-heading	31.01	5200.3	309.73
A_z1_C	random	31.32	6152.3	309.52
	min-heading	31.42	5167.0	309.58
A_z2_C	random	31.18	6403.5	308.99
	min-heading	31.14	5369.0	310.21
A_z3_C	random	31.09	6296.5	309.62
	min-heading	31.30	5375.0	310.66
A_Man_C	random	30.98	6523.8	309.24
	min-heading	31.00	5545.2	310.97

Table 4.9.: Simulation results for straddle carrier-based scenarios

				Turnaround time of	
Layout Solution	Block assignment	QCR	Distances	Trucks	Trains
B_z1	random	38.94	7667.5	64.91	1.89
	min-heading	38.93	7169.9	65.17	1.89
B_z2	random	38.87	8290.4	67.04	1.89
	min-heading	38.90	7701.6	67.39	1.90
B_z3	random	38.81	9026.8	72.88	1.89
	min-heading	38.85	8277.5	72.00	1.89
B_Man	random	38.92	7835.4	69.19	1.89
	min-heading	38.90	7294.7	68.97	1.88
B_z1_C	random	38.93	7795.0	65.14	1.89
	min-heading	38.93	7300.6	65.39	1.89
B_z2_C	random	38.85	8326.4	67.57	1.89
	min-heading	38.88	7746.9	67.19	1.89
B_z3_C	random	38.81	9114.2	72.84	1.89
	min-heading	38.82	8363.0	72.07	1.89
B_Man_C	random	38.90	7937.3	69.59	1.89
	min-heading	38.90	7387.2	69.31	1.89

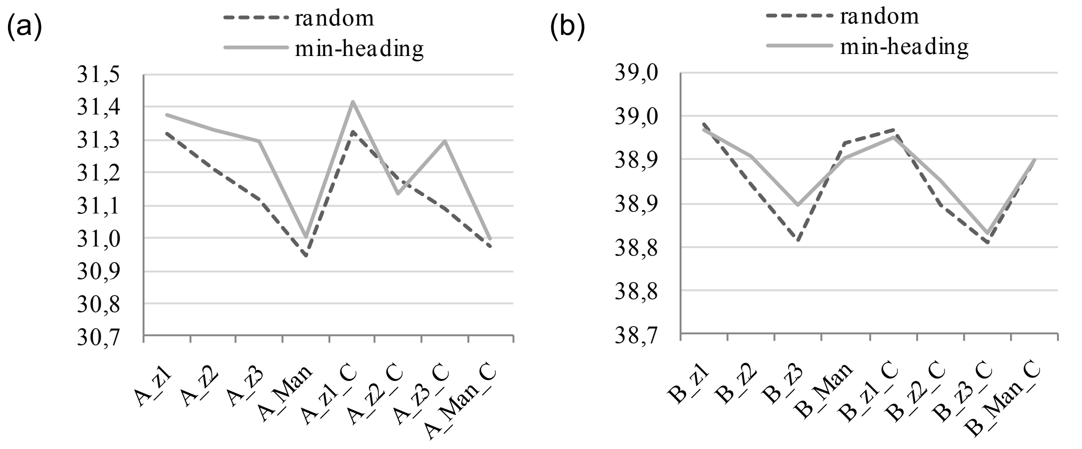


Figure 4.3.: Average quay crane moves per hour for (a) yard crane-based (b) straddle carrier-based scenario

for the straddle carrier-based scenario. We assume a sufficiently high value of six HMT per quay crane and other items which have to be serviced by the HMT (e.g., the truck service lanes). For the straddle carrier-based scenario only slight differences of about 0.34% occur for QCR. The best results for QCR achieves the B_z1 solution which is the optimal solution found by the FBM. Nevertheless the manual solution achieves a quite competitive solution with just a 0.1% lower value for the QCR.

For the yard crane-based scenario higher differences with a maximum of 1.5% occur for the QCR values. Again the highest QCR values are achieved by the z1 solutions which are the best solutions found by the FBM. The highest QCR value for the manual solution is 1.3% lower than the best value. However, the manual solution achieves the best result for the turnaround times of trucks when the random block assignment is used. In the case of the straddle carrier-based scenario the best result for turnaround times of trucks is achieved by the B_z1 solution.

Layout solutions with a competitive solution value z seem to achieve lower values for the sum of distances traveled by the HMT. In most cases a layout solution having a better solution value z achieves a lower sum of distances than a solution with a worse solution value[1]. For the straddle carrier and the yard crane-based scenario the best results for the sum of distances are achieved by the best found solution of the FBM (z1). In consequence the layout solutions of the FBM achieve lower travel distances for the HMT even when the real-time decisions of block assignment are considered. Moreover, these lower travel distances lead

[1] An exception are for instance the solutions A_z2 and A_z3.

to good results for the other performance measures. Nevertheless, the manually constructed solutions achieve quite competitive results, e.g. the distances for the B_Man_C solution are 1.2% higher than those of the B_z1_C solution.

4.3. Summary

In this chapter we have presented a mixed integer formulation for the layout planning of container terminals. In more detail the model can be used to find positions for blocks storing non-standard containers considering the different flow intensities and to find a position for the gate, truck service area and rail tracks. Upon two scenarios we build different instances and present computational results. The results show that instances of practical size are hard to solve.

We analyze the adequacy of the FBM for the layout planning by a simulation study in which different layout solutions are simulated. The results show that a better performance is gained for better solutions found by the FBM than solutions having a worse solution value z. Nevertheless, the manually constructed solutions achieve quite competitive solution values and performance values in the simulation study. For example, the solution value z for A_Man differs by 3% from the best solution found by the FBM and the manual solution B_Man achieves a lower solution value than the B_z2 and B_z3 solution.

In summary, the proposed model can be used to find positions for the landside facilities (e.g., the gate) and for blocks storing non-standard containers. The simulation results show that the positions affect the terminal performance (e.g., the QCR). Terminal operators should therefore carefully consider whether different positions of these elements are possible. However, the model cannot be used to find optimal yard configurations considering for instance different numbers of driving lanes, as this would lead to a variable number of blocks. In the following chapters methods and models are proposed for the detailed planning of container terminal storage yards.

5. Designing Yard Layouts with Transfer Lanes

In Chapter 4, a model was proposed which is able to find positions of storage blocks and other terminal facilities within a given terminal area. The approach was used to analyze the influence of the positions of storage blocks for non-standard containers on the terminal performance. The approach cannot, however, be used for planning yard layouts in detail because the FBM is limited to a given number of blocks with a fixed dimension. For planning of the yard layouts in detail different numbers of driving lanes have to be considered which lead to a variable number of blocks and to flexible block dimensions. In the following chapters we consider these flexible dimensions of the blocks for the approaches concerned with the planning of yard layouts.

As mentioned above, for the yard layouts different categories can be distinguished. Firstly, the yard layouts connected to the use of gantry cranes are considered. In this chapter we focus on yard layouts with transfer lanes. The next chapter deals with yard layouts with transfer points. A structure of a block with transfer lanes is depicted in Figure 5.1. In the next section we propose a new method which considers the influence of different numbers of driving lanes and their position on the yard layout. The flexible positions and numbers of driving lanes lead to different block lengths. The block widths, however, are assumed to be constant. In Section 5.2 we propose a method which considers different block widths to plan a yard layout with transfer lanes.

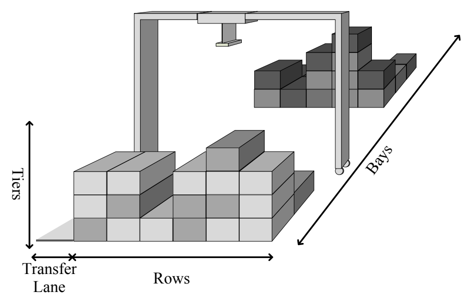


Figure 5.1.: Structures of blocks with transfer lanes

5.1. Planning Yard Layouts Considering Variable Block Lengths

This section proposes a method of planning yard layouts with transfer lanes considering both different numbers of driving lanes and driving lane positions. The structure of this section is as follows: in Section 5.1.1 we describe the regarded problem in detail. The problem is formulated as an integer program in Section 5.1.2. In the case of instances for non-rectangularly shaped terminals the formulation is non-linear. We develop in Section 5.1.3 a variable neighborhood descent heuristic, which is able to solve instances for non-rectangular yards. In Section 5.1.4 numerical results are presented for several instances. Finally, Section 5.1.5 summarizes the results of this section. This section is based on Wiese et al. (2010).

5.1.1. Yard Layout Problem

The problem of designing storage yards with transfer lanes of container terminals has also been described by Kim et al. (2008). We call this the yard layout problem. The aim of the yard layout problem (YLP) is to find optimal layouts for the storage yard of a container terminal. In this chapter we focus on parallel and perpendicular yard layouts with transfer lanes as depicted in Figure 5.2. In parallel yard layouts the blocks are orientated parallel to the quay and in perpendicular layouts perpendicular to the quay. The dimensions and shape of the container terminal area as well as the storage yard area are assumed to be fixed. The shape of the terminal is not restricted to any special geometrical form.

Besides the storage yard, elements of the layout with fixed positions called stream points are considered in the YLP. Stream points represent positions, respectively positions of objects, at which containers enter or leave the terminal area by a mode of transport. Thus stream points can be seen as sources or sinks for container flows in the terminal. An example of a stream point is the gate where external trucks enter and leave the terminal area. Moreover, quay cranes (see Figure 5.2 b) or bridges that connect the quay wall with the storage yard (see Figure 5.2 a) are common stream points. Where the quay wall is connected with bridges to the storage yard only the bridges are assumed to be stream points. For yard layouts with transfer lanes typically trucks are used for horizontal transport (see Section 2.3.2).

The storage yard layout with transfer lanes is composed of several blocks. A block consists of a number of rows of containers and a transfer lane parallel to these rows (see Figure 5.1). As we do not consider the influence of the block

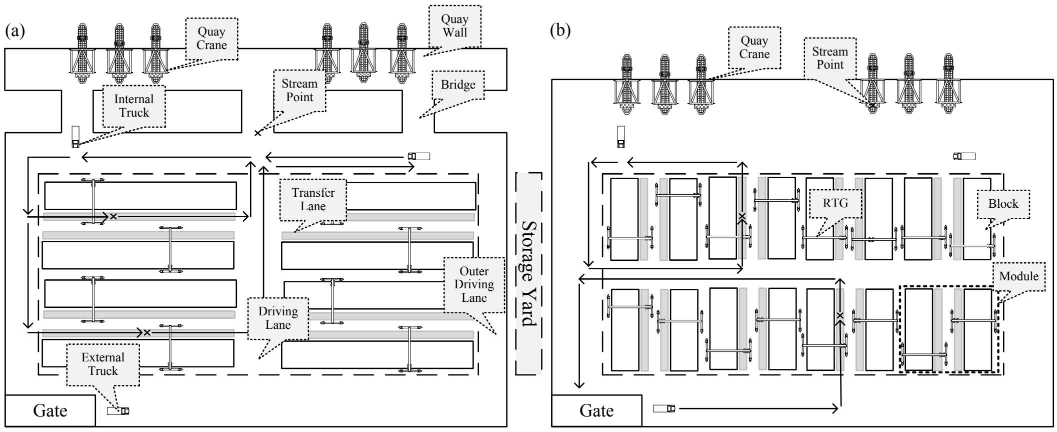


Figure 5.2.: Parallel (a) and perpendicular (b) yard layout with transfer lanes

width, it is assumed to be fixed. The length of a block is defined by the number of bays (see Figure 5.1). A combination of two blocks with transfer lanes composes a module (see Kim et al. 2008). Modules (see Figure 5.2 b) are separated by driving lanes for the movements of trucks. These driving lanes are bi-directional unlike the other type, the transfer lanes. The latter are uni-directional and are reserved for trucks having a drop-off or pick-up job at the corresponding block. Vertical driving lanes at the left and right side of the storage yard (outer driving lanes) are always present and are assumed to be fixed. The storage yard to be optimized is defined by the remaining area without these outer driving lanes (see Figure 5.2).

As the width of a block is fixed, the remaining decision variable is the length (number of bays) of a block. This directly corresponds to the decision about the optimal number of driving lanes in a layout and their corresponding positions. When a driving lane is installed in a yard, the ground space needed for the driving lane cannot be used for container storage. The decrease in storage space can be handled either by extending the terminal area or by using more tiers for container storage. As the container terminal area and thus the storage yard area is assumed to be fixed in our study, the decrease in storage space for a driving lane has to be handled by increasing the average stacking height. An increased average stacking height has the disadvantage that it implies an increase in the likelihood of rehandle occurrences (see Section 2.2.3), which should be avoided. By contrast, a driving lane enables the trucks to drive shorter distances as they can use driving lanes to get back to the sea- or landside (see Section 2.4.3).

In summary, the yard layout problem considered in this section is to find the optimal number of driving lanes and the optimal positions of those driving lanes for a parallel or perpendicular layout, with the objective of minimizing the handling costs. These are composed of the costs for the yard cranes performing rehandle operations, together with costs of trucks traveling. Both costs depend on the length of the blocks or respectively on the number of driving lanes. The costs for the gantry travel of a yard crane are not considered as those costs depend on the total length of blocks. As the storage yard has a fixed size, this distance is not influenced by the decision of the block length. Other performance criteria, such as the transfer time of a container to a truck by a yard crane, are not influenced by the length of the blocks either (see Kim et al. 2008) and are therefore ignored.

5.1.2. Modeling Container Terminal Yard Layouts

In this section the yard layout problem is formulated as an integer linear program (ILP). The ILP is formulated assuming a given orientation of the blocks, either parallel or perpendicular to the quay wall. Thus for each orientation an individual problem can be generated, solved and in the end compared. Kim et al. (2008) show that the perpendicular layout has for all configurations a higher expected travel distance than is the case with the parallel layout. Thus we ignore the calculation of perpendicular yard layouts in the computational study. Nevertheless, the model and methods introduced in the following can be used to calculate an optimal perpendicular yard layout. First of all we introduce the following assumptions to model the yard layout problem:

– Internal trucks operate in single cycle mode and thus transport either a container from the seaside to the storage yard and return for the next job to the seaside or vice versa. U-turns are not allowed. (see Kim et al. 2008)

– External trucks enter the terminal through the gate, pick up or deliver a container and leave the terminal again through the gate. (see Kim et al. 2008)

– The number and positions of the stream points are fixed and are defined by the set Q. The number of containers entering and leaving the terminal at stream point $q \in Q$ are given by parameter f_q with $f_q > 0$. For example the gate has a fixed position and a given flow of containers that will be delivered or picked up by external trucks.

– The transfer lanes are uni-directional and reserved either for pickups or deliveries of containers. No driving lanes are used between parallel modules or blocks.

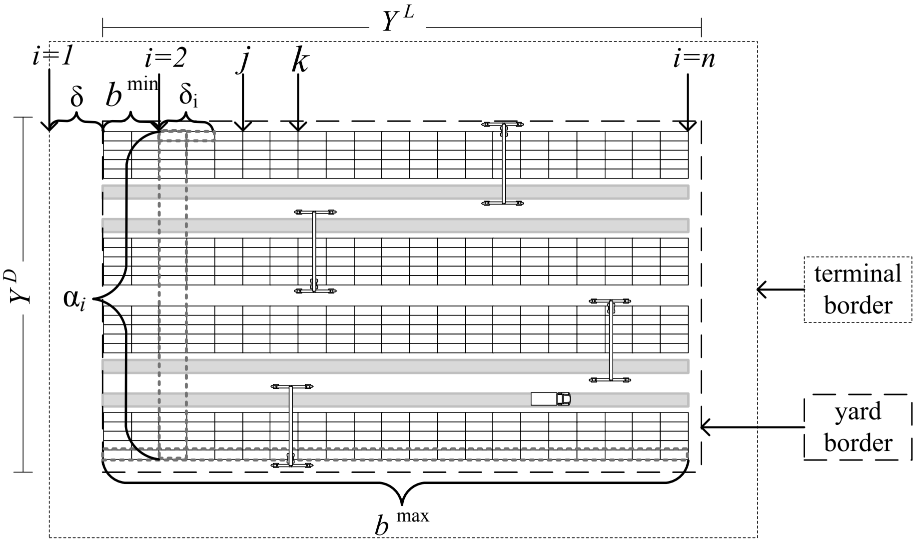


Figure 5.3.: Used parameter and enumerated driving lane positions

- The basic measure to enumerate the possible driving lanes is the length of a ground slot to store a twenty-foot container. Using another measure would lead to blocks that waste ground space.

Figure 5.3 illustrates the main parameters used for modeling. The boundaries of the yard are defined by the yard length Y^L and the yard depth Y^D. Furthermore, we calculate the number of TEUs that fit into the yard with length Y^L by $Y^L_T = \left\lfloor \frac{Y^L}{tgs^l} \right\rfloor$ where tgs^l defines the length of a twenty-foot ground slot. Accordingly, the parameter tgs^w defines the width of a twenty-foot ground slot and Y^D_T the number of ground slots in TEUs that fit into the yard with depth Y^D. The possible driving lane positions p are enumerated by calculating all linear combinations of possible block lengths between a minimal block length $b^{\min}$ and a maximal block length $b^{\max}$ (measured in ground slots). In addition, the number of bays δ used to install a driving lane is considered in the enumeration. In the parallel case the positions are enumerated as follows:

$$\tilde{N} = \left\{ p \middle| p = \sum_{s=b^{\min}}^{b^{\max}} \tau_s(s+\delta) - \delta, \tau_s(s+\delta) - \delta \leq Y^L_T, \tau_s \in \mathbb{Z}_+ \right\} \cup \left\{ -\delta \right\} \cup \left\{ Y^L_T \right\} \tag{5.1}$$

Hence the driving lane positions $p_i \in \tilde{N}$ are the left edges of the driving lanes measured in ground slots and thus are not actual x-axis coordinates. To calculate a position value of a driving lane as x-coordinate the length of a twenty-foot ground slot tgs^l is multiplied with p_i. The positions $-\delta$ and Y^L_T define the outer

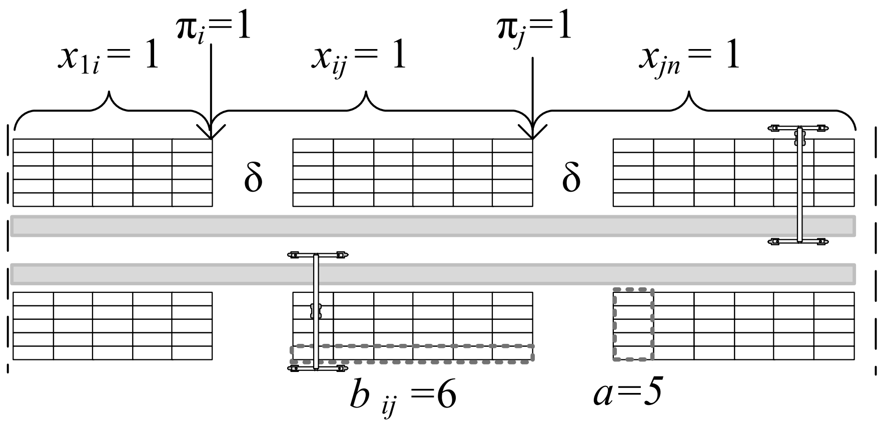


Figure 5.4.: Decision variables of the yard layout model and further parameters

driving lanes that always exist (see $i = 1, i = n$ in Figure 5.3). In the following we assume that the values of set N are indices of $\tilde{N}$: $N = \{i|p_i \in \tilde{N}\}$. The indices in N are sorted in ascending order according to their position value. Therefore when $i < j$ then $p_i \leq p_j, i, j \in N$ is valid. Thus the indices 1 and n represent the outer driving lanes. In the case of a perpendicular layout the value of Y_T^L in equation (5.1) is replaced by Y_T^D and the sets are generated equally to the parallel case. In the following a driving lane i means the abstract object of a possible driving lane represented by index i in set N.

The parameter δ_i in Figure 5.3 defines the number of bays that are actually needed for a driving lane. As mentioned before, the outer driving lanes 1 and n are not included in the definition of the storage yard as they are always present. Therefore δ_1 and δ_n are zero, whereas $\delta_i = \delta \ \forall i \in N$ with $i \neq 1, i \neq n$. The parameter α_i represents the total number of rows at driving lane i. Thus when installing a driving lane i, $\delta_i \times \alpha_i$ ground slots are used for the new driving lane instead of being available for stacking.

A block is defined by a 2-tuple of driving lanes (i, j) for which $p_i + \delta + b^{\min} \leq p_j$. For instance, in Figure 5.3 the driving lanes $i = 2$ and k would define feasible blocks unlike $i = 2$ and j. We define set A as a set that contains all possible blocks between the enumerated driving lanes. Thus A contains pairs of driving lanes (i, j) with $i, j \in N$ that together define a possible block. The set A_{ij} is defined as set of possible blocks lying somewhere between driving lane i and j. Parameter a defines the number of rows of a block and parameter b_{ij} the number of bays of block (i, j) (see Figure 5.4). As the positions of the driving lanes are enumerated in advance and the positions of the stream points are known, the distances d_{qij} (in meters) for a round trip between stream point q and a block (i, j) can be calculated. Therefore the distances of the round trips shown in

Figure 5.2 are calculated for each pair of stream point and possible module. To calculate the distances d_{qij} the values of tgs^l and tgs^w are used. In summary the following primary parameters and sets are used in the model:

N	Set of possible driving lanes $1 \dots n$
A	Set of all possible blocks defined by two driving lanes ($A \subset N \times N$)
A_{ij}	Set of possible blocks lying between the boundaries marked by driving lanes i and j
Q	Set of stream points (e.g., quay cranes)
Y^L	Yard length in meters
Y^D	Yard depth in meters
Y_T^L	Yard length in TEUs
Y_T^D	Yard depth in TEUs
δ	Number of bays needed for a driving lane
δ_i	Number of bays actually needed for driving lane i
a	Number of rows of a block
α_i	Total number of rows at driving lane i
b_{ij}	Number of bays of block $(i,j) \in A$
$b^{\min}$	Minimal number of bays of a block ($b^{\min} \geq 1$)
$b^{\max}$	Maximal number of bays of a block
f_q	Number of containers entering (or leaving) the terminal at stream point q
d_{qij}	Round trip distance for horizontal means of transport from q to a block (i,j) (in meters)
tgs^l	Length of a twenty-foot ground slot
tgs^w	Width of a twenty-foot ground slot

The used decision variables are given in Figure 5.4. The variable π_i indicates whether driving lane i is used. The variable x_{ij} determines whether block $(i,j) \in A$ is used. For example in Figure 5.4 driving lanes i and j are used in addition to the outer driving lanes 1 and n. Thus $\pi_i = \pi_j = 1$ and in addition $x_{1i} = x_{ij} = x_{jn} = 1$. This example clearly indicates that the decision variable π_i can be concluded from the values of x_{ij} ($2x_{ij} \leq \pi_i + \pi_j \; \forall (i,j) \in A$ and $\sum_{i:(i,k)\in A} x_{ik} + \sum_{j:(k,j)\in A} x_{kj} \geq \pi_k$ $\forall k \in N$) and therefore π_i is not needed to model the problem as an ILP. The remaining decision variable is y_h, which indicates that at least h driving lanes are used in the layout. To sum up, the following decision variables are defined:

π_i	$\pi_i = 1$, if driving lane $i \in N$ is used, otherwise $\pi_i = 0$
x_{ij}	$x_{ij} = 1$, if block $(i,j) \in A$ is used

y_h $y_h = 1$, if at least h driving lanes are used in the layout

Rehandle Approximation and Cost Calculation

As described in Section 5.1.1 we need to consider the expected number of rehandles. Kim et al. (2008) use a formula derived from a former work (see Kim 1997) to approximate the expected number of rehandles for their method to calculate optimal yard layouts. To approximate the expected number of rehandles for picking up an arbitrary container out of a bay with $a \times t^s$ container we again use the formula of Kim et al. (2008):

$$R(t^s, a) = \frac{2t^s - 1}{4} + \frac{t^s + 1}{8a} \tag{5.2}$$

The expected number of rehandles depends on the average stacking height t^s and the number of rows of a block a. As we do not examine a variation of a on finding an optimal layout, the expected number of rehandles depends on the average stacking height t^s of solution s which is calculated as follows:

$$t^s = \frac{Gt^0}{G - \sum_{i \in N} \pi_i^s \alpha_i \delta_i} \tag{5.3}$$

where G is the maximal number of ground slots that can be provided by the yard with length Y^L and a depth of Y^D. Moreover, t^0 is the initial average stacking height and the variables π_i^s represent the values of the variables π_i in solution s.

The general calculation of t^s is nonlinear and cannot be used to model the problem as an integer linear program. In the case of a rectangular storage yard a linearization is possible: For a rectangular storage yard we know that $\alpha_i = \alpha_j = \alpha, \forall i, j \in N$. Therefore the different average stacking heights when h driving lanes are used can be calculated in advance by:

$$T_h = \frac{Gt_0}{G - h\alpha\delta} \tag{5.4}$$

In addition, G can be calculated by $G = \alpha \times Y_T^L$. Thus besides the possible driving lanes, we enumerate in advance the differences in the expected number of rehandles when an hth driving lane is added to the layout:

$$\Delta R_0 = 0 \tag{5.5}$$

$$\Delta R_h = R(T_h, a) - R(T_{h-1}, a) \qquad \forall h = 1 \dots \gamma \tag{5.6}$$

The number of driving lanes used is restricted by the maximal number of driving lanes γ. The value γ depends on the available space (Y_T^L), the minimal block length ($b^{\min}$) and the space needed for a driving lane (δ). We assume that between two driving lanes there is at least a block of minimal length:

$$\gamma = \frac{Y_T^L + \delta}{b^{\min} + \delta} \tag{5.7}$$

The flow of containers starting at a stream point q is given by the parameter f_q. The total flow is given by parameter $F = \sum_{q \in Q} f_q$. To determine the costs we need to evaluate the flow of containers going to the possible blocks. The flow of containers f_q starting at stream point q is distributed according to the number of bays of each potential column of blocks. For example in Figure 5.2 (a) there are two columns of blocks. The number of containers going from stream point q to a column of blocks between i and j is defined as $f_{qij} = f_q(\frac{b_{ij}}{b^{\max}} + \frac{\delta_i + \delta_j}{2b^{\max}})$. For equally sized blocks the flow of containers is equally distributed. For different sizes blocks of a greater capacity (more bays) will have a higher overall flow of containers than smaller blocks. Moreover, the fraction $\frac{\delta_i + \delta_j}{2b^{\max}}$ ensures that the bays used for driving lanes i and j are still considered for the flow of the corresponding block (i, j). Otherwise, the simple sum of $\sum_{i,j \in A} x_{ij}(\frac{b_{ij}}{b^{\max}})$ without $\frac{\delta_i + \delta_j}{2b^{\max}}$ could be less than one for a valid solution and thus only a fraction of the total flow F would be distributed to the blocks.

With the flow values of f_{qij} and the distances d_{qij} the cost coefficients for expected travel times c_{ij}^d are calculated as follows:

$$c_{ij}^d = \sum_{q \in Q} f_{qij} d_{qij} v^d c^d \qquad \forall i, j \in A \tag{5.8}$$

where v^d is the travel time in seconds of a yard truck per meter and c^d are the truck costs per second. The cost coefficients for rehandle levels c_h^r are calculated by:

$$c_h^r = \Delta R_h c^r v^r F \mu \qquad \forall h = 0 \dots \gamma \tag{5.9}$$

where v^r is the time in seconds required to perform a rehandle, c^r the costs for a yard crane per second and μ is the container load factor. The load factor is used to define the portion of the containers that have to be retrieved from a block. This is important because rehandles only occur during the retrieval, not the storage, of containers. To sum up, the following additional parameters and cost coefficients are used:

γ	Maximal number of driving lanes that can be used in the yard
G	Maximal number of ground slots that are provided by a yard without driving lanes
t^0	Initial average stacking height using all ground slots (G) for stacking
t^s	Average stacking height for a valid solution s
T_h	Average stacking height when h driving lanes are used
ΔR_h	Difference in the expected number of rehandles when an hth driving lane is added to the layout
f_{qij}	Number of containers going from q to a block (i, j)
F	Total number (flow) of containers $F = \sum_{q \in Q} f_q$
μ	Load factor of containers: proportion of the total flow of containers to be picked up by the designated mode of transport. Therefore rehandles can occur.
v^r	Time required (seconds) for a yard crane to perform a rehandle
c^r	Costs for a yard crane per second
c^r_h	Cost coefficient for rehandles (yard crane costs) when the hth driving lane is used
v^d	Travel time (seconds) of yard trucks per meter
c^d	Truck costs per second
c^d_{ij}	Cost coefficient for truck costs when driving lanes i and j are used

For the cost coefficients c^r_h and c^d_{ij} it can be observed that the following inequalities are valid:

$$c^r_{h+1} > c^r_h \qquad \forall h = 0 \dots \gamma - 1 \tag{5.10}$$

$$c^d_{ij} > c^d_{ik} + c^d_{kj} \qquad \forall i, j, k \in N \text{ with } i < k < j \tag{5.11}$$

Obviously, inequality (5.10) is valid due to increasing values of ΔR_h when values of h increase. Additionally, the expected distances always decrease when between two driving lanes i,j a third driving lane k is installed. Therefore inequality (5.11) is valid. For a proof see Appendix A.

An Integer Linear Model

The decision problem is to find optimal positions $i \in N$ at which to install driving lanes in the yard. Unless otherwise stated we assume in the following a rectangular storage yard. Using the above described parameters and variables we define a first intuitive formulation, the yard layout model (YLM):

$$\min \sum_{h=0}^{\gamma} y_h c_h^r + \sum_{(i,j)\in A} x_{ij} c_{ij}^d \tag{5.12}$$

s.t.

$$1 \leq \sum_{(i,j)\in A} x_{ij} \tag{5.13}$$

$$x_{ij} \leq \sum_{k:(j,k)\in A} x_{jk} \qquad \forall (i,j) \in A \text{ with } j \neq n \tag{5.14}$$

$$x_{ij} \leq \sum_{k:(k,i)\in A} x_{ki} \qquad \forall (i,j) \in A \text{ with } i \neq 1 \tag{5.15}$$

$$\sum_{(l,m)\in A_{ij}} x_{lm} \leq |A_{ij}|(1 - x_{ij}) \qquad \forall (i,j) \in A \tag{5.16}$$

$$\sum_{(i,j)\in A} x_{ij} \leq \sum_{h=0}^{\gamma} y_h \tag{5.17}$$

$$y_h \leq y_{h-1} \qquad \forall h = 1 \dots \gamma \tag{5.18}$$

$$x_{ij}, y_h \in \{0,1\} \qquad \forall (i,j) \in A, h = 0 \dots \gamma \tag{5.19}$$

Constraint (5.13) forces the existence of at least one block (e.g., at least the two outer driving lanes $1, n$). Constraints (5.14) and (5.15) are needed to ensure for chosen driving lanes i and j that at least one driving lane after j is used as well as a driving lane before i (see Figure 5.4). When driving lanes i and j are used, constraint (5.16) prevents that driving lanes between i and j are additionally used. That is, to ensure that block (i,j) is defined correctly. Constraints (5.17) and (5.18) are used for the activation of rehandle levels when $\sum_{(i,j)\in A} x_{ij}$ columns of blocks are installed. Due to the cost structure it is obvious that (5.16) is not needed, because it is always valid for optimal solutions. In other words a violated constraint (5.16) would mean that driving lanes are installed within a block but not used as the distance costs for the original block are still active. Moreover, due to constraint (5.10) and the minimization objective, constraint (5.18) can be seen as a valid inequality and is not explicitly needed for a correct formulation.

Reformulation as a Network Model

Figure 5.5 shows an example of enumerated driving lanes and valid solutions of the YLM. Those solutions are represented as combinations of edges in Figure 5.5. The gray-shaded edges represent a valid solution. The number of valid solutions (ψ) for the YLM can be calculated assuming $\delta = 0$ and $b^{\min} = 0$: The first

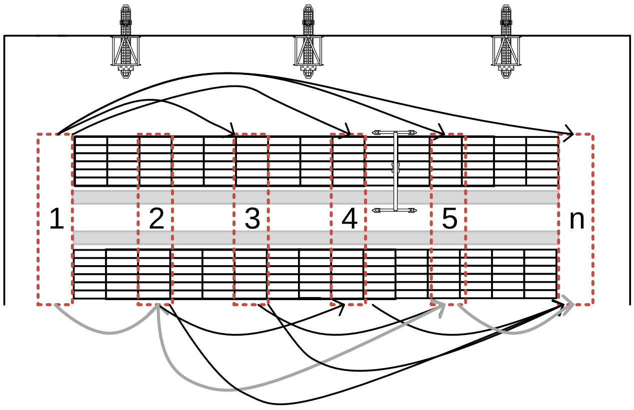


Figure 5.5.: Solution structure for the YLM

simple valid solution allowing just one block is $x_{1n} = 1$. Another possible solution allowing two blocks is $x_{1,n-1} = 1 \wedge x_{n-1,n} = 1$ which means choosing a driving lane between outer driving lanes 1 and n. Hence the number of solutions allowing two blocks is $n-2$. For $k > 2$ blocks $k-1$ interior driving lanes have to be selected from $n-2$ possible interior driving lanes. This is similar to picking $k-1$ unordered outcomes from $n-2$ possibilities. Thus for $k > 2$ the number of solutions is $\binom{n-2}{k-1} = \frac{(n-2)!}{(k-1)!(n-1-k)!}$. Therefore the total number of valid solutions can be calculated by: $\psi = 1 + (n-2) + \sum_{k=3}^{\gamma} \frac{(n-2)!}{(k-1)!(n-1-k)!}$.

The above argument for valid solutions and Figure 5.5 indicate that the yard layout problem can be reformulated as a network model. In such a formulation we define a directed acyclic graph $G = (V, A)$. The set of vertices V is the set of driving lanes $V = N$, and the edge $(i,j) \in A$ between two vertices i, j defines a block between driving lanes $i, j \in N$. The network formulation of the yard layout model (NYLM) is then defined as:

$$\min \sum_{h=0}^{\gamma} y_h c_h^r + \sum_{(i,j)\in A} x_{ij} c_{ij}^d \tag{5.20}$$

s.t.

$$\sum_{j:(i,j)\in A} x_{ij} - \sum_{k:(k,i)\in A} x_{ki} = \begin{cases} 1 & \text{for } i = 1 \\ 0 & \forall i \neq 0 \neq n \\ -1 & \text{for } i = n \end{cases} \tag{5.21}$$

$$\sum_{(i,j)\in A} x_{ij} \leq \sum_{h=0}^{\gamma} y_h \tag{5.22}$$

$$x_{ij}, y_h \in \{0,1\} \quad \forall (i,j) \in A, h = 0 \dots \gamma \tag{5.23}$$

Please note that by definition of the NYLM for all $(i,j) \in A$, $i < j$. Ignoring constraint (5.22) the formulation is similar to a shortest path formulation. Due to the integrality property of the linear programming (LP) relaxation (see e.g. Ahuja et al. 1993) the shortest path problem can be solved in polynomial time. By adding constraint (5.22) the characteristic of the shortest path formulation leading to the totally unimodular characteristic is destroyed. However, it can be shown that the LP relaxation of the NYLM (LP-NYLM) always has at least one integral optimal solution.

Proposition 5.1. *The LP relaxation of the NYLM has at least one integral optimal solution.*

A proof of the above proposition can be found in Appendix A.

As the formulation is a shortest path formulation with an additional constraint it can be seen as a special case of the resource-constrained shortest path problem (RCSP) (see e.g. Irnich and Desaulniers 2005). Beasley and Christofides (1989) define classes for the RCSP, and the NYLM formulation can be seen as special case of the RCSP with a single resource and a single additional constraint. Nevertheless, the NYLM formulation differs from the RCSP with a single resource and a single constraint considered, e.g. by Handler and Zang (1980) as in the NYLM solely the number of edges is constrained and, moreover, costs are connected to the number of edges.

Adoption for Non-Rectangular Storage Yards

In above sections a rectangular storage yard is assumed. This allows the formulation of the yard layout problem as an ILP. When a yard of arbitrary shape is planned, the assumption that the number of rows α_i, affected by an installation of a driving lane, is identical for all driving lanes $i \in N$ is no longer valid. An example with different values for α_i is shown in Figure 5.6. The average stacking heights T_h for a layout with h driving lanes cannot be calculated in advance as the value differs for different driving lanes in the solution. Nevertheless, the formulation of the NYLM can be used with a different, non-linear objective function as the cost factor for rehandles is calculated as follows:

$$c_h^r = R\Big(\frac{Gt_0}{G - \sum_{i\in N} \pi_i \alpha_i \delta}, a\Big) c^r v^r F \mu \qquad \forall h = 0 \dots \gamma \tag{5.24}$$

Replacing the cost calculation (5.9) by (5.24) defines the non-rectangular network yard layout model (NR-NYLM).

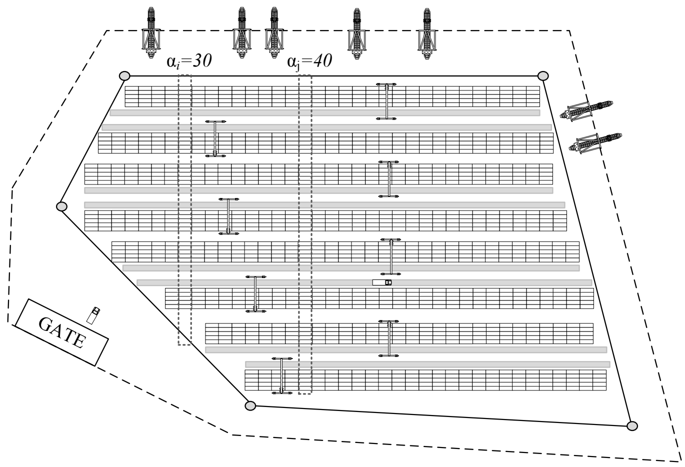


Figure 5.6.: Non-rectangular yard layouts

5.1.3. A Local Search Algorithm

To solve non-rectangular instances we develop a local search algorithm. Several neighborhoods are considered in a special type of variable neighborhood search (VNS) called deterministic variable neighborhood descent (VND) originally proposed by Mladenovic and Hansen (1997). For a survey and a general scheme of VNS and VND we refer to Hansen and Mladenovic (2001). Let $\mathcal{S}$ denote the solution space ($s \in \mathcal{S}$). A solution $s = (1, \ldots, n)$ is defined as path going from vertex 1 to vertex n. The neighborhood structures $\mathcal{N}(s)_k$ are defined as follows:

The first neighborhood operator `AddDL` removes edge (i, j) from given solution $s = (1, \ldots, i, j, \ldots, n)$ and adds edges (i, j) and (j, m) to get the new neighboring solution $s' = (1, \ldots, i, j, m, \ldots, n)$. $\mathcal{N}(s)_1$ is then defined as all solutions s' which can be generated by `AddDL` using solution s. This corresponds to adding a driving lane to the yard layout. Similarly, the neighborhood operator `RemoveAdd` removes a driving lane and adds two driving lanes. Given a solution $s = (1, \ldots, i, j, m, \ldots, n)$ `RemoveAdd` removes edges (i, j) and (j, m) while edges (i, k), (k, l) and (l, m) are added. The last neighborhood operator `Shift-`β exchanges β connected vertices. Let s_k be the vertex in solution s at position k. `Shift-`β removes β vertices $\mathcal{O} := \{s_k, s_{k+1}, \ldots, s_{k+\beta-1} | 1 < k < n\}$ from a given solution s and adds β vertices $\mathcal{O}' := \{s_j | k - 1 < j < k + \beta\}$, where at least one vertex $j \in \mathcal{O}'$ and one vertex $k \in \mathcal{O}$ exists with $j \neq k$. Figure 5.7 illustrates the three different neighborhood operators starting at a solution s.

The idea of the algorithm is to start with the trivial initial solution $s = (1, n)$ having no driving lanes beside the outer driving lanes $1, n$ (see Figure 5.7) and using the `AddDL` operator to add driving lanes. The `AddDL` operation is repeated until distance savings due to additional driving lanes are inferior to higher rehandle

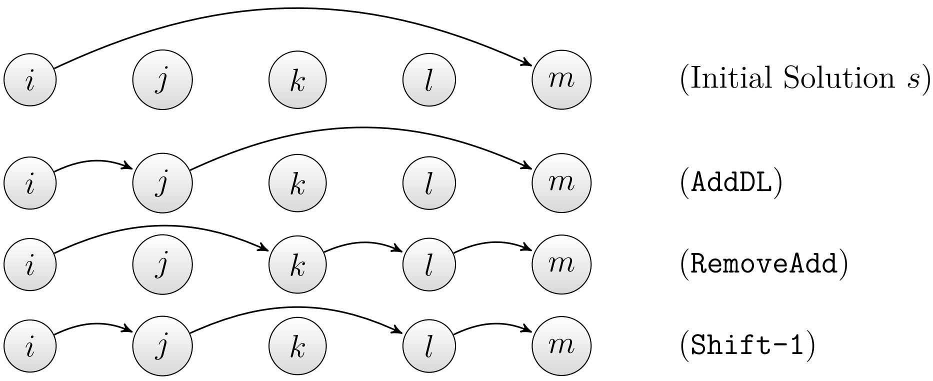


Figure 5.7.: Neighborhood operators for VND algorithm

costs. At this point the next neighborhood operator `Shift-`β is used to change the positions of the driving lanes (choosing other vertices). When shifting of driving lanes cannot improve the solution value, the `RemoveAdd` operator is used to add a driving lane even if this does not improve the solution value. After adding the additional driving lane `Shift-`β is used to improve the current solution. When shifting cannot improve the best solution value the algorithm terminates. Solutions s' having a solution value inferior to the current solution s are only used for further exploration for the `RemoveAdd` operator. Shifting is then used to find an improved solution. Details of the VND procedure are given in Figure 5.8. When the `Shift-`β operator is used cycling has to be avoided. We therefore use a tabu list where for κ iterations the occurrence of edges (s_{k-1}, s_k) and (s_{k-1}, s_j) is forbidden.

Different versions of the VND procedure can be generated by terminating the procedure after different steps. For example, using Step 2 only would result in a greedy procedure. Depending on the desired maximal solution time different versions of the VND procedure can be used.

5.1.4. Computational Results

In this section we present computational results for terminals with different dimensions and characteristics. To be able to compare the results of the VND procedure with optimal solutions of a linear programming solver we calculate results only for rectangular shaped storage yards. Nevertheless, the proposed VND procedure is able to calculate yard layouts for non-rectangular storage yards.

For all instances we assume that twenty-foot ground slots have a length of $tgs^L = 6.36$ m and a width of $tgs^W = 2.7$ m. The depth of the yard is assumed to be 500 m. The values of the cost factors are adopted from Kim et al. (2008)

Step 1: Generate initial solution $s \leftarrow (1, n)$ and set $\beta \leftarrow 2$ and *improved* $\leftarrow$ *true*;
Step 2: Explore neighborhood $\mathcal{N}(s)_1$ (`AddDL` operator) for the best neighboring solution s';
if s' *is better than* s **then** set $s \leftarrow s'$, and repeat Step 2 **else** goto Step 3;
Step 3: Explore neighborhood $\mathcal{N}(s)_2$ (`Shift-`β operator) for the best neighboring solution s';
if s' *is better than* s **then**
    set $s \leftarrow s'$;
    set tabu status for new solution s';
    set *improved* $\leftarrow$ *true*; repeat Step 3;
else
    if $\beta = 2$ **then** set $\beta \leftarrow 3$; repeat Step 3 **else** goto Step 4;
end
Step 4: **if** *improved* $=$ *true* **then**
    Explore neighborhood $\mathcal{N}(s)_3$ (`RemoveAdd` operator) for the best neighboring solution s';
    set $\beta \leftarrow 2$;
    if s' *is better than* s **then** set $s \leftarrow s'$; goto Step 5;
    else
        save current best solution s and set $s \leftarrow s'$ even if s' is inferior to s; goto Step 5;
    end
else
    Algorithm terminates;
end
Step 5: Set *improved* $\leftarrow$ *false* and goto Step 3;

Figure 5.8.: Steps of the VND procedure

with $v^r = 74.19$ seconds, $v^d = 0.2$ seconds, $c^r = 15.56$ and $c^d = 1$. The number of rows per block $a = 6$, the initial stacking height $t^0 = 3$, and the container load factor $\mu = 0.25$. Furthermore, we use $\delta = 4$ and $b^{\min} = 1$. To calculate the total number of rows at position i (α_i) we calculate the maximal number of modules that fit on the terminal area using a module width of 50.88 m. Different instances are generated by changing the length of the yard from 600 m up to 3500 m.

The stream points are generated on two scenarios. The first distributes the stream points for the quay cranes equally over the seaside border of the terminal (quay wall) and the gate is positioned in the middle of the landside border. This is called the standard scenario. The second scenario has an additional quay wall at the righthand side of the terminal area, where the side quay wall is half the length of the terminal depth. The gate is assumed to have the rightmost position at the landside border. Both scenarios are illustrated in Figure 5.9. All stream

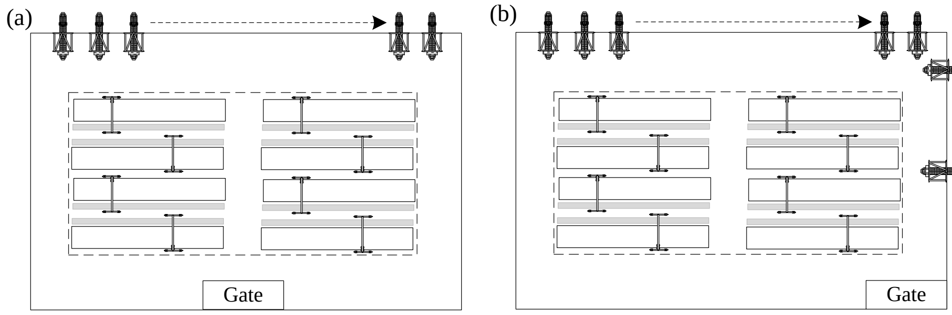


Figure 5.9.: (a) Standard scenario and (b) scenario with additional side quay wall

points representing quay cranes are generated over the described directions every 10 m as an equal distribution is assumed. This corresponds to an equal likelihood of the occurrence of pickup and delivery jobs for internal trucks at the quay walls (see Kim et al. 2008). Each stream point representing quay cranes is assumed to inject 240 containers. The stream point representing the gate injects 30% of the total flow of containers injected by quay cranes.

The VND procedure is implemented in C#. To solve the LP-NYLM we use the solver MOPS 9.27 (see Suhl 1994, MOPS 2009). The tests run on an Intel Core 2 Duo 2.2 GHz, 2 GB RAM. Table 5.1 shows the results for the standard scenario and Table 5.2 for the scenario with an additional side quay wall. For all instances of both scenarios the solutions of the LP-NYLM have been integral. The VND procedure is compared to the optimal results calculated by MOPS. VND is the procedure described by Figure 5.8, greedy the VND procedure excluding steps 3-4 and shifting the VND procedure excluding step 4. The column #Vars illustrates the problem complexity as the value shows the number of variables of the NYLM calculated by $|A|+\gamma$. The column #Bays shows the average number of bays of the blocks in the optimal solution and #DL the number of used driving lanes in the optimal solution (without the outer driving lanes). The "Gap" columns show gaps of the best objective value found by the corresponding heuristic compared with the optimal solution. The entries "$-$" in column gap show that the corresponding heuristic has found the optimal solution.

The results in Table 5.1 show that all instances can be solved in reasonable time. For higher values of Y^L the problem complexity increases. The maximal run time needed by MOPS is 4.5 seconds to compute the optimal solution for the instance $Y^L = 3500$. The heuristics achieve competitive results for the standard scenario: The VND heuristic is able to calculate the optimal solution for 14 standard instances (47%) and the maximal gap is less than or equal to 1.3%. The run time needed is higher than that of MOPS and all other heuristics. The greedy heuristic in most cases calculates a solution in less than one millisecond.

Table 5.1.: Computational results for standard scenario

		Optimal Solution				Greedy		Shifting		VND	
Y^L	#Vars	$\frac{\text{Obj.}}{1000}$	sec	#Bays	#DL	Gap(%)	sec	Gap(%)	sec	Gap(%)	sec
600	3768	4703.8	0.02	20.5	3	-	0.001	-	0.03	-	0.05
700	5283	5724.7	0.03	24.5	3	0.0	0.000	-	0.02	-	0.09
800	6936	6849.9	0.04	28.3	3	-	0.000	-	0.03	-	0.11
900	8948	8048.0	0.06	25.0	4	0.7	0.000	0.7	0.05	0.0	0.16
1000	11215	9310.9	0.08	22.8	5	1.5	0.000	-	0.08	-	0.36
1100	13573	10638.9	0.09	25.3	5	1.3	0.000	1.3	0.05	1.3	0.15
1200	16336	12086.0	0.11	28.0	5	0.5	0.000	0.5	0.07	0.5	0.14
1300	19355	13603.8	0.16	25.7	6	0.1	0.000	0.1	0.09	0.1	0.27
1400	22630	15176.8	0.21	24.0	7	-	0.000	-	0.12	-	0.23
1500	25933	16819.6	0.27	25.9	7	-	0.000	-	0.14	-	0.28
1600	29705	18579.7	0.28	27.9	7	0.0	0.000	-	0.17	-	0.35
1700	33732	20410.5	0.34	23.1	9	0.1	0.000	0.1	0.21	-	1.46
1800	38015	22297.5	0.45	24.7	9	0.4	0.000	0.4	0.26	0.0	1.59
1900	42263	24251.6	0.48	26.2	9	0.7	0.000	0.7	0.31	-	1.06
2000	47042	26326.6	0.60	27.8	9	0.9	0.000	0.4	0.66	-	1.23
2100	52077	28468.4	0.67	23.8	11	1.0	0.000	0.0	0.92	0.0	1.50
2200	57030	30644.8	0.75	25.1	11	1.0	0.000	0.1	0.50	0.1	0.97
2300	62562	32941.7	0.90	26.4	11	0.8	0.000	0.8	0.20	0.8	0.42
2400	68349	35330.2	1.03	27.8	11	0.5	0.000	0.5	0.24	0.5	0.68
2500	74392	37783.0	1.36	24.4	13	0.3	0.000	0.3	0.26	0.3	0.55
2600	80290	40270.6	1.70	25.4	13	0.2	0.001	0.2	0.31	0.2	3.25
2700	86829	42884.6	1.84	26.6	13	0.1	0.001	0.1	0.35	0.1	0.90
2800	93624	45587.6	2.25	25.6	14	0.0	0.001	0.0	0.40	0.0	0.97
2900	100227	48313.6	2.29	24.7	15	-	0.001	-	0.45	-	1.18
3000	107519	51155.2	2.43	25.7	15	0.0	0.001	-	0.51	-	2.04
3100	115066	54085.0	2.78	26.7	15	0.0	0.001	-	1.08	-	2.26
3200	122869	57101.7	3.07	25.8	16	0.0	0.002	0.0	1.81	-	5.18
3300	130417	60134.3	3.45	25.0	17	0.0	0.001	0.0	0.71	0.0	5.16
3400	138716	63292.7	3.89	25.9	17	0.1	0.001	0.1	0.76	0.0	3.60
3500	147271	66539.4	4.50	26.8	17	0.1	0.001	0.1	1.64	0.0	5.47

Table 5.2.: Computational results for scenario with side quay wall and gate in lower right corner

		Optimal Solution				Greedy		Shifting		VND	
Y^L	#Vars	$\frac{\text{Obj.}}{1000}$	sec	#Bays	#DL	Gap(%)	sec	Gap(%)	sec	Gap(%)	sec
600	3768	7833.4	0.02	28.7	2	0.4	0.001	0.4	0.03	0.4	0.05
700	5283	9169.7	0.03	24.5	3	-	0.000	-	0.02	-	0.05
800	6936	10631.0	0.04	28.3	3	-	0.000	-	0.03	-	0.08
900	8948	12144.6	0.06	25.0	4	0.6	0.000	0.6	0.05	-	0.18
1000	11215	13776.5	0.08	28.2	4	1.2	0.000	-	0.08	-	0.15
1100	13573	15480.1	0.09	25.3	5	1.3	0.000	1.3	0.05	1.3	0.11
1200	16336	17293.1	0.12	28.0	5	0.5	0.000	0.5	0.07	0.5	0.15
1300	19355	19170.9	0.15	25.7	6	0.2	0.000	0.2	0.09	0.2	0.21
1400	22630	21163.0	0.20	24.0	7	0.0	0.000	-	0.11	-	0.76
1500	25933	23239.4	0.29	25.9	7	0.0	0.000	-	0.15	-	0.35
1600	29705	25413.4	0.28	24.3	8	0.0	0.000	0.0	0.18	-	1.06
1700	33732	27665.8	0.34	26.1	8	0.2	0.000	0.2	0.21	-	1.80
1800	38015	30022.9	0.47	24.7	9	0.3	0.000	0.3	0.27	-	1.99
1900	42263	32472.3	0.47	26.2	9	0.5	0.000	0.5	0.31	-	1.84
2000	47042	35013.4	0.55	24.9	10	0.8	0.000	0.8	0.36	0.0	3.86
2100	52077	37639.4	0.66	26.4	10	0.9	0.000	0.0	0.38	0.0	2.14
2200	57030	40373.8	0.78	25.1	11	0.9	0.000	0.1	1.05	0.1	1.38
2300	62562	43186.3	0.89	26.4	11	0.7	0.000	0.7	0.38	0.7	4.00
2400	68349	46094.8	1.08	25.3	12	0.5	0.000	0.5	0.24	0.5	1.30
2500	74392	49094.1	1.29	26.5	12	0.3	0.000	0.3	0.30	0.3	3.26
2600	80290	52197.2	1.95	25.4	13	0.2	0.000	0.2	0.31	0.2	1.49
2700	86829	55382.1	1.60	26.6	13	0.1	0.000	0.1	0.35	0.1	1.13
2800	93624	58660.0	1.92	25.6	14	0.0	0.001	0.0	0.41	0.0	1.13
2900	100227	62040.7	2.09	26.6	14	0.0	0.001	0.0	1.30	0.0	6.03
3000	107519	65503.7	2.64	25.7	15	0.0	0.001	-	0.52	-	1.25
3100	115066	69060.7	2.61	26.7	15	0.0	0.001	-	0.55	-	5.52
3200	122869	72708.3	3.35	25.8	16	0.0	0.001	0.0	0.66	0.0	15.49
3300	130417	76460.9	3.62	26.7	16	0.0	0.001	0.0	2.01	0.0	17.37
3400	138716	80293.6	3.75	25.9	17	0.1	0.001	0.1	0.78	0.0	15.60
3500	147271	84223.0	4.95	26.8	17	0.1	0.001	0.1	2.58	0.0	23.82

Naturally, the gaps (maximal 1.5%) are higher than that of Shifting and VND. Shifting achieves for 33% of the standard instances optimal solutions.

The results for the scenario with side quay wall are similar to the standard scenario with the difference that the instances seem to be more complex: 12 instances (40%) can be optimally solved by the VND heuristic. Moreover, the computational times are higher: in total 41.66 seconds are needed to calculate all solutions for the standard scenario compared with 113.54 for the scenario with side quay wall using the VND heuristic. Figures 5.10 and 5.11 show the results for the instance $Y^L = 1200$. The number on each module defines the number of bays of each block. The dots indicate stream points representing the quay cranes. For the sake of simplicity we just draw the upper seaside modules; the lower

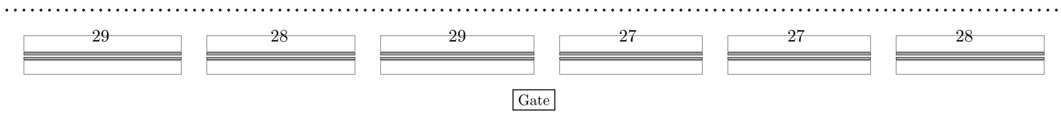


Figure 5.10.: Result for instance $Y^L = 1200$ for the standard scenario

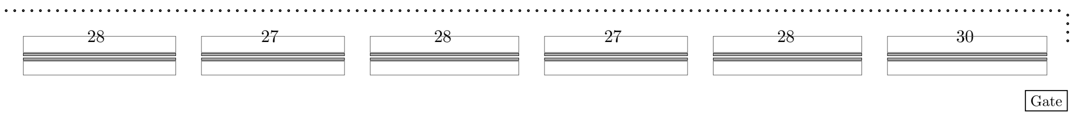


Figure 5.11.: Result for instance $Y^L = 1200$ for the scenario with side quay wall

modules are not illustrated. In the standard scenario the longest block (29 Bays) is placed in the middle of the yard, whereas in the side quay wall scenario the longest block is positioned on the right. The average number of bays is identical (28 bays) for both scenarios in the case of $Y^L = 1200$.

The results of Tables 5.1 and 5.2 show that the average number of bays of a block stays on a level between 20 and 29 bays for all different yard lengths. Therefore, to hold the level of bays the number of driving lanes used in the solutions has to increase for higher yard lengths. In other words the trade-off between truck distance costs and yard crane costs implies a specific number of driving lanes. For example, for a yard length of 600 m three driving lanes achieve the lowest solution value and thus achieve the best trade-off between truck distance costs and yard crane costs. The use of three driving lanes remains favorable until a yard length of 900 m where four driving lanes are used. Consequently, the results of Tables 5.1 and 5.2 show no overall trend that a higher yard length leads to a higher number of bays in the blocks. In general, a terminal planner should carefully consider the trade-off between truck costs and yard crane costs as well as the available yard length when planning the layout of the yard.

5.1.5. Summary

In this section we have introduced different formulations for planning the yards of arbitrary shaped container terminals. We show that for rectangular container yards the problem can be formulated as a special RCSP and, moreover, we show that the linear relaxation of the special RCSP formulation has at least one optimal integer solution. For container yards of arbitrary shape the problem is nonlinear, and we develop a VND procedure to solve non-rectangular instances. The computational study shows that the VND heuristic achieves competitive results with a gap less than 1.5% in rectangular cases and, most important, the

VND procedure calculates optimal solutions for 43% of the instances. We assume that the solution quality is similar for non-rectangular instances. Moreover, the VND procedure is scalable using the trade-off between computational time and solution quality. Either the best possible solution can be found using all steps, or a first quick solution can be found by using the greedy procedure defined by step 2.

5.2. Planning Yard Layouts Considering Variable Block Widths

In the previous section we proposed a new method of planning yards considering different numbers and positions of driving lanes in the layout. The different numbers of driving lanes leads to different block lengths. In this section, however, we consider the influence of different block widths on planning a yard of a container terminal. We therefore again focus on yard layouts with transfer lanes. In particular, we deal in this section only with the more common layout where the blocks are orientated parallel to the quay (see Section 2.4.3); a perpendicular orientation is ignored.

The remainder of this section is structured as follows: In Section 5.2.1 we discuss the different trade-offs resulting from different block widths. In Section 5.2.2 we derive different estimates to measure the performance of yard blocks. In Section 5.2.3 we present numerical examples using the derived estimates. In Section 5.2.4 we summarize the results of this section. This section is based on Wiese (2009).

5.2.1. The Influence of Block Width on the Terminal Layout and Performance

Different block widths influence the number of blocks that fits in a given terminal area. Thus when a wider block width is used, fewer blocks can be arranged in the same area than is the case using thinner blocks. However, wider blocks usually use the area more efficiently as less space is needed between the blocks (e.g., for transfer lanes). Figure 5.12 shows two possible configurations of a storage yard, with blocks composed of either four or seven rows. Obviously, the configuration with seven rows has a total number of 21 rows; the four-row configuration 16. Evidently, the configuration with four rows has fewer ground slots. This lower level of terminal land usage can be handled in two ways: either to stack containers higher or use a larger area. Both possibilities are restricted. In most ports land is a scarce resource and therefore the available land can be assumed to be limited. Additionally, the stacking height is limited by the technical restrictions of the cranes used, whereas there are RTGs that can stack up to seven tiers high (see Section 2.2.3).

The drawback of wider and thus fewer blocks in the yard is that traffic jams become more likely and, furthermore, crane trolleys have to cover longer distances. Figure 5.13 shows different parameters and travel distances (like trolley travel)

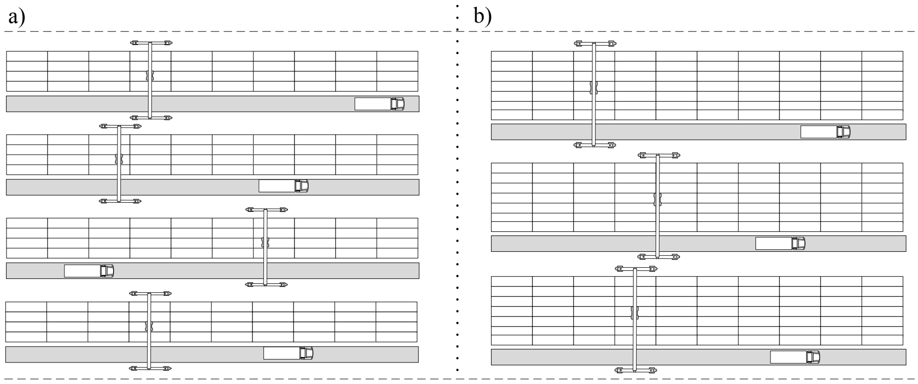


Figure 5.12.: Yard layout with four rows (a) and with seven rows per block (b)

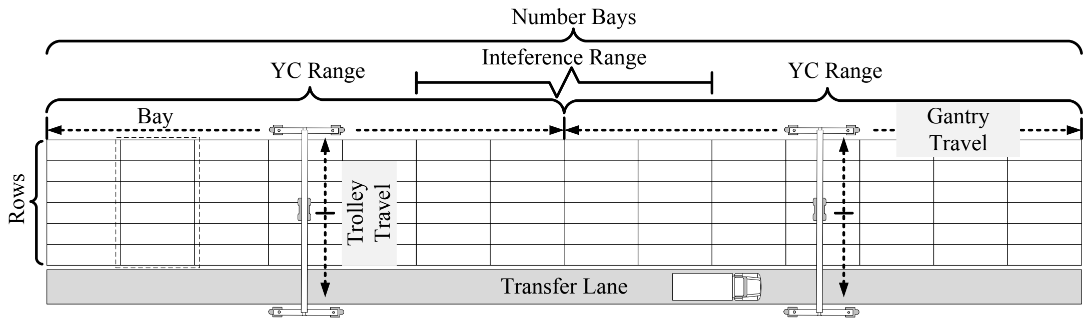


Figure 5.13.: Structure and parameter of a storage block with transfer lane

that are influenced by different block widths. Assuming that for different block widths the number of yard cranes is constant, the ranges per yard crane decrease for wider blocks. This reduces on the one hand the gantry travel distances, and on the other, interferences between two yard cranes on the block become more likely. Interference between yard cranes occurs when a yard crane operates too close to another crane. Thus between two cranes a minimal range has to hold (see Petering and Murty 2009) so that the cranes can operate without interference. This range is called interference range.

The costs for each block width differ because of the number of cranes needed, the cost for each crane and the costs for the area needed. Greater widths of a yard crane may lead to higher costs for each crane. Thinner block widths lead either to the use of more land or to higher average stacking heights. In both cases higher costs may occur either for more land or for cranes with higher stacking capabilities.

In summary, it can be stated that several trade-offs have to be considered when the block width is planned for a yard layout of a container terminal. The aim of this section is to introduce a method to quantify the different influences of block width either on the terminal performance or on the terminal costs.

5.2.2. Performance and Cost Calculation

In this section different formulas are derived which estimate the influence of different block widths on several aspects of terminals. For simplification, we assume that the terminal has one berth with just one column of blocks as depicted in Figure 5.12 (a). A yard crane is assigned to a single block and thus cross gantry moves are ignored. Therefore the number of yard cranes has at least to be equal to the number of blocks. Above different possibilities are described to handle the different uses of the area. In the following we assume that a maximal depth of the yard is given and that the given space is occupied as well as possible. The remaining changes in the number of ground slots are handled by increasing the average stacking height. The following parameters are used for the formulas:

b	the number of bays of a block,
yc	the number of yard cranes,
ir	the number of bays in the interference range,
rw	the width of a row (m),
lw	the width of the transfer lane (m),
cw	the maximal depth of the storage yard area (m),
l	the length of a bay (m),
ht	height of a container (m),
cp	the yard capacity,
sg	the gantry speed (m/sec),
st	the trolley speed (m/sec),
sh	the hoisting speed (sh^f full, sh^e empty m/sec).

Moreover, the following different variables are considered:

r	the number of rows of a block,
n	the number of blocks,
g	the number of ground slots,
d	the actual depth of the yard,
a	the actual yard area used,
yb	the range of bays for each yard crane,
ah	the average stacking height.

The variables n, g, ah depend on the number of rows of a block r. The number of blocks which can be placed on the terminal area is defined as follows:

$$n = \frac{cw}{r \times rw + lw}. \tag{5.25}$$

Thus the number of ground slots fitting on the terminal area is

$$g = n \times r \times b, \tag{5.26}$$

and the average stacking height is

$$ah = \frac{cp}{g} \tag{5.27}$$

containers high. We assume that each yard crane operates on an assigned range (YC Range in Figure 5.13). To distribute the workload the ranges are equal for all yard cranes:

$$yb = \frac{b \times n}{yc}. \tag{5.28}$$

The cycle time Tc of a yard crane for handling a container is composed of the time needed to gantry to the bay Tg, to travel with the trolley Tt, to hoist a container Tl as well as the time to dock on a container and place it on a truck Td. Additionally, interferences with other yard cranes cause waiting times Tw. Moreover, rehandles occur and therefore rehandle times Tr have to be considered as well. The expected cycle time for handling a container can be calculated as:

$$E(Tc) = E(Tg) + E(Tt) + E(Tl) + E(Td) + E(Tw) + E(Tr) \tag{5.29}$$

We assume that yard cranes perform jobs solely in their assigned range (yb). Additionally, we assume a uniform distribution of job positions in the assigned range. Therefore the maximal bays to gantry are $yb - 1$ and the minimum is 0. The probability that the two successive jobs occur in the same bay (a distance of 0 bays) is $\frac{1}{yb}$. The probability for a distance of one bay is $\frac{2(yb-1)}{yb^2}$ and for a distance of two bays is $\frac{2(yb-2)}{yb^2}$ until a distance of $yb - 1$ bays with a probability of $\frac{2}{yb^2}$ (see Kim et al. 2008). Thus $E(Tg)$ can be computed as

$$E(Tg) = \frac{l}{sg} \sum_{i=1}^{yb-1} \frac{2(yb-i)}{yb^2} i = \frac{l(yb-1)(yb+1)}{3 \times sg \times yb}. \tag{5.30}$$

The value $E(Tt)$ depends on the number of rows of the block r. The spreader has to go to the row where the designated container has to be picked up and back to the transfer lane or vice versa. The probability of a movement with a distance of two rows is $\frac{1}{r}$. This is a movement of a container from the first row next to the transfer lane to the transfer lane. The maximal distance for a spreader move is

$2r$ (see Figure 5.13) again with a probability of $\frac{1}{r}$. For all moves we assume that the spreader has to travel the additional distance of $\frac{lw}{2}$ (half the transfer lane).

$$E(Tt) = \frac{lw}{2st} + \frac{rw}{st}\sum_{i=1}^{r} 2i\frac{1}{r} = \frac{(r+1)rw}{st} + \frac{lw}{2st} \tag{5.31}$$

A container has to be lifted over the stacked containers and set down on a waiting truck. Therefore we assume that

$$E(Tl) = ah \times ht \times \frac{1}{sh^e} + ah \times ht \times \frac{1}{sh^f} \tag{5.32}$$

where the distance $ah \times ht$ is run one time empty and one time loaded. For docking the spreader onto a container we assume on average 10 seconds and for the positioning of the container on a truck 30 seconds.

$$E(Td) = 40 \tag{5.33}$$

A waiting time of the yard crane has to be considered when a yard crane waits for another yard crane on the block to finish its tasks. As we assume that yard cranes operate in their given range on a block an interference can only occur when more than one crane operates on a block. For two cranes simultaneously performing a job on the same block the probability of interference is:

$$\sum_{i=1}^{yb} \frac{1}{yb}\frac{\max(0, \min(ir - (yb - i), yb))}{yb} \tag{5.34}$$

Figure 5.14 illustrates the derivation of the interference probability. The probability that a YC is in a specific bay i is $\frac{1}{yb}$. The probability that interferences occur is similar to the probability that the second crane is at the same time within the interference range that is spanned starting from the bay i of the first crane: $\max(0, \min(ir - (yb - i), yb))$. Obviously the interferences occur only for blocks with more than one crane. We therefore weight the waiting times by the number of blocks for which interferences can occur. The value n_x defines the number of blocks with x yard cranes assigned. For simplification we assume that for x yard cranes on a block $x - 1$ interferences can occur, e.g. for a block with two cranes one interference can occur with a probability defined by (5.34). The time a yard crane has to wait depends on the time the other crane takes to finish its job. We

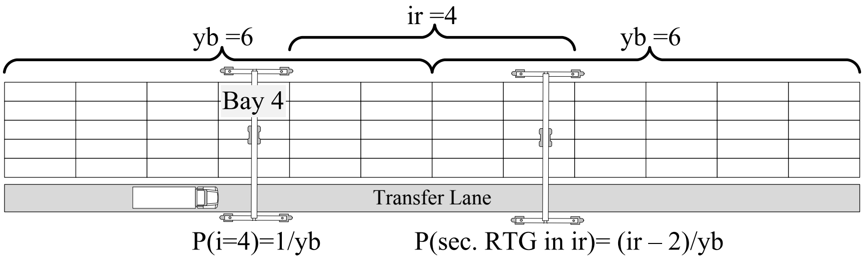


Figure 5.14.: Example for interference probabilities

assume that the other crane has finished its gantry travel to the final bay, which leads to the following approximate estimate:

$$E(Tw) = \Big(E(Tt) + E(Tl) + E(Td)\Big) \times \frac{\sum_{x=2}^{\max(x)} n_x(x-1)}{n} \times \sum_{i=1}^{yb} \frac{1}{yb} \frac{\max(0, \min(ir - (yb - i), yb))}{yb}. \quad (5.35)$$

The occurrence of rehandles depends on the average stacking height. We use the formula of Kim et al. (2008):

$$R(ah, r) = \frac{2ah - 1}{4} + \frac{ah + 1}{8r}. \quad (5.36)$$

As mentioned in Kim et al. (2008), several strategies and pre-stacking operations are available which aim to decrease the number of rehandles. In such a case the values for $R(ah, r)$ should be adjusted carefully by a factor. Furthermore, as mentioned in the section above, rehandles occur only when a container is retrieved from a block. We therefore assume a factor of 0.5. We also assume that containers on top of the target container are moved to a position in the same bay. Therefore

$$E(Tr) = 0.5R(ah, r) \times (E(Tt) + E(Tl) + E(Td)). \quad (5.37)$$

The expected distances of trucks change only due to the actual depth of the yard area as the length of the blocks remains unchanged. The actual depth of the yard depends on the number of blocks n and their width $lw + r \times rw$. The actual depth of the yard is defined by $d = n \times (lw + r \times rw)$ and the expected travel distance of trucks traveling to a block and back to the quay or the gate is equal to d (see Kim et al. 2008).

As described above the costs depend on the number of yard cranes yc (which are not considered to be variable) and the area required for the terminal. The required yard area a for an actual block width is calculated by $a = l \times b \times d$.

Table 5.3.: Numerical results for the scenario

r	n	g	ah	Tg	Tt	Tl	Td	Tw	Tr	Tc	mov/h
3	8	1008	4.5	45.5	12.4	55.7	40.0	0.0	120.5	274.1	13.1
4	7	1176	3.9	39.8	14.6	47.8	40.0	0.4	93.7	236.2	15.2
5	6	1260	3.6	34.1	16.8	44.6	40.0	1.2	84.4	220.9	16.3
6	6	1512	3.0	34.1	18.9	37.1	40.0	1.1	64.0	195.3	18.4
7	5	1470	3.1	28.4	21.1	38.2	40.0	3.2	67.8	198.7	18.1
8	5	1680	2.7	28.4	23.3	33.4	40.0	3.1	56.0	184.1	19.6
9	4	1512	3.0	22.7	25.4	37.1	40.0	8.4	66.9	200.6	17.9
10	4	1680	2.7	22.7	27.6	33.4	40.0	8.2	57.9	189.8	19.0
11	3	1386	3.3	17.0	29.8	40.5	40.0	25.8	79.1	232.2	15.5
12	3	1512	3.0	17.0	31.9	37.1	40.0	25.6	70.4	222.0	16.2
13	3	1638	2.8	17.0	34.1	34.3	40.0	25.4	63.4	214.2	16.8

Thus in this study the costs influenced by different block widths are determined only by the costs for the area a.

5.2.3. Numerical Example

In the previous section several formulas are derived to quantify the different effects of block widths on yard performances and on costs. These estimates can be used to identify adequate block widths. In practice, a typical block width is six rows and there are also configurations having up to eight rows for RTGs (see Petering 2009). A typical width for RMGs is ten rows. We assume that the possible block width could range from about three to 13 rows. These 11 possible configurations can easily be enumerated.

The considered scenario is defined as follows: The maximal depth of the storage yard $cw = 150$ m, the number of bays of a block $b = 42$, the number of yard cranes $yc = 8$, the interference range $ir = 8$ bays (see Petering and Murty 2009), the width of a row $rw = 2.6$ m, the width of the transfer lanes $lw = 9$ m, the length of a bay $l = 6.5$ m, the height of a container $ht = 2.6$ m and the yard capacity $cp = 4536$ containers. Furthermore, the velocity of the cranes is defined by $sg = 2$ meter per second (m/sec) for gantry speed, $st = 1.2$ m/sec for trolley speed, $sh^f = 0.3$ m/sec, and $sh^e = 0.7$ m/sec for hoisting speeds (full and empty) (see Stahlbock and Voß 2008).

Table 5.3 shows the results for the different block widths. Additionally to the expected values for Tc, Table 5.3 displays the expected number of moves per hour (mov/h) for the yard cranes (mov/h$= 3600/Tc$). The best yard crane

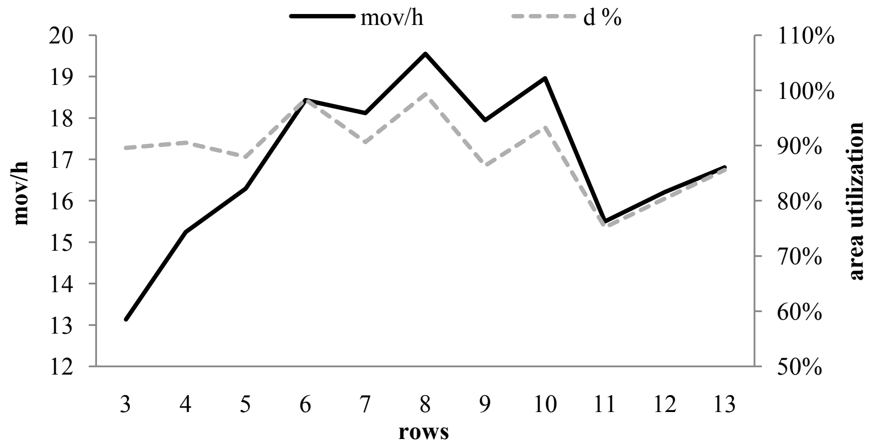


Figure 5.15.: Moves per hour (mov/h) and area utilization

performance can be achieved for a block width of eight rows, where 19.6 mov/h are expected. Furthermore, row widths of six to ten rows achieve good results with about 18 mov/h. Evidently, for a higher number of rows the gantry time decreases continuously. In contrast, the trolley travel time increases constantly. The interference probability also increases continuously for higher number of rows. In some cases the effect of a higher interference probability is dominated by lower lifting times. In those cases the waiting time decreases. Normally the waiting time increases for a higher number of rows. The lifting and rehandle times both tend to decrease in accordance with a higher number of rows. In some cases this tendency is discontinued as less area is used by the resulting block width, which leads to a higher average stacking height.

The relation of area use and mov/h is shown in Figure 5.15. The values of d % are calculated by $\frac{d}{cw}$ and represent the use of the maximal yard depth. On the one hand, the results show that for a high area use high performance values can be achieved. On the other hand, a high area use leads to higher expected travel distances for trucks and to higher costs for land. Thus if yard crane performance alone is considered, eight rows is the most promising solution. If truck performance and terminal costs are also considered, the decision gets more complex. In this case all performance and costs measures should be considered carefully for a proper decision on the optimal block width.

5.2.4. Summary

In this section we discuss the effect of different block widths on terminal performance and terminal costs. To quantify the different trade-offs several estimates are derived. For an exemplary scenario numerical results are presented. The results show that typical block widths between six and ten rows achieve good results. This corresponds to block widths of actual RTG-based container terminals where six to eight rows are common (see Petering 2009). The results show, furthermore, that there is a relation between area use and the corresponding performance. In practice, comparing different widths (even of a single row) can lead to higher area use. This may induce a higher yard performance. A special knapsack problem (only allowing identical widths) can be used to evaluate the block width with the highest area use.

The results of the proposed model are, however, approximative. For instance, we propose a rough estimate to measure the interferences between two cranes. This approximation should be extended to the case in which more than two yard cranes operate on a single block and to consider the simultaneous time in more detail. Moreover, in this chapter a complete randomized occurrence of jobs is assumed. In practice, more than one job will be performed in sequence on a single bay. Therefore the gantry time in this study may be overestimated. In future studies a more detailed discussion of gantry movements would be appropriate. Nevertheless, the proposed method provides a tool which can quickly identify promising block widths.

6. Designing Yard Layouts with Transfer Points

The two common yard layouts in which gantry cranes are used for stacking are that with transfer lanes and that with transfer points. The previous chapter deals with the design of layouts with transfer lanes. In this chapter we focus on the design of the other yard layout category, i.e. we examine yard layouts with blocks having transfer points. The structure of a block with transfer points is shown in Figure 6.1. In the following sections we present a procedure for calculating promising configurations of storage yards and their block designs by considering blocks with transfer points. More precisely, we focus on a perpendicular layout with transfer points as depicted in Figure 6.2. Thus we focus on a layout where the blocks are orientated perpendicularly to the quay and the landside traffic is separated from that of the seaside. These layouts are frequently found in major ports in Europe, the CTA in Hamburg or the ECT in Rotterdam e.g. implement such a configuration. Following Wiese et al. (2009a) six terminals in Europe use or plan to use A-RMG configurations. In the CTA and the ECT terminals AGVs are used for the horizontal transport at the seaside and an A-RMG system in the storage yard.

The remainder of this chapter is structured as follows: in Section 6.1 we present a model for designing a perpendicular yard layout with transfer points which considers different block widths and lengths. Cycle times for crane movements

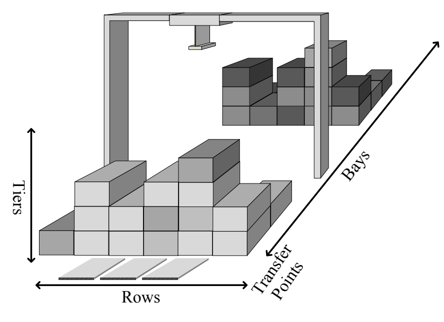


Figure 6.1.: Structures of blocks with transfer points using RMGs

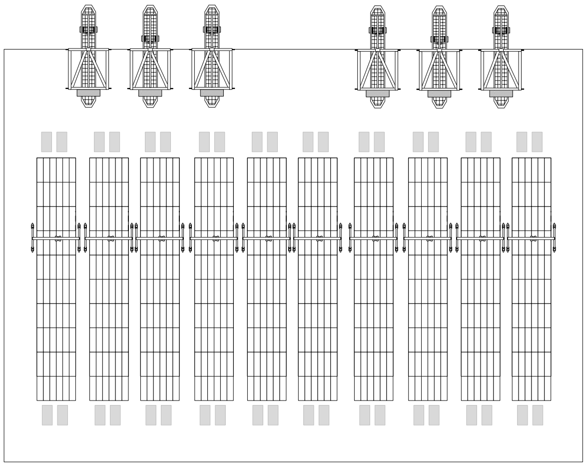


Figure 6.2.: Schema of a perpendicular layout with transfer points

are estimated considering the movements for standard and reefer containers. In Section 6.2 we present numerical results and we also discuss the positioning of reefer racks in the yard. Finally, we summarize the results of this chapter in Section 6.3. This chapter is based on Wiese et al. (2011b).

6.1. A Model for the Layout Design of Yard Layouts with Transfer Points

In this section we propose a model for planning perpendicular yard layouts with transfer points. In such a layout landside traffic is separated from seaside traffic (see Figure 6.2). Thus external trucks are only handled by the landside transfer points, whereas the seaside traffic is handled by the seaside transfer points. In a perpendicular layout configuration reefer racks are frequently positioned at the landside end of the blocks. This make it easier for service workers to access the reefer containers. Thus we assume that the reefer racks are positioned at the landside end of the blocks. Furthermore, we assume that the gantry cranes operate in single cycle mode where the crane goes empty into the block, collects a container and goes back to the transfer point and vice versa to store a container. Gantry moves and sideward movements of the trolley can be made simultaneously. We assume that the time spent on gantry moves is greater than that for sideward movements of the trolley. We therefore ignored the time taken for sideward movements of the trolley. Nor do we consider acceleration and deceleration of the equipment.

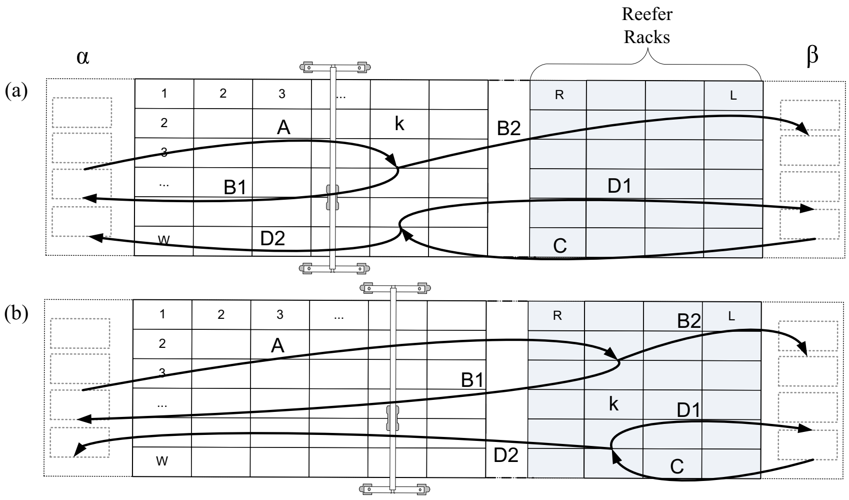


Figure 6.3.: Possible cycle moves for (a) standard containers (b) reefer containers

6.1.1. Cycle Distance of Gantry Movements

In this section approximate estimates of the expected average cycle distances for storing a container into a block or of removing a container from a block and returning for the next task are derived for a single A-RMG. The expected distances depend on the length of a block, the number of reefer racks in the block and the ratio of containers to be handled either at the seaside or landside transfer points. The following variables and parameter are used for the calculation of the expected cycle gantry distance d_g^t where $t = \{STD, REEF\}$ denotes the container type to pickup. α denotes the probability that a container has to be moved from or to a seaside transfer point. Likewise β denotes the probability that a container has to be moved from or to a landside transfer point. Naturally, $\beta = 1 - \alpha$. In other words α and β can be calculated using the ratios of import, export and transhipment of a terminal. Every import or export container passes through the terminal using both sides of a block (seaside and landside). In contrast transhipment containers are stacked into a block and retrieved from a block only via the seaside. Thus in a pure transhipment terminal α would be one. For all terminals α is between 0.5 and 1 depending on the transhipment ratio of the specific terminal. w denotes the width of a block in rows and l the length in bays. r is the number of reefer racks at the landside end of a block. The considered possible cycle moves for a gantry travel are illustrated in Figure 6.3.

Using the probabilities α and β we are able to describe the likelihoods for all cycles displayed in Figure 6.3. In the following we assume that the probability that a crane has to move to a specific bay (to store or retrieve a container) is equal for all bays. The probability of a first move A is α and of C is β. The

Table 6.1.: Expected cycle distances

	Cycle	Distance of cycle	Probability
Reefer:	(A,B1)	$2 \times (l - r + k)$	$\sum_{k=1}^{r} \frac{1}{r}\alpha^2$
	(A,B2) or (C,D2)	$l + 1$	$\alpha\beta$
	(C,D1)	$2 \times k$	$\sum_{k=1}^{r} \frac{1}{r}\beta^2$
Regular:	(A,B1)	$2 \times k$	$\sum_{k=1}^{(l-r)} \frac{1}{(l-r)}\alpha^2$
	(A,B2) or (C,D2)	$l + 1$	$\alpha\beta$
	(C,D1)	$2 \times (k + r)$	$\sum_{k=1}^{(l-r)} \frac{1}{(l-r)}\beta^2$

probability that move B1 or B2 follows after move A as well as the probability that move D1 or D2 follows after C depends again on the probabilities α and β. For example the likelihood of cycle (A,B2) is $\alpha \times \beta$. The expected distance for standard containers is calculated as follows: A possible cycle move is (A, B1) having a distance $2 \times k$ with $k < (l - r)$ and $P\{k = 1, \dots, (l - r)\} = \frac{1}{(l-r)}$. The probability of cycle (A, B1) is α^2. Cycle (A,B2) as well as (C,D2) have a distance $l + 1$ and a probability of $\alpha \times \beta$ or $\beta \times \alpha$. The last possible cycle is (C,D1) with a distance $2 \times (k + r)$ with $k < r$, and a probability β^2. The cycles for the reefer containers can be described similarly. All possible cycles are depicted in Table 6.1.

By summing up the possible cycles for standard containers, the approximate estimate of the expected average distance can be calculated as follows:

$$d_g^{STD}(\alpha, \beta, l, r) = \sum_{k=1}^{(l-r)} \frac{1}{(l-r)}\alpha^2 2k + \sum_{k=1}^{(l-r)} \frac{1}{(l-r)}\beta^2 2(k + r) + (2\alpha\beta)(l + 1) \tag{6.1}$$

$$d_g^{STD}(\alpha, \beta, l, r) = \alpha^2(l - r + 1) + \beta^2(r + l + 1) + (2\alpha\beta)(l + 1) \tag{6.2}$$

Concerning reefer containers, the approximate estimate of the expected average distance can be calculated as follows:

$$d_g^{REEF}(\alpha, \beta, l, r) = \sum_{k=1}^{r} \frac{1}{r}\alpha^2 2(l - r + k) + \sum_{k=1}^{r} \frac{1}{r}\beta^2 2k + (2\alpha\beta)(l + 1) \tag{6.3}$$

$$d_g^{REEF}(\alpha, \beta, l, r) = \alpha^2(2l - r + 1) + \beta^2(r + 1) + (2\alpha\beta)(l + 1) \tag{6.4}$$

6.1.2. The Block Design Problem

Using the equations (6.2) and (6.4) presented above we propose a procedure for structuring the blocks in the storage yard in the case of a perpendicular layout with transfer points. In practice the width w and the length l of a block is the same for all installed blocks in the terminal. Let I be the set of blocks installed on a terminal. For simplification we assume $\forall i, j \in I, i \neq j$ that $w_i = w_j \wedge l_i = l_j$. Moreover, we assume that the reefer racks are equally distributed over the blocks $\forall i, j \in I, i \neq j \; r_i = r_j$. The length of a bay is defined by the length cl and the width cw of a ground slot. We assume that the total width of a block is defined by the width of the rows ($w \times cw$) and by a width δ_1 representing the additional space needed, e.g. for rail tracks. In addition we consider a space between two blocks δ_2. At each block operates a single A-RMG crane. We assume a rectangular area available for the storage yard defined by a maximal width W. The terminal depth is not restricted. As mentioned above the seaside and landside traffic of containers has to be handled by the storage yard blocks. We assume a flow F of containers which have to be stacked into the storage blocks in a given time period (e.g. one hour). γ denotes the ratio of reefer containers among the total flow F of containers. TGS^t defines for container type t the required ground slots that have to be accommodated by the storage blocks. The gantry speed of the RMG is defined by v. The number of blocks used in the yard n depends on the used width w:

$$n = \left\lfloor \frac{W + \delta_2}{w \times cw + \delta_1 + \delta_2} \right\rfloor \tag{6.5}$$

δ_2 has to be added to the yard width as the space between the blocks only occurs $n - 1$ times. The area a in square meters occupied by the blocks is calculated as follows:

$$a = (w \times cw + \delta_1) \times (l \times cl) \times n + \delta_2 \times (l \times cl) \times (n - 1) \tag{6.6}$$

The overall width of all blocks is defined by B and is calculated as follows:

$$B = (w \times cw + \delta_1) \times n + \delta_2 \times (n - 1) \tag{6.7}$$

The expected distance for horizontal transport depends on the overall width of all blocks B. As we assume that we have a given maximal width W which is more or less occupied by the installed blocks, B changes only slightly for different layout configurations. We furthermore assume a uniform distribution of containers among all blocks of the terminal. Given these facts the distance of the horizontal transport will change just slightly. We therefore ignore in this study the effect of the changes in the expected traveling distances (for the horizontal transport) on the yard performance.

The aim of a terminal operator who designs a container yard is to maximize performance on the one hand and to minimize cost on the other. We define the following block design problem (BDP):

$$\begin{aligned}
\min_{w} \quad & f1: & & a + n \times c^c & (6.8)\\
\min_{w} \quad & f2: & & d_g^{STD}(\alpha,\beta,l,r) \times \tfrac{cl}{v} \times \tfrac{F}{n} \times (1-\gamma) + \\
& & & d_g^{REEF}(\alpha,\beta,l,r) \times \tfrac{cl}{v} \times \tfrac{F}{n} \times \gamma + \tfrac{F}{n} \times L & (6.9)\\
& \text{s.t.} & & n \times w \times (l - r) \geq TGS^{STD} & (6.10)\\
& & & n \times w \times r \geq TGS^{REEF} & (6.11)
\end{aligned}$$

Objective (6.8) minimizes the cost, where c^c defines a factor representing the ratio of crane costs to area costs. The objective (6.9) minimizes the time needed to store the number of containers F (either standard or reefer containers) into the blocks. In addition to the pure gantry times estimated by $d_g^t(\alpha,\beta,l,r)$, we consider a constant time per container (L) for additional movements (e.g., positioning of containers on the horizontal means of transport or the assigned yard slot). The constraints (6.10) and (6.11) ensure that the required number of ground slots is achieved. We assume that the flow is distributed equally over the blocks and thus we divide the flow by n. Ignoring horizontal transport this distribution of containers leads to a high performance of the yard system due to an equally distributed workload. In practice, however, an equal distribution of the workload might not be possible in each situation.

To calculate a solution for the BDP we calculate the required value of reefer racks r per block:

$$r = \left\lceil \frac{TGS^{REEF}}{n \times w} \right\rceil \qquad (6.12)$$

To achieve the required capacity of TGS we are able to calculate the necessary length of the blocks by:

$$l = \left\lceil \frac{TGS^{STD}}{n \times w} \right\rceil + r \qquad (6.13)$$

Using a greater length than needed would reduce the performance, because d_g^{STD} and d_g^{REEF} increase for greater values of l. Thus by using equations (6.12) and (6.13) we can calculate a valid solution for a given width w of the blocks. As we round up the block length values, different values of w will lead to yard configurations with slightly differing numbers of total ground slots. However, the required number of ground slots is provided by all solutions. Accordingly, we do not consider possible effects that might occur due to the slightly different numbers of ground slots. The span of A-RMG cranes and of other gantry cranes is for technical reasons restricted. We assume a minimal span of three container rows and a maximal span of 15 rows. A typical span for an A-RMG is about 10 rows wide. Due to the restricted span of the A-RMG we can easily enumerate all possible values for $w = 3, \ldots, 15$.

6.2. Numerical Results and Interpretation

In this section we present numerical results for a typical container terminal configuration. The width W of the terminal is 900 m. The storage capacity is 9450 ground slots with $TGS^{STD} = 9000$ and $TGS^{REEF} = 450$. The space for cranes is $\delta_1 = 4$ m, the distance between blocks is $\delta_2 = 5$ m and length and width of a ground slot are $cl = 6.5$ m and $cw = 2.9$ m. The total flow of containers is $F = 650$. Regarding the performance of the storage yard we assume an average gantry velocity of $v = 3.5$ meters per second. The additional time for hoisting etc. is $L = 35$ seconds, where we assume 20 seconds for hoisting and lowering of a container and 15 seconds for the time to position a container (e.g. in the block or on a means of transport).

The different values for the number of blocks n, for the block length l, for the total width of all blocks B and for the number of reefer rows per block r when changing the block width w between 3 and 15 rows are displayed in Table 6.2. Naturally, the number of blocks decreases when the block width increases. In all cases an increased block width leads to a shorter or at least identical length of the blocks. The maximal occupation of the available total width of 900 m is achieved by the solution with three rows ($B = 898$ m). By contrast, for a value of $w = 10$ rows only 869 m of the available 900 m are used. Consequently the low use of the available width has to be compensated by a greater block length, which in this case leads to a block length identical with $w = 9$ rows. In other words, some block widths fit better into the available yard width than others.

Table 6.2.: Influence of the different widths ($w = 3, \ldots, 15$) on the total width of all blocks (B), on the number of blocks (n), on the length of the block (l) and on the number of reefer rows per block (r)

w	3	4	5	6	7	8	9	10	11	12	13	14	15
block width	12.7	15.6	18.5	21.4	24.3	27.2	30.1	33	35.9	38.8	41.7	44.6	47.5
B	898	881	888	893	874	897	873	869	895	871	882	888	888
n	51	43	38	34	30	28	25	23	22	20	19	18	17
l	62	56	51	48	46	44	42	42	40	40	39	38	38
block length	403	364	332	312	299	286	273	273	260	260	254	247	247
r	3	3	3	3	3	3	2	2	2	2	2	2	2

6.2.1. Distribution of Reefer Racks

For the BDP we assume that the reefer racks are distributed equally over the blocks. In this section we briefly discuss what consequences a non-equal distribution has. We analyze options where a subset of the blocks stores solely standard containers. Variable Q defines the number of blocks i which have no reefer racks. We define $R = n - Q$ the number of blocks where reefer racks exist. In this case note that r is redefined as follows:

$$r = \left\lceil \frac{TGS^{REEF}}{R \times w} \right\rceil \tag{6.14}$$

Again we assume that among the R blocks the reefer racks are distributed equally. Furthermore, the number of blocks Q without reefer racks is restricted by

$$Q \leq n - \left\lceil \frac{TGS^{REEF}}{l \times w} \right\rceil . \tag{6.15}$$

In other words, if constraint (6.15) is not satisfied the remaining $n - Q$ blocks are not able to accommodate the needed number of reefer slots (TGS^{REEF}) even if the full block length l is used. Consequently the possible values for Q can again be enumerated. As we do not aim to analyze the influence of the block width w, the performance of the blocks depending on l remains unchanged. Varying the number of blocks with no reefer racks Q (standard blocks), changes the distribution of the flow, as the reefer containers can only be distributed among the R blocks with reefer racks (reefer blocks). The flow of reefer containers is distributed to these R reefer blocks

$$F^{REEF} = \frac{F \times \gamma}{R}. \tag{6.16}$$

Thus F^{REEF} is the reefer flow per reefer block. The flow of standard containers can be distributed to all blocks (standard and reefer blocks) that not consist purely of reefer racks. For simplification we assume that the standard flow is distributed on the ratio of storage capacity provided by the different blocks. Thus the Q standard and R reefer blocks have to be distinguished, as a standard block possesses $l \times w$ standard slots in contrast to the $(l - r) \times w$ slots provided by a reefer block. Thus the flow to the standard blocks is defined as

$$F_Q^{STD} = \begin{cases} \frac{F \times (1-\gamma)}{Q} \times \frac{l \times Q}{l \times Q + (l-r) \times R} & \text{when } Q > 0, \\ 0 & \text{else,} \end{cases} \tag{6.17}$$

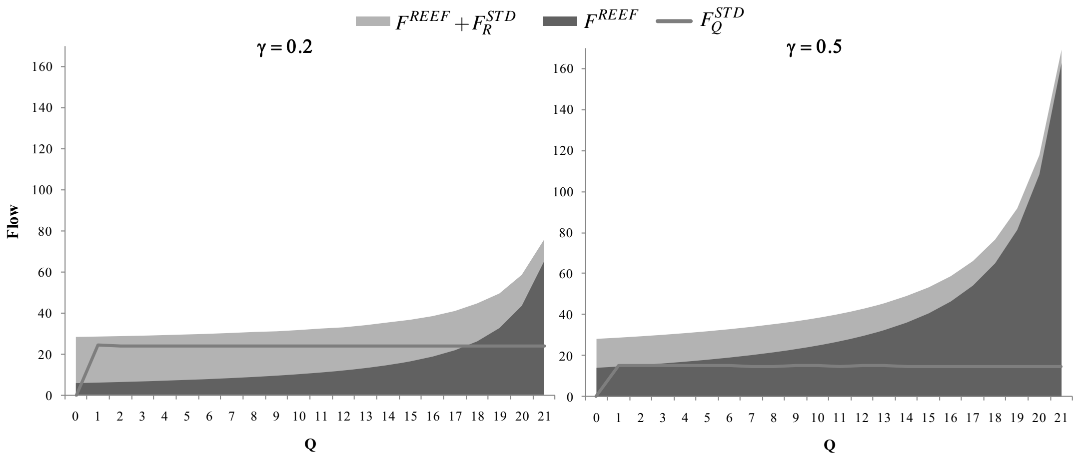


Figure 6.4.: Flow values F^{REEF}, F_R^{STD} and F_Q^{STD} per block for different values of Q and $\gamma = 0.2$ or $\gamma = 0.5$

and the flow to the reefer blocks as

$$F_R^{STD} = \frac{F \times (1-\gamma)}{n-Q} \times \frac{(l-r) \times R}{l \times Q + (l-r) \times R}. \tag{6.18}$$

Consequently, F_R^{STD} represents the flow of standard containers per reefer block and F_Q^{STD} represents the flow of standard containers per standard block. Hence the reefer blocks have to handle the total flow $F_R^{STD} + F^{REEF}$ consisting of reefer and standard containers where the standard blocks only process the standard container flow F_Q^{STD}.

Firstly, the flow distribution depending on different values of Q is illustrated. We therefore define the used width of blocks $w = 10$ which results in a yard layout with $n = 23$ blocks. We enumerate all possible values of Q and calculate the values for F^{REEF}, F_Q^{STD} and F_R^{STD} considering different values of γ. Figure 6.4 displays the results for $\gamma = 0.2$ and $\gamma = 0.5$.

The results depicted in Figure 6.4 show that an increase of Q and consequently a decrease of R leads to a higher total flow ($F^{REEF} + F_R^{STD}$) per reefer block. The additional flow of standard containers to be processed by a reefer block (F_R^{STD}) decreases for higher values of Q. Thus for both reefer ratios ($\gamma = 0.2$ and $\gamma = 0.5$) the proportion of standard containers to be handled by a reefer block decreases significantly for higher values of Q. In case of $\gamma = 0.5$ and $Q = 21$ only about 4% of the flow to a reefer block is of standard containers (see Figure 6.4). The flow of standard containers to be handled per standard block F_Q^{STD} remains on an identical level for different values of Q. Naturally this level is lower in the case of the higher reefer ratio of $\gamma = 0.5$ than in that of the lower ratio of $\gamma = 0.2$. To sum up, in the case of high values of Q a comparatively high flow of reefer containers has to be handled by each of the remaining reefer blocks. This might lower the performance of the yard, especially in situations of high reefer ratios (high values of γ). Hence an equal distribution of reefer racks over the existing storage blocks allows the best workload distribution.

In the following we analyze the effect of the reefer rack distribution on the yard performance. To analyze the performance we consider that of the reefer and standard blocks. We thus need to introduce new estimates to measure the performance of the different block types. Firstly, the time t_R^{REEF} taken by a reefer block to handle the reefer containers F^{REEF} is calculated by

$$t_R^{REEF} = d_g^{REEF}(\alpha, \beta, l, r) \times \frac{cl}{v} \times F^{REEF}, \tag{6.19}$$

and the time t_R^{STD} to handle the standard containers F_R^{STD} is calculated by

$$t_R^{STD} = d_g^{STD}(\alpha, \beta, l, r) \times \frac{cl}{v} \times F_R^{STD}. \tag{6.20}$$

Secondly, the time t_Q^{STD} of a standard block to handle the standard containers F_Q^{STD} is calculated by

$$t_Q^{STD} = d_g^{STD}(\alpha, \beta, l, 0) \times \frac{cl}{v} \times F_Q^{STD}. \tag{6.21}$$

For an exemplary calculation we assume a peak scenario in which most containers have to be handled on the seaside $\alpha = 0.8$ and the total flow of containers is $F = 400$ which has to be handled in one hour. We further assume that half of the containers in the system are reefer containers (i.e., half of the quay cranes unload reefer containers). Thus γ is set to 0.5. Again we assume a block width of $w = 10$ rows. In this context the calculation of l in equation (6.13) has to be changed as the number of reefer racks per block r changes for different values of Q. For the sake of brevity we simply set $l = 42$ (see Table 6.2).

The different performance times for the peak scenario are shown in Figure 6.5. The results show that the change in performance due to different values of Q is obviously similar to the change of flow values in Figure 6.4. For higher values of Q the time needed for a reefer block to handle the assigned number of containers increases as the flow of containers increases. The time needed for the standard blocks stays at a similar level for different values of Q. Thus the reefer blocks might become the bottleneck in the terminal system. As mentioned above, congestion at the blocks can lead to a reduction in the overall terminal performance. For instance, we assume in this peak scenario that the flow of containers occurs during one hour and thus we have to consider a time limit of one hour (3600

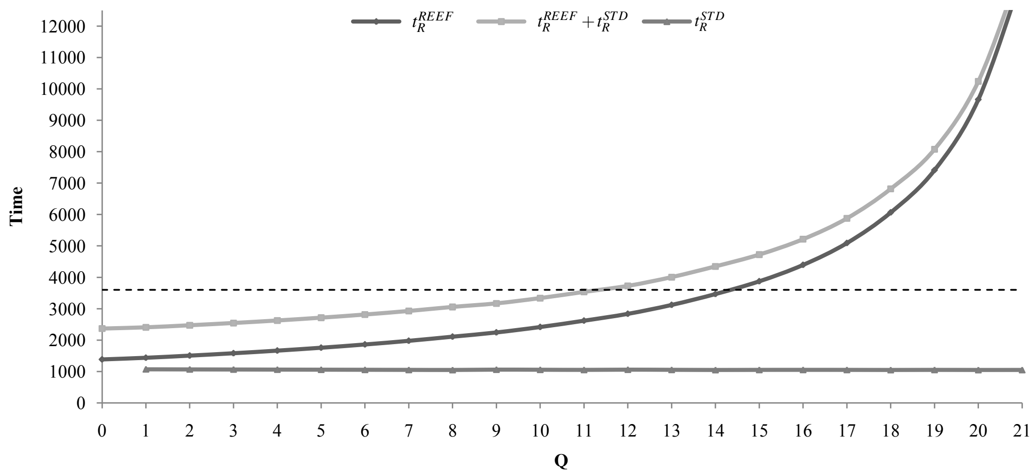


Figure 6.5.: Performance times t_R^{REEF}, t_R^{STD} and t_Q^{STD} for different values of Q and $\gamma = 0.5$

seconds) for each block to handle the container flow (dotted line in Figure 6.5). Where the time limit is exceeded by a block configuration, congestion may occur which reduces the overall performance. In other words, the flow of containers F induced during one hour by quay cranes and by the landside cannot be handled properly by the yard system. For the current scenario solutions with $Q \geq 15$ standard blocks exceed the time limit in the case that only reefer containers are handled by the reefer blocks. When reefer blocks additionally process standard containers, a solution with $Q \geq 12$ already exceeds the time limit. In this way the above-described method can be used to estimate an adequate number of reefer or standard blocks for a given performance limit. For instance, a solution with $Q = 10$ standard blocks and thus $R = 13$ reefer blocks would be an adequate solution for the given scenario. To sum up, the results show that if high reefer rates occur, the reefer racks should be distributed to a sufficient number of blocks. A sufficient number of reefer blocks allows a good distribution of the workload and thus avoids yard congestion.

6.2.2. Calculating Block Designs

First we analyze optimal costs of the BDP. We ignore the performance values of the different block configurations. Realistic values for the parameter c^c are difficult to determine and thus we use a broad range of values for c^c between 1 and 10000. First of all, the resulting area costs (a) for different values of w are presented in Figure 6.6. Figure 6.6 shows that the occupied area decreases for wider block width as block length decreases. In the case of an increase in the

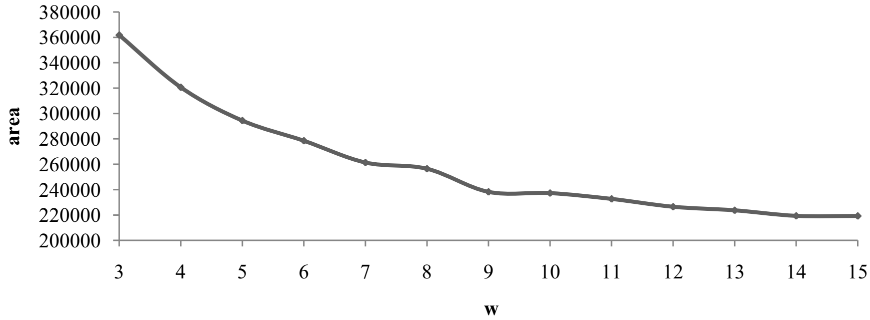


Figure 6.6.: The area (a) for different values of w

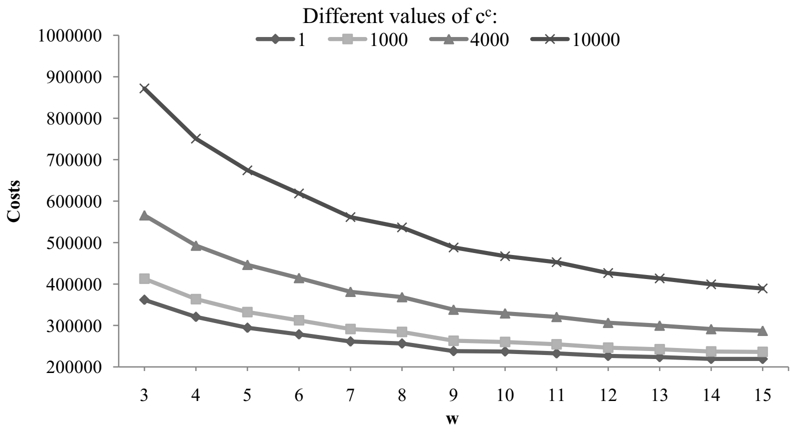


Figure 6.7.: The costs ($f1$) for different values of w and c^c

block width from seven to eight rows the area occupation stays at a nearly similar level. As already described above this is because in the case of eight rows the available total width is used more efficiently than in the case of seven rows (see also Table 6.2). Figure 6.7 shows the results when crane costs are also considered. Again, the costs decrease for wider block widths for all different crane cost ratios ($c^c \geq 4000$). Smaller block width leads to a higher number of blocks (see also Table 6.2) and consequently to a higher number of cranes and total crane costs. Thus in most situations a yard configuration with minimal costs uses a great block width w.

In the following we analyze the effect of different block widths on the performance. We assume that $\gamma = 0.2$. Figure 6.8 shows numeric results of the performance for different values of α. As we assume that at least the seaside traffic equals the landside traffic, we assume that $\alpha \geq 0.5$. Using the smallest possible block width w achieves the highest performance. For smaller block widths the flow of containers is distributed to more blocks than is the case for solutions where wider blocks are used. This effect outweighs the effect that the gantry

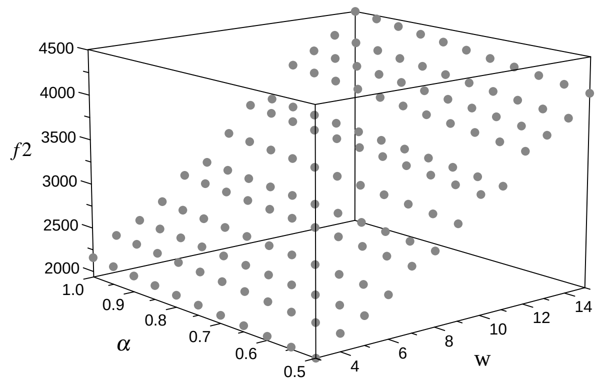


Figure 6.8.: Values of $f2$ for different values of w and α

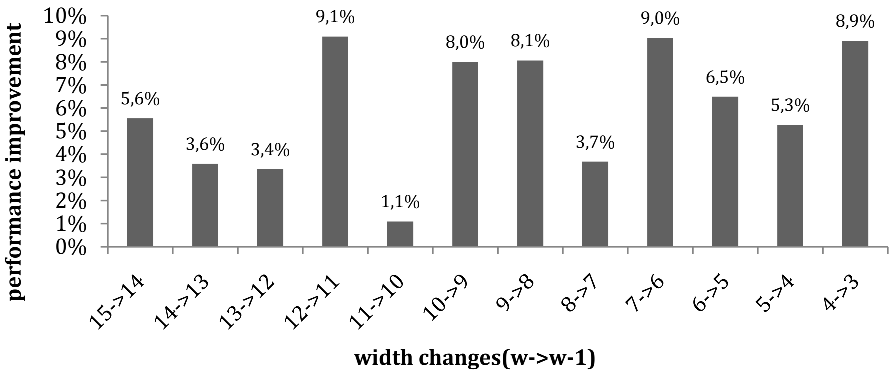


Figure 6.9.: Improvement of the performance (percentage decrease of $f2$) when reducing the block width by one row ($\alpha = 0.6$)

travel distances increase with increased block length l. An increase in the value α leads to an increase of $f2$.

Figure 6.9 shows the different performance improvements (for $\alpha = 0.6$) when the block width is reduced by one row, starting with a block width of 15 rows. Thus the value of 5.6% in column 15 → 14 in Figure 6.9 shows that the value of $f2$ is 5.6% lower for $w = 14$ compared to the value of $f2$ for $w = 15$. In other words the performance improves by 5.6% when block width is reduced from 15 to 14 rows. As shown in Figure 6.9 the level of improvement changes with different values of w. For instance, a high improvement occurs when the block width is reduced from 12 to 11 rows (9.1%). However, only a small improvement of 1.1% occurs with a block width reduction from 11 to 10 rows. Again, an explanation for this finding is the comparatively good use of the available total yard width by the solution with 11 rows (see Table 6.2). Thus the reduction from 11 to 10

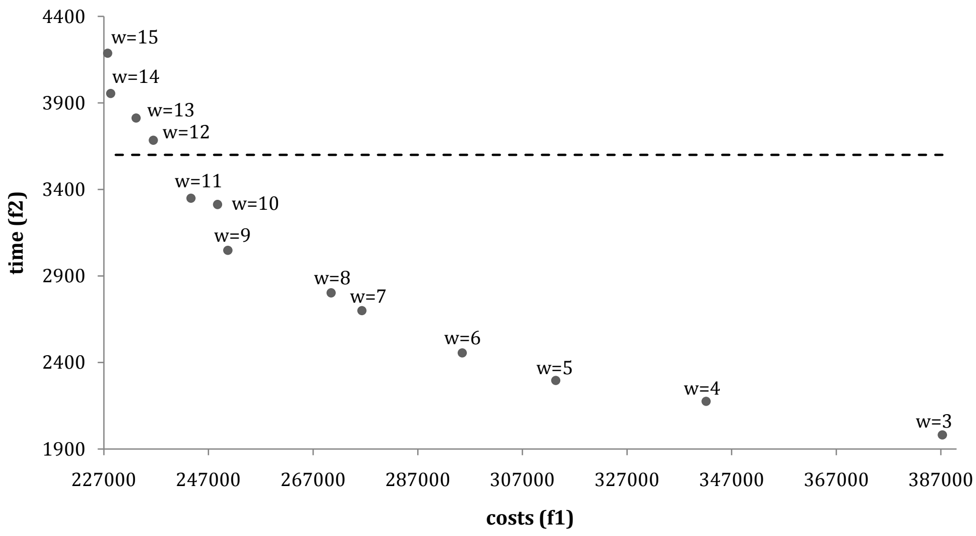


Figure 6.10.: Solutions for the BDP with a time limit $f2 \leq 3600$ seconds

rows only causes a small improvement. This effect can also be seen in Figure 6.8 where the value of $f2$ increases just slightly from 10 to 11 rows.

A remaining question is how to configure the block designs when cost and performance are considered simultaneously: With a multi-criteria problem like the BDP the aim is to find solutions which are not dominated by any other possible solution. If a solution is dominated by another solution, i.e. the solution has higher costs and lower performance, this solution can be ignored for planning. In the case of the BDP we can easily enumerate all solutions for a given set of parameters and check if some solutions are dominated by others. As the performance objective decreases when the block sizes are reduced and the costs increase most solutions for $w = 3, \dots, 15$ are non-dominated solutions. For $\alpha = 0.6$ and $c^c = 500$ the solutions are displayed in Figure 6.10. In this case all solutions ($w = 3, \dots, 15$) are non-dominated, i.e. each solution has either lower costs or a better performance value compared to all other solutions.

As mentioned in Section 2.4.1 a first step in planning a container terminal is to evaluate the expected seaside, yard and landside capacities. In addition to these values a yard performance level can be derived which, e.g. postulates a minimum number of moves per crane needed to handle the flow of containers in a peak scenario. Consequently, in planning a yard layout we have to consider the yard performance level. Such performance level has to be achieved by the installed yard configuration. Otherwise congestion occurs in the yard and thus the overall performance of the terminal is reduced. We assume that the defined flow of containers $F = 650$ represents a peak scenario for one hour, i.e. 650 containers have to be processed by all blocks in the yard in one hour. Thus we assume a simple performance level using a time limit of one hour. Again, as already described in Section 6.2.1, exceeding the time limit by a block configuration could lower the overall terminal performance. In Figure 6.10 the dotted line represents the time limit (3600 seconds) and all solutions under the line are within the time limit. In order to find a solution of minimum cost for the BDP which achieves the required performance simply choose the leftmost solution that still is within the time limit. For the current example this would be the solution $w = 11$ in Figure 6.10 with $n = 22$ blocks, $f2 = 3349.6$ seconds and a used length of $l = 40$ bays. In this way a terminal planner can quickly identify promising block configurations that match the requirements of their particular scenario with respect to costs and performance.

6.3. Summary

In this chapter we have proposed a procedure for finding promising block designs and thus a yard layout for a perpendicular layout using RMGs. We first analyzed different distributions of the reefer racks over the storage blocks in the yard. The results show that especially in situations with high reefer rates a sufficient number of blocks should contain reefer racks, as in this case the workload can more easily be distributed. Moreover, we analyze the effect of different block configurations on the yard performance and on costs. The numerical example shows that using smaller block widths increases the terminal performance but also costs. Given both opposed objectives non-dominated solutions can be easily calculated. These non-dominated solutions can be used by a terminal planner quickly to determine promising block designs. The results, however, are a first approximation of yard performance as the proposed method does not consider, e.g. the influence of double cycles in which two containers are handled during one crane cycle, the influence of rehandles, and effects that occur during real-time operations.

7. Designing Yard Layouts with Direct Transfer

The previous chapters have been concerned with the yard layout categories where gantry cranes are used for stacking. In this chapter we consider the yard layout category without gantry cranes in the yard. Thus we consider a yard layout where a direct transfer is used between blocks and horizontal transport. Figure 7.1 illustrates the structure of a block with direct transfer. Such configurations are possible when active transport equipment such as straddle carriers or automated straddle carriers (see Section 2.2.2) is used. In the following we shall mainly speak of straddle carriers. The approach, however, can also be used to plan layouts where automated straddle carriers are used.

Obviously the layouts of straddle carrier-based yards and for instance the layouts of RTG-based yards differ due to their distinct equipment types and their characteristics (e.g., different block structures, see Section 2.2.3). Nevertheless, there are similarities between the horizontal travel of trucks within an RTG-based layout and that of SCs. The main difference in the movements at a terminal of SCs to the movements of trucks, however, is that SCs additionally perform the stacking operation. In consequence the distances of SCs movements within the yard differ from those of trucks within an RTG-based layout. In addition, the influence of the yard layout design on the stacking operation of SCs has to be considered in the case of a SC-based layout as well. In consequence the use of the approaches in the previous chapters to plan the layouts of SC-based yards is not possible. We accordingly discuss the problem of designing SC-based storage yards in the following.

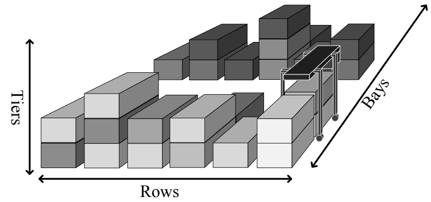


Figure 7.1.: Structures of blocks with direct transfer using SCs

The remainder of this chapter is structured as follows: Section 7.1 describes the underlying problem of planning yard layouts with direct transfer. In Section 7.2 we derive estimates for the expected cycle times of SCs considering different layout options. Section 7.3 presents results for different scenarios. Several parameter configurations are presented and the results are discussed. Finally, Section 7.4 summarizes the findings of this chapter. This chapter is based on Wiese et al. (2011a).

7.1. The Problem of Designing Straddle Carrier-Based Storage Yards

In this section we describe the problem of designing a storage yard for container terminals where SCs are used as equipment in a direct transfer system. The elements of a storage yard for a parallel and perpendicular layout are given in Figure 7.2. Again the storage yard is composed of several blocks (see also Figure 7.1) and of driving lanes separating the blocks. We distinguish between vertical and horizontal driving lanes (see Figure 7.2, b). The storage yard itself is surrounded by driving lanes which we call outer driving lanes. These outer driving lanes at least are necessary, as otherwise the SCs are not able to access all elements of the terminal. Moreover, we consider a rectangular terminal area in which there is a single truck service area. Rail tracks are not considered.

A possible yard layout is composed of a single block without driving lanes, as shown in Figure 7.3. A disadvantage of this layout is that the SCs always have to travel the whole yard distance to store (retrieve) a container in (from) a block. Thus in a parallel yard layout as depicted in Figure 7.2 (a) SCs have to travel

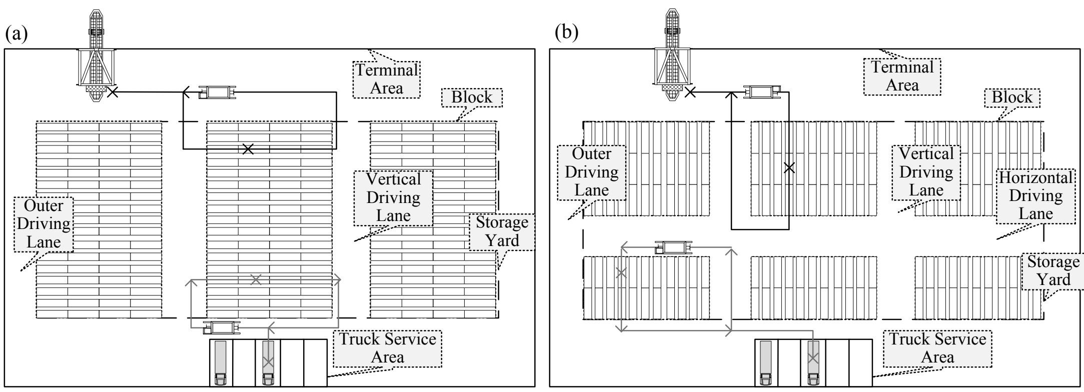


Figure 7.2.: SC cycles and elements of a storage yard for a parallel (a) and perpendicular layout (b)

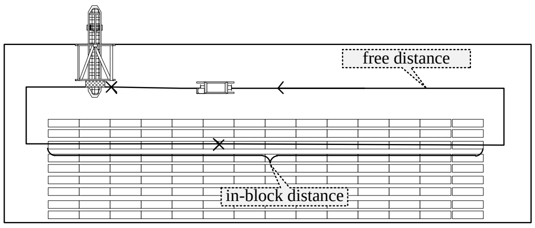


Figure 7.3.: Parallel layout with a single block and an exemplary SC cycle

shorter distances than in the layout shown in Figure 7.3. Another advantage of driving lanes is the shorter distance which the SCs have to travel within a block. We call this in-block distance in contrast to the free distance which the SCs travel outside of the blocks (see Figure 7.3). Obviously the in-block distance is shorter in the case of Figure 7.2 (a) than in Figure 7.3. For the driving lanes, however, either additional space is needed or the average stacking height has to be increased, as less space can be used for the stacking of containers. In the following we consider both options to compensate for the loss of ground space. Thus a driving lane can be installed in a yard either by increasing the average stacking height or by increasing the yard area and in consequence the terminal area. Both compensation options again have disadvantages: Increasing the average stacking height increases the probabilities of rehandles. The disadvantage of an increased storage yard area is the higher demand of land. Moreover, as the size of the whole yard area increases, the cycle distances of the SCs might increase. In the following we ignore the costs for different demand of land. Consequently a layout with different numbers of driving lanes solely influences the costs that are caused by SCs as the SCs perform both, stacking and horizontal transport of containers. The costs of a SC are composed of the investing and running costs which we assume can both be expressed as costs per minute for the use of a SC. Therefore minimizing the cycle times also minimizes the costs of a yard layout. Moreover, minimal cycle times are important for the operations as they allow a quick processing of external trucks as well as internal transport jobs. In sum, the yard design problem is to determine the optimal number of driving lanes in the yard layout with the aim of minimizing the cycle times of the SCs.

As illustrated in Figure 7.2 the parallel layout only has vertical driving lanes, while the perpendicular layout has vertical and horizontal driving lanes. In the parallel layout no horizontal driving lanes are needed for our scenario because the SCs can enter the rows of each block via the vertical driving lanes. Thus an additional horizontal driving lane would not shorten the distances for a SC to travel from an arbitrary point in the seaside or landside area of the terminal to retrieve (store) a container from (to) a block (see Watanabe 2006). Horizontal driving lanes, however, might reduce the traffic density and therefore might improve the terminal performance or they might reduce the distances when SCs travel from one block to another. As we do not consider the influence of traffic density and assume that cycles of a SC start either in the seaside area or at the TSA at the landside we furthermore assume that no horizontal driving lanes are needed for a parallel layout. We also introduce the following assumptions:

- The SCs operate in single cycle mode and thus either perform a stacking or a retrieval cycle, not both combined. During a stacking cycle a SC collects a container at the seaside, transports the container to the designated block, stores the container in the block and returns to the seaside. As just mentioned we assume that the cycles either start at the seaside or the landside. In the following we assume that SCs are assigned either to seaside or landside cycles. We also assume that each cycle starts and ends at the same point in the terminal. Finally, we assume that the jobs at the TSA start and end on average in the middle of the TSA.

- We assume that the velocity of a SC is reduced for in-block in relation to free travel. Given the small driving lanes between container rows, we assume that the SCs cannot achieve the same travel speed within a block as outside. Moreover, SCs have to decelerate and accelerate within the blocks when approaching the container storage position. We assume that this influence is incorporated into the reduced travel speed. We further assume that the reduction is identical for forward and backward travel and thus that the velocity of the SCs is the same for forward and backward travel. The time needed for a SC to enter or leave a container row, e.g. for turning, is not considered.

- SCs are only allowed to enter a row of a block if they have to perform a stacking operation in this row. SCs are not allowed to cross a block via a row to get to another block.

- We assume that each block in the yard has the same length (number of bays) and width (number of rows). We also assume that the terminal is rectangular and has a single straight quay wall (as shown e.g. in Figure 7.2).

- Similarly to Kim et al. (2008), we assume that the whole yard is uniformly used for stacking: that the storage positions for a container are selected randomly from all possible positions. We assume that import and export containers are not stored in separate areas. Moreover, the quay cranes handle containers uniformly distributed on the quay. As mentioned by Kim et al. (2008) even if the terminal and thus the yard is enlarged and the yard is divided into partitions for the storage of containers, the approach in this chapter can be applied to the partitions instead of the whole terminal.

- For the later derivation of the estimates, we assume (unless otherwise stated) that the terminal is separated into segments according to the width of the blocks. We assume that each job for a SC starts and ends in the middle of these segments (see Kim et al. (2008)).
- For the later derivation of the estimates we moreover assume that SCs always enter a row of containers from the near end of the row (i.e., the end that is nearer to the starting point of the journey).
- The costs of different terminal sizes are not considered in this study.

This study does not consider effects that occur during real-time operations. For example, traffic jams in the yard and blocking of SCs due to an operation of SCs on adjacent or identical rows are not considered. Moreover, organizational aspects that influence decisions on layout are not considered or discussed in this chapter. An organizational aspect, for instance, that might influence the decision to use a parallel or perpendicular layout is the following: SCs have to merge into the traffic at the seaside at each row of a block as well as at each vertical driving lane for a perpendicular layout. In a parallel layout, however, SCs merge into the seaside traffic only at the vertical driving lanes. Thus a parallel layout might result in fewer obstructions of the seaside traffic due to crossings than a perpendicular layout.

7.2. Estimate of the Cycle Times for Straddle Carriers

In the following we estimate the cycle times of a SC in performing a single cycle. Figure 7.4 presents the main variables and parameters used for the estimation of the cycle times. The parameter Y^L defines the initial length of the terminal and Y^D the initial depth of the terminal. The parameter L defines the length of a ground slot for storing a container and W its width. The parameters δ_v and δ_h define the number of bays and rows which are needed to install a horizontal or vertical driving lane. Figure 7.4 also shows the variables l,r,x_e and b_e, where e is a set of indices $e = \{v, h\}$. The variable l defines the length of the blocks by the number of bays, where each bay has the length of a ground slot L. The variable r defines the width of the blocks by the number of rows, each with a width of

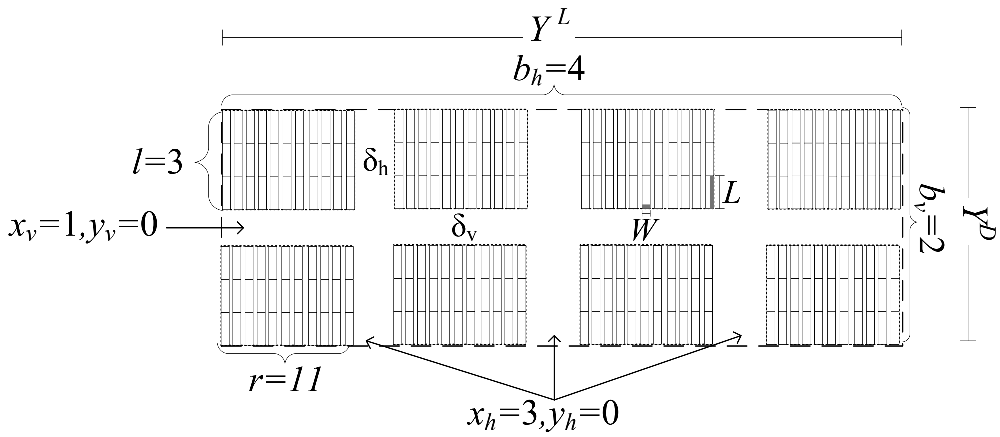


Figure 7.4.: Parameter and variables for the estimation of the SC cycles

W. The variables x_e define how many vertical respectively horizontal driving lanes are used where the loss of ground space is compensated by increasing the average stacking height. In contrast, the variables y_e define how many vertical or horizontal driving lanes are used where the loss of ground space is compensated by increasing the terminal area. Consequently, the variable $b_h = x_h + y_h + 1$ defines the number of horizontal blocks in the layout separated by vertical driving lanes. The variable $b_v = x_v + y_v + 1$ defines the number of vertical blocks in the layout separated by horizontal driving lanes. Thus x_h and y_h define the vertical driving lanes that separate horizontal blocks and x_v, y_v the number of horizontal driving lanes that separate the vertical blocks (see Figure 7.4). In addition to the starting length and depth of the terminal, we define AY^L as the actual length and AY^D as the actual depth of the terminal. Thus AY^L and AY^D determine the actual terminal area when the loss of ground space for driving lanes is compensated by increasing the terminal area. Obviously, when $y_v = 0$ then $Y^L = AY^L$ and when $y_h = 0$ then $Y^D = AY^D$.

The average velocity in meters per second of SCs traveling on the driving lanes (free distance) is defined by the parameter ν. As mentioned above, we assume that SCs must move at a lower velocity within blocks. The reduction in velocity within blocks is defined by the parameter γ with $0 < \gamma \leq 1$. Thus the velocity of the SCs within a block is given by $\nu \times \gamma$. The average time in seconds a SC needs to lift or lower a container is defined by t^l and the average time in seconds needed to perform a rehandle is defined by t^r. The average storage capacity needed for containers that have to be stored in the yard is defined by C. The number of ground slots resulting from the actual layout configuration is denoted by the variable G. Thus the average stacking height can be expressed by variable T as

$$T = \frac{C}{G}. \tag{7.1}$$

As mentioned above, the probability of rehandling increases with an increase in the average stacking height T. Kim et al. (2008) use a formula derived from a former work of Kim (1997) to approximate the expected number of rehandles for their method to calculate optimal yard layouts. To approximate the expected number of rehandles in picking up a container at random assuming an average stacking height of T we use the formula of Kim et al. (2008):

$$R(T, a) = \frac{2T - 1}{4} + \frac{T + 1}{8a} \tag{7.2}$$

where Kim et al. (2008) assume that a defines the number of rows of a bay operated by a yard crane. We assume that in the SC system a row corresponds to a bay in the yard crane systems as, e.g. interfering containers are relocated within a row for a SC system. Thus we define a as $a = l$. For high values of l (long rows) it might be unrealistic that the whole row is used in relocation of interfering containers. We assume, however, that $a = l$.

To estimate cycle times we divide the cycles into those starting at the seaside (seaside cycles) and those starting in the landside truck service area (landside cycles). We assume that the SCs are assigned either to perform seaside or landside cycles. To distinguish these we use the indices Q for seaside and H for landside cycles ($K = \{Q, H, QH\}$). QH is used later to indicate that both cycles (weighted combination of sea- and landside cycles) are considered simultaneously in the model. For the landside cycle we use the index HM if we assume a TSA in the middle of the yard and the index HL if we assume a TSA on the left edge of the yard ($H = \{HM, HL\}$). We also distinguish between the expected distances of free travel D and the expected in-block distances I. The indices pa (parallel) and pe (perpendicular) in set $p = \{pa, pe\}$ are used to distinguish between the parallel and perpendicular layouts. Different driving strategies are possible for the in-block travel (solely forward travel or forward and backward travel). We define a set o of different driving strategies as $o = \{1, 2, 3\}$. The following expected distances are used to calculate the total expected cycle times of SCs:

$Dh_o^{p,K}$ Estimate of the expected horizontal distance of a cycle K for a layout p using driving strategy o.

$Dv_o^{p,K}$ Estimate of the expected vertical distance of a cycle K for a layout p

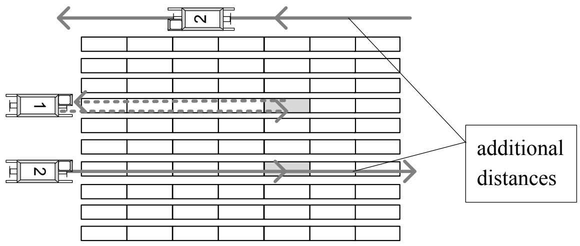


Figure 7.5.: Driving strategy one and two for the in-block travel

using driving strategy o.

I_o Estimate of the expected in-block distance using driving strategy o.

t_o^s Estimate of the expected time a SC spends stacking using driving strategy o.

$t_o^{d,p,K}$ Estimate of the expected driving time of a SC for a layout p considering cycle K and using driving strategy o.

7.2.1. Estimate of In-Block Distances

In Watanabe (2006) two types of SC are described: One which is favorable for so-called switch-back operations (type one SCs) and a second for passing through operations. The switch-back operation is to travel forward and backward in a block (see Figure 7.5 strategy one) and the passing trough operations to travel forward only. Another possible driving strategy is to travel only backward if the target container is positioned in or before the middle bay. In other words backward travel is only used when the backward distance is smaller than the forward distance. Thus this driving strategy is a combination of the first and second strategies. Watanabe (2006) states that type one SCs are mainly used in a perpendicular layout and type two SCs in a parallel layout. We assume, however, that type one SCs can also be used in a parallel layout. Thus we assume that all three driving strategies can be used for both layouts. The distance to the final destination after a stacking operation is shorter when backward-travel is used as we consider cycles which start and end at the same position. Hence it is obvious that the distance to the final destination is shorter when backward travel is allowed (see Figure 7.5).

To calculate the in-block distance we distinguish between the three driving strategies. The first strategy assumes that after storage or retrieval the SCs always leave the block using backward-travel. Let k be the bay (position) of the target container in the row. The minimal distance is two bays (travel to the first bay and backward) and the maximal distance is $2 \times l$. As we assume an equal distribution of the storage and retrieval jobs, the probability of an occurrence is the same for all positions. Thus the probability of a job in a bay k with $1 \leq k \leq l$ is $\frac{1}{l}$. The estimated in-block distance for the first driving strategy I_1 is

$$I_1 = \Big(\sum_{k=1}^{l} \frac{1}{l} 2 \times k\Big) \times L = (l+1) \times L. \tag{7.3}$$

The second driving strategy uses backward travel only if the target container is in bay k with $k < \lfloor \frac{l}{2} \rfloor$. The probability of travel forward and backward can be expressed by $\sum_{k=1}^{\lfloor \frac{l}{2} \rfloor} \frac{1}{l}$ and of travel forward only by $\sum_{k=\lfloor \frac{l}{2} \rfloor+1}^{l} \frac{1}{l}$. The distance a SC has to travel within a block using solely forward travel is $(l+1) \times L$, as the SC has to travel the whole block length plus the distance of one bay to get out of the block. Thus the estimated in-block distance for the second driving strategy I_2 is

$$\begin{aligned} I_2 &= \Big(\sum_{k=1}^{\lfloor \frac{l}{2} \rfloor} \frac{1}{l} 2 \times k + \sum_{k=\lfloor \frac{l}{2} \rfloor+1}^{l} \frac{1}{l}(l+1)\Big) \times L \\ &= L \times \frac{\lfloor \frac{l}{2} \rfloor(\lfloor \frac{l}{2} \rfloor + 1)}{l} + \frac{(l+1)(l - \lfloor \frac{l}{2} \rfloor)}{l} = L \times \frac{l^2 - l\lfloor \frac{l}{2} \rfloor + l + \lfloor \frac{l}{2} \rfloor^2}{l}. \end{aligned} \tag{7.4}$$

In the following sections we need to know in which direction the SC leaves the block. In the case of the second driving strategy the SCs can either leave the block in the forward or backward direction. In the second driving strategy we assume in the following that both directions are equally likely. Hence the probability that the SC leaves a block in the forward direction is $\frac{1}{2}$.

The third driving strategy uses solely forward travel. Therefore the estimated in-block travel distance for the third driving strategy is $l+1$ bays and thus

$$I_3 = (l+1) \times L. \tag{7.5}$$

As already mentioned, the free travel distance is shorter when backward travel is allowed (I_1 and I_2). Consequently it is obvious that the third driving strategy is dominated by the other strategies. We, therefore, consider for the estimate of the horizontal and vertical distances only the first and second driving strategies in the case of the perpendicular layout. For the parallel layout, however, we also consider the third strategy. We are thus able to compare a parallel layout using solely forward travel with a perpendicular layout using the first and second driving strategies. This allows us to consider the case where backward travel is impractical for a parallel layout.

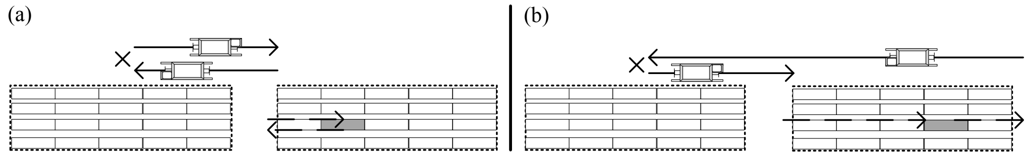


Figure 7.6.: Horizontal distances in case of (a) the first driving strategy and (b) the second driving strategy

7.2.2. Seaside-Cycle Estimate for Parallel Layouts

In this section we estimate the SC cycles for parallel layouts as illustrated in Figure 7.2 (a). The actual yard length is defined as $AY^L = Y^L + \delta_h \times L \times y_h$. As mentioned above, no horizontal driving lanes are considered for the parallel layout. Thus the variables b_v, x_v, y_v can be ignored. In this case $x_v, y_v = 0$ and thus $b_v = 1$. It follows that $AY^D = Y^D$. The number of rows can be calculated by

$$r = \left\lfloor \frac{Y^D}{W} \right\rfloor, \tag{7.6}$$

and the number of bays can be calculated by

$$l = \left\lfloor \left(\left\lfloor \frac{Y^L}{L} \right\rfloor - \delta_h \times x_h \right) \times \frac{1}{b_h} \right\rfloor. \tag{7.7}$$

The number of ground slots can be calculated by

$$G = r \times l \times b_h. \tag{7.8}$$

The expected horizontal distance in a parallel layout $Dh_o^{pa,Q}$ depends on the number of blocks b_h, the actual yard length AY^L, and the driving strategy o. For simplification we ignore the discrete nature of the blocks. The different expected distances for the first and the second driving strategy are illustrated in Figure 7.6. The probabilities for the horizontal distance can be calculated in the same way as in Kim et al. (2008). The distances, however, differ depending on the used driving strategy.

First we consider the driving strategy which uses only backward-travel ($o = 1$). Similar to Kim et al. (2008) we assume that the quay is partitioned into b_h segments corresponding to the b_h blocks and that the jobs start in the middle of these segments (see Figure 7.6). The probability that a randomly chosen destination on the quay is in the same segment as the randomly chosen block is $\frac{1}{b_h}$. In this case the expected distance is $\frac{AY^L}{b_h}$. Let n be the difference between a randomly chosen segment and a randomly chosen block. The probability that

$n = 1$ is $\frac{2(b_h-1)}{b_h^2}$ with a distance of $\frac{AY^L}{b_h}$ (see Figure 7.6, a). The probability that $n = k$ is $\frac{2(b_h-k)}{b_h^2}$ (see Kim et al. 2008) with a distance of $\frac{AY^L}{b_h} + (k-1)\frac{2AY^L}{b_h}$. The estimate of the expected distance can then be expressed as

$$\begin{aligned} Dh_1^{pa,Q} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{b_h-1} \frac{2(b_h-k)}{b_h^2}\left(\frac{2(k-1)AY^L + AY^L}{b_h}\right) \\ &= \frac{AY^L(2b_h^2 - 3b_h + 4)}{3b_h^2}. \end{aligned} \tag{7.9}$$

Considering the second driving strategy ($o = 2$), the distance changes as in the case of $n > 0$ a distance of $\frac{AY^L}{b_h}$ has additionally to be traveled when the SC leaves the block in the forward direction (see Figure 7.6, b). As mentioned above the likelihood for a forward travel is $\frac{1}{2}$. Thus $Dh_2^{pa,Q}$ is

$$\begin{aligned} Dh_2^{pa,Q} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{b_h-1} \frac{2(b_h-k)}{b_h^2}\left(\frac{2(k-1)AY^L + AY^L}{b_h} + \frac{AY^L}{2b_h}\right) \\ &= \frac{AY^L(4b_h^2 - 3b_h + 5)}{6b_h^2}. \end{aligned} \tag{7.10}$$

In the case of the third driving strategy ($o = 3$) the additional distance of $\frac{AY^L}{b_h}$ has to be traveled every time. Hence $D_{h3}^{pa,Q}$ is

$$\begin{aligned} Dh_3^{pa,Q} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{b_h-1} \frac{2(b_h-k)}{b_h^2}\left(\frac{2(k-1)AY^L + AY^L}{b_h} + \frac{AY^L}{b_h}\right) \\ &= \frac{AY^L(2b_h^2 + 1)}{3b_h^2}. \end{aligned} \tag{7.11}$$

The expected vertical distance depends on the depth of the terminal. For the sake of brevity we assume a uniform distribution of $U(0, 2AY^D)$ for the vertical distances. Therefore the estimate for the expected vertical travel distance is

$$Dv^{pa,Q} = AY^D. \tag{7.12}$$

The time a SC spends stacking in a block depends on the in-block distance, the average time needed to drop or lift a container t^l, and the time needed to perform the average number of rehandles $R(T, a) \times t^r$. Thus

$$t_o^{s,pa} = \frac{I_o}{\nu \times \gamma} + 0.5R(T, a) \times t^r + t^l. \tag{7.13}$$

The factor 0.5 for the rehandles is needed as they can occur only for retrievals

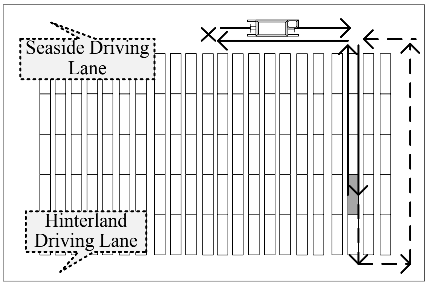


Figure 7.7.: Distances of a SC for a perpendicular layout with one block ($b_v = 1$), where the solid lines represent the distances for the first driving strategy and the dashed lines the alternative distances for the second driving strategy

(see Kim et al. 2008). The estimate for the time a SC spends traveling a cycle can be expressed by

$$t_o^{d,pa,Q} = (Dh_o^{pa,Q} + Dv^{pa,Q})\frac{1}{\nu}. \tag{7.14}$$

7.2.3. Seaside-Cycle Estimate for Perpendicular Layouts

The actual yard length for a perpendicular layout is defined as $AY^L = Y^L + \delta_h \times W \times y_h$ and the actual yard depth as $AY^D = Y^D + \delta_v \times L \times y_v$. The number of rows can be calculated by

$$r = \left\lfloor \left(\left\lfloor \frac{Y^L}{W} \right\rfloor - \delta_h \times x_h \right) \times \frac{1}{b_h} \right\rfloor, \tag{7.15}$$

and the number of bays can be calculated by

$$l = \left\lfloor \left(\left\lfloor \frac{Y^D}{L} \right\rfloor - \delta_v \times x_v \right) \times \frac{1}{b_v} \right\rfloor. \tag{7.16}$$

The number of ground slots can be calculated by

$$G = l \times r \times b_h \times b_v. \tag{7.17}$$

The horizontal distance for the perpendicular layout differs from that in the parallel case. We first derive an estimate which considers the first driving strategy. In the case where $b_v = 1$ and $b_h = 1$ each row of the block can be reached by the seaside driving lane as shown in Figure 7.7. The distance depends solely on the number of rows r. Correspondingly, the segments of the berth can be assumed to be the number of rows. The probability that a randomly chosen segment and a randomly chosen stacking position (row) are identical is then $\frac{1}{r}$. In this case the

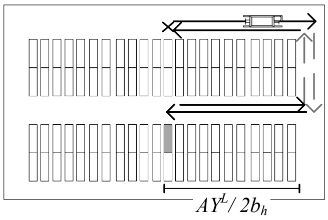


Figure 7.8.: Distances of a SC for a perpendicular layout with two blocks ($b_v = 1$ and $b_v = 2$)

horizontal distance is zero. The probability that k segments (rows) have to be traveled is again $\frac{2(r-k)}{r^2}$ (see Kim et al. 2008) with a distance of $2 \times k \times W$. Thus the first distance estimate $E_1^{(1)}$ in case of $b_v = 1$ and $b_h = 1$ is

$$E_1^{(1)} = \sum_{k=1}^{r-1} \frac{2(r-k)}{r^2} 2 \times k \times W = \frac{2W(r^2-1)}{3r}. \tag{7.18}$$

Considering the second driving strategy the estimate $E_1^{(1)}$ has to be changed as shown in Figure 7.7. The SCs have to go around the block to get back to the seaside. When the number of rows is odd, the maximal additional distance occurs when the randomly chosen row and the randomly chosen segment both correspond to the middle row. When the number of rows is even, the maximal additional distance occurs when the randomly chosen row and the randomly chosen segment both correspond to one of two middle rows. Thus the probability of the maximal distance is either $\frac{1}{r}$ if the number of rows is odd, or $\frac{2}{r}$ if the number of rows is even. The probability of another distance is in all cases $\frac{2}{r}$. For simplification we ignore the discrete characteristic of the rows. Thus the maximal additional distance is $\frac{AY^L}{b_h}$ and the minimal distance is zero. This leads to a uniform distribution $U(0, \frac{AY^L}{b_h})$ for the additional distances, and the expected additional distance is $\frac{AY^L}{2b_h}$. The additional distance occurs only in half the cases (in the rest a SC travels backward). Thus the estimate $E_2^{(1)}$ for the second driving strategy is

$$E_2^{(1)} = \frac{2W(r^2-1)}{3r} + \frac{AY^L}{4b_h}. \tag{7.19}$$

When $b_h = 1$ and $b_v > 1$ the distance estimate $E_o^{(1)}$ has to be changed, as shown in Figure 7.8. The distance to the upper block is $E_o^{(1)}$ with a probability of $\frac{1}{b_v}$. For the distances to the lower blocks we again assume for simplification that the whole block forms a segment (not the rows) and that the jobs start at the center of each segment and end in the center. For example, we assume that in Fig. 7.8 a SC has to travel from the center of the upper block to the center of

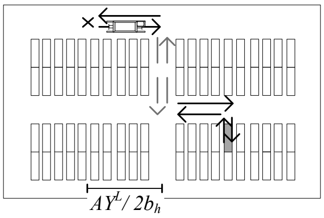


Figure 7.9.: Distances of a SC for a perpendicular layout with four blocks ($b_h = 2$ and $b_v = 2$)

the lower block and back to the center of the upper block. Thus the distance to the lower blocks is $\frac{2AY^L}{b_h}$ and the second distance estimate $E^{(2)}$ in case of $b_v > 1$ and $b_h = 1$ is

$$E_o^{(2)} = \frac{1}{b_v} E_o^{(1)} + \frac{b_v - 1}{b_v} \frac{2AY^L}{b_h}. \tag{7.20}$$

When $b_h > 1$ and $b_v > 1$ the estimate $E_o^{(2)}$ has to be extended. The distances are illustrated in Figure 7.9. Again we assume that the quay is partitioned into segments of size $\frac{AY^L}{b_h}$. With a probability of $\frac{1}{b_h}$ the randomly chosen block is identical with the randomly chosen segment. In this case the distance can be expressed by $E_o^{(2)}$. The probability that k segments have to be traveled is similar to the parallel case with $\frac{2(b_h-k)}{b_h^2}$ (see again Kim et al. 2008). The distance for k segments is $k\frac{2AY^L}{b_h}$ and the third estimate for $b_h > 1$ and $b_v > 1$ is

$$E_o^{(3)} = \frac{E_o^{(2)}}{b_h} + \sum_{k=1}^{b_h-1} \frac{2(b_h - k)}{b_h^2} k \frac{2AY^L}{b_h} = \frac{E_o^{(2)}}{b_h} + \frac{2AY^L(b_h^2 - 1)}{3b_h^2}. \tag{7.21}$$

In summary, $Dh_1^{pe,Q}$ can be defined as

$$Dh_o^{pe,Q} = E_o^{(3)} \tag{7.22}$$

Please note that $E_o^{(3)}$ reduces to $E_o^{(2)}$ when $b_h = 1$ and $E_o^{(2)}$ reduces to $E_o^{(1)}$ when $b_v = 1$.

To estimate the expected vertical distance $Dv_o^{pe,Q}$ we distinguish the two driving strategies as shown in Figure 7.10. The following estimate holds for the first

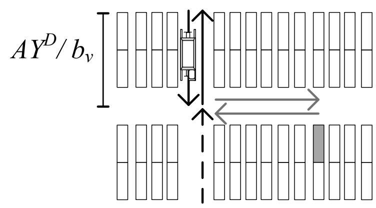


Figure 7.10.: Vertical distances for SCs in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines)

driving strategy: The distance to the first upper block is 0 with a probability of $\frac{1}{b_v}$. The distance to the second block is $\frac{2AY^D}{b_v}$ again with a probability of $\frac{1}{b_v}$. Thus

$$Dv_1^{pe,Q} = \sum_{k=0}^{b_v-1} \frac{1}{b_v} \times k \times \frac{2AY^D}{b_v} = \frac{AY^D(b_v-1)}{b_v}. \tag{7.23}$$

For the second driving strategy the vertical travel distance changes as a SC has to travel the additional distance from the end of the block back to the top with a probability of $\frac{1}{2}$ (see Figure 7.10). Thus the distance to the first block is $\frac{AY^D}{b_v}$ with a probability $\frac{1}{b_v} \times \frac{1}{2}$. The distance to the second block changes to $\frac{3AY^D}{b_v}$. In total the vertical distance changes to

$$Dv_2^{pe,Q} = \sum_{k=0}^{b_v-1} \frac{1}{b_v} \times \left(2k \times \frac{AY^D}{b_v} + \frac{1}{2}\frac{AY^D}{b_v}\right) = \frac{AY^D(2b_v-1)}{2b_v}. \tag{7.24}$$

The estimate for the time a SC spends within a block can be expressed similarly to that for the parallel case by

$$t_o^{s,pe} = \frac{I_o}{\nu \times \gamma} + 0.5R(T,a) \times t^r + t^l. \tag{7.25}$$

The estimate for the time a SC spends on traveling a cycle can be expressed by

$$t_o^{d,pe,Q} = \left(Dh_o^{pe,Q} + Dv_o^{pe,Q}\right)\frac{1}{\nu}. \tag{7.26}$$

7.2.4. Landside-Cycle Estimate for Parallel Layouts

As mentioned before, the hinterland connections may consist of rail and truck connections. We assume a single TSA only. The rail tracks in terminals are often arranged along the landside of the yard. Therefore the estimate of cycles between the rail tracks and the yard would be similar to that of seaside cycles. By contrast, there are some differences regarding the truck service area. We assume in the following that the TSA is located in the middle of the landside side of the

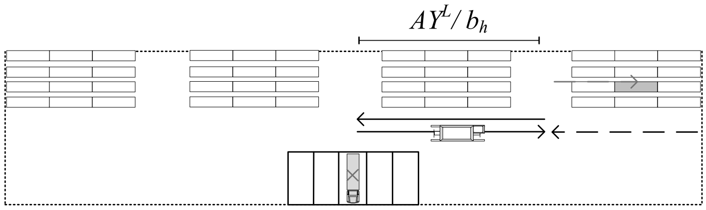


Figure 7.11.: Horizontal distances for a SC landside cycle in a parallel layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with an even number of horizontal blocks b_h

terminal as shown in Figure 7.11. A similar assumption is made by Kim et al. (2008) for the gate in an RTG-based layout. Thus there are some similarities to the gate distances in Kim et al. (2008). The difference between landside and seaside cycles is that the TSA has a fixed position at which all jobs start whereas the start of seaside jobs can be distributed over the whole quay.

To estimate the expected distances we distinguish the cases where b_h is odd respectively even. Figure 7.11 shows the distances for the case in which b_h is even. We assume that the cycles start from the center of the TSA and thus that the horizontal distance to the two closest blocks (blocks above the TSA in Figure 7.11) is zero. The probability that the SC has to travel to the first block is $\frac{2}{b_h}$ with a distance of zero. The distance to the second block is $\frac{2AY^L}{b_h}$ with a probability of $\frac{2}{b_h}$. For the second driving strategy an additional distance of $\frac{AY^L}{b_h}$ has to be considered with a probability of $\frac{1}{2}$. For the first driving strategy this leads to

$$E_1^{(4)} = \sum_{k=1}^{\frac{b_h}{2}} \frac{2}{b_h}(k-1)\frac{2AY^L}{b_h} = \frac{AY^L(b_h-2)}{2b_h}, \tag{7.27}$$

for the second driving strategy to

$$E_2^{(4)} = \sum_{k=1}^{\frac{b_h}{2}} \frac{2}{b_h}\left((k-1)\frac{2AY^L}{b_h} + \frac{1}{2}\frac{AY^L}{b_h}\right) = \frac{AY^L(b_h-1)}{2b_h}, \tag{7.28}$$

and for the third driving strategy to

$$E_3^{(4)} = \sum_{k=1}^{\frac{b_h}{2}} \frac{2}{b_h}\left((k-1)\frac{2AY^L}{b_h} + \frac{AY^L}{b_h}\right) = \frac{AY^L}{2}. \tag{7.29}$$

Figure 7.12 shows the distances for the case that b_h is odd. The probability that a SC has to deliver a container at the block closest to the TSA is $\frac{1}{b_h}$. The

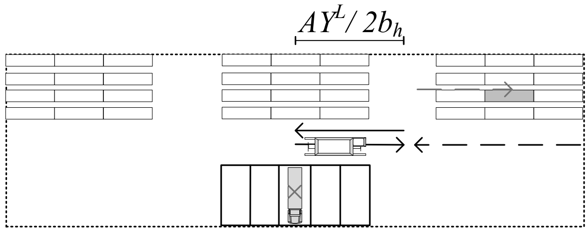


Figure 7.12.: Horizontal distances for a SC landside cycle in a parallel layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with an odd number of horizontal blocks b_h

distance to the closest block is $\frac{AY^L}{b_h}$ (for both driving strategies). The probability that a SC has to travel to a block further away is $\frac{2}{b_h}$. The distance to the second block on the righthand side of the TSA is $\frac{AY^L}{b_h}$ (see Figure 7.12). The distance to the third block on the right is $\frac{3AY^L}{b_h}$ for the first driving strategy. For the second driving strategy an additional distance of $\frac{AY^L}{b_h}$ has to be considered. For the first driving strategy this leads to

$$\begin{aligned} E_1^{(5)} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{\frac{b_h-1}{2}} \frac{2}{b_h}\left(\frac{AY^L}{b_h} + (k-1)\frac{2AY^L}{b_h}\right) \\ &= \frac{AY^L(b_h^2 - 2b_h + 3)}{2b_h^2}, \end{aligned} \tag{7.30}$$

for the second driving strategy to

$$\begin{aligned} E_2^{(5)} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{\frac{b_h-1}{2}} \frac{2}{b_h}\left(\frac{1}{2}\frac{AY^L}{b_h} + \frac{AY^L}{b_h} + (k-1)\frac{2AY^L}{b_h}\right) \\ &= \frac{AY^L(b_h^2 - b_h + 2)}{2b_h^2}, \end{aligned} \tag{7.31}$$

and for the third driving strategy to

$$\begin{aligned} E_3^{(5)} &= \frac{1}{b_h}\frac{AY^L}{b_h} + \sum_{k=1}^{\frac{b_h-1}{2}} \frac{2}{b_h}\left(\frac{AY^L}{b_h} + \frac{AY^L}{b_h} + (k-1)\frac{2AY^L}{b_h}\right) \\ &= \frac{AY^L(b_h^2 + 1)}{2b_h^2}. \end{aligned} \tag{7.32}$$

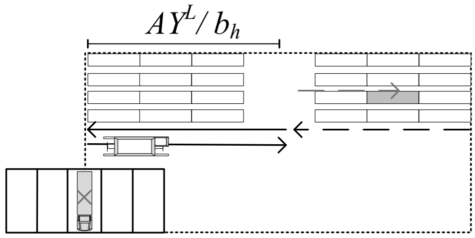


Figure 7.13.: Horizontal distances for a SC landside cycle in a parallel layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with a TSA on the left edge of the yard

In sum, this leads to the following estimate for the expected horizontal landside cycle distance in a parallel layout

$$Dh_o^{pa,HM} = \begin{cases} E_o^{(4)} & \text{when } b_h \text{ is even,} \\ E_o^{(5)} & \text{when } b_h \text{ is odd.} \end{cases} \tag{7.33}$$

Another possible position of the TSA is at one of the corners of the yard. In the following we assume a position of the TSA in the lower left corner of the yard as in Figure 7.13. We assume that the distance of a SC from the center of the TSA to the first block is zero. Consequently the distance to the second block is $\frac{2AY^L}{b_h}$ for the first driving strategy (see Figure 7.13). For the second driving strategy the additional distance is $\frac{AY^L}{b_h}$. The distance to block k ($k = 1, \ldots, b_h$) is $\frac{2(k-1)AY^L}{b_h}$ for the first driving strategy. The probability that a SC has to travel to block k is $\frac{1}{b_h}$. This leads to the estimate

$$Dh_1^{pa,HL} = \sum_{k=1}^{b_h} \frac{1}{b_h} \frac{2(k-1)AY^L}{b_h} = \frac{AY^L(b_h - 1)}{b_h} \tag{7.34}$$

for the first driving strategy and to

$$Dh_2^{pa,HL} = \sum_{k=1}^{b_h} \frac{1}{b_h} \left(\frac{2(k-1)AY^L}{b_h} + \frac{1}{2} \frac{AY^L}{b_h} \right) = \frac{AY^L(2b_h - 1)}{2b_h} \tag{7.35}$$

for the second driving strategy. For the third driving strategy the estimate is

$$Dh_3^{pa,HL} = \sum_{k=1}^{b_h} \frac{1}{b_h} \left(\frac{2(k-1)AY^L}{b_h} + \frac{AY^L}{b_h} \right) = AY^L. \tag{7.36}$$

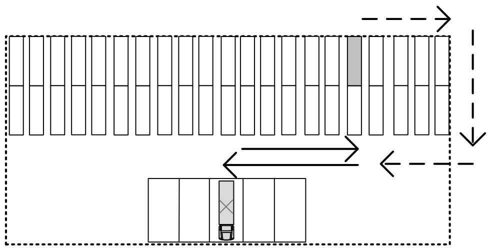


Figure 7.14.: Horizontal distances for a SC landside cycle in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines)

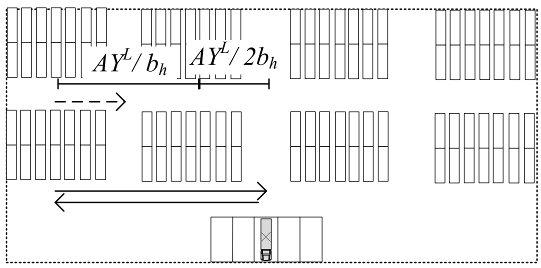


Figure 7.15.: Horizontal distances for a SC landside cycle in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with b_h even

7.2.5. Landside-Cycle Estimate for Perpendicular Layouts

For the expected horizontal cycle distance in a perpendicular layout we first consider the case where $b_h = 1$ and $b_v = 1$ as in Figure 7.14. As with the seaside cycles we consider the distance to single rows. In case where $b_h = 1$ and $b_v = 1$ the expected distance using the first driving strategy can be expressed by

$$E_1^{(6)} = \begin{cases} \sum_{k=1}^{\frac{r}{2}} \frac{2}{r} 2k \times W = \frac{W(r+2)}{2} & \text{when } r \text{ is even,} \\ \sum_{k=1}^{\frac{r-1}{2}} \frac{2}{r} 2k \times W = \frac{W(r^2-1)}{2r} & \text{when } r \text{ is odd.} \end{cases} \tag{7.37}$$

When r is odd we assume that the distance to the closest row is zero with a probability of $\frac{1}{r}$. For the second driving strategy we assume for the sake of brevity an additional distance similar to that in case of seaside cycle of $\frac{AY^L}{2b_h}$ (see Section 7.2.3) which leads to

$$E_2^{(6)} = \begin{cases} \frac{W(r+2)}{2} + \frac{AY^L}{4b_h} & \text{when } r \text{ is even,} \\ \frac{W(r^2-1)}{2r} + \frac{AY^L}{4b_h} & \text{when } r \text{ is odd.} \end{cases} \tag{7.38}$$

Figure 7.15 shows the horizontal distances when $b_h \geq 1$, $b_v \geq 1$, and b_h is even. In this case the horizontal distances are identical for both driving strategies (see

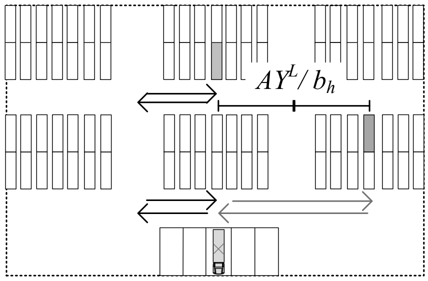


Figure 7.16.: Horizontal distances for a SC landside cycle in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with b_h odd

Figure 7.15). We consider the travel distance from the center of the TSA to the center of the blocks and back to the TSA. The travel distance to block k (with $k = 1, \dots, \frac{b_h}{2}$) is $\frac{2(k-1)AY^L + AY^L}{b_h}$ and has a probability of $\frac{2}{b_h}$. Thus

$$E_o^{(7)} = \sum_{k=1}^{\frac{b_h}{2}} \frac{2}{b_h} \frac{2(k-1)AY^L + AY^L}{b_h} = \frac{AY^L}{2}. \tag{7.39}$$

Figure 7.16 shows the horizontal distances in case where $b_h \geq 1$, $b_v \geq 1$ and b_h is odd. Where $b_h = 1$ and $b_v > 1$ the estimate $E_o^{(6)}$ has to be extended as with estimates for the seaside cycles. The distance to the lower block (the block closer to the TSA) is $E_o^{(6)}$ with a probability of $\frac{1}{b_v}$, and the distance to the second block is $\frac{2AY^L}{b_h}$ with a probability of $\frac{b_v-1}{b_v}$. Thus

$$E_o^{(8)} = \frac{1}{b_v} E_o^{(6)} + \frac{b_v - 1}{b_v} \frac{2AY^L}{b_h}. \tag{7.40}$$

Where $b_h > 1$ the distance to the blocks above the TSA is expressed by $E_o^{(8)}$ with a probability of $\frac{1}{b_h}$. The distance to the other blocks k ($k = 1, \dots, \frac{b_h-1}{2}$) is $\frac{2kAY^L}{b_h}$ with a probability of $\frac{2}{b_h}$. Hence

$$E_o^{(9)} = \frac{1}{b_h} E_o^{(8)} + \sum_{k=1}^{\frac{b_h-1}{2}} \frac{2}{b_h} \frac{2kAY^L}{b_h} = \frac{1}{b_h} E_o^{(8)} + \frac{AY^L(b_h^2 - 1)}{2b_h^2}. \tag{7.41}$$

Please note that $E_o^{(9)}$ reduces to $E_o^{(8)}$ when $b_h = 1$ and to $E_o^{(6)}$ when $b_v = 1$. This

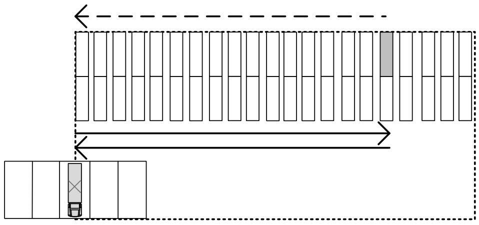


Figure 7.17.: Horizontal distances for a SC landside cycle in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with a TSA in the lower left corner and $b_h = 1$

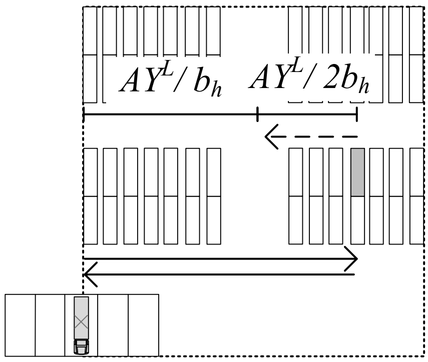


Figure 7.18.: Horizontal distances for a SC landside cycle in a perpendicular layout for the first driving strategy (solid lines) and the second driving strategy (dashed lines) with a TSA in the lower left corner and $b_h > 1$

leads to the following expected horizontal distance for a perpendicular layout with a TSA in the middle of the yard:

$$Dh_o^{pe,HM} = \begin{cases} E_o^{(7)} & \text{when } b_h \text{ is even,} \\ E_o^{(9)} & \text{when } b_h \text{ is odd.} \end{cases} \tag{7.42}$$

Where we assume a TSA in the left corner of the yard, as in Figure 7.17, we need to change the horizontal distance estimates. We first consider the case where $b_h = 1$. In this case we consider each individual row of the block. We assume that the distance of a SC from the center of the TSA to the first row is zero. Consequently the distance to the second row is $2 \times W$ for both driving strategies (see Figure 7.17). The probability that a SC has to travel to a specific row is $\frac{1}{r}$. Thus

$$E_o^{(10)} = \sum_{k=1}^{r} \frac{1}{r} 2(k-1) \times W = W(r-1). \tag{7.43}$$

The case where $b_h > 1$ is shown in Figure 7.18. We assume that the distance from the middle of the TSA to the middle of the first block (and back) is $\frac{AY^L}{b_h}$. The distance to the second block is $\frac{3AY^L}{b_h}$. The probability that a SC has to travel to a specific block is $\frac{1}{b_h}$. Hence

$$E_o^{(11)} = \sum_{k=1}^{b_h} \frac{1}{b_h} \frac{2(k-1)AY^L + AY^L}{b_h} = AY^L. \tag{7.44}$$

In sum, this leads to

$$Dh_o^{pe,HL} = \begin{cases} E_o^{(10)} & \text{when } b_h = 1, \\ E_o^{(11)} & \text{when } b_h > 1. \end{cases} \tag{7.45}$$

The vertical distances are similar to the seaside cycles. Moreover, the time needed for stacking is identical with that of the seaside cycles and needs not to be redefined. Thus we can define the estimate of the travel time of a SC considering landside and seaside cycles simultaneously as

$$t_o^{d,p,QH} = \left(\left(0.5 - \frac{\alpha}{2} \right) Dh_o^{p,H} + \left(0.5 + \frac{\alpha}{2} \right) Dh_o^{p,Q} + Dv_o^{p,Q} \right) \frac{1}{\nu} \tag{7.46}$$

where α defines a weight for the seaside and landside cycles corresponding to the transhipment ratio. We assume that $0 \leq \alpha \leq 1$. Consequently a pure transhipment terminal ($\alpha = 1$) will lead to a model which considers solely seaside cycles.

7.2.6. The Model Formulation

The aim is to minimize the estimated average straddle carrier cycle time defined by the time needed for stacking operations t^s and by the time t^d needed for traveling from the quay (or the TSA) to the designated storage block and back to the quay (or the TSA). This results in the following model:

$$\min_{x_e, y_e, o} z = \quad t_o^{s,p} + t_o^{d,p,QH} \tag{7.47}$$

$$\text{s.t.} \quad T \leq \chi \tag{7.48}$$

$$AY^L \leq MY^L \tag{7.49}$$

$$AY^D \leq MY^D \tag{7.50}$$

Constraint (7.48) ensures that the average stacking height does not exceed a maximal average stacking height χ. In addition, this constraint ensures that not all available space is used for driving lanes. If constraint (7.48) is relaxed, the following natural constraint must be held: $G > 0$. Furthermore, constraints (7.49) and (7.50) restrict the yard length and depth to a maximal yard length MY^L and depth MY^D.

To solve this problem the values of x_e, y_e, o can easily be enumerated given the restriction of the average stacking height. We, therefore, enumerate the different driving strategies $o = \{1, 2\}$ and different numbers of driving lanes x_h, y_h, x_v, y_v. How many values are enumerated depends on the parameter used, e.g. the yard length or the maximal stacking height. For a typical instance of a parallel layout we enumerate values for x_h between zero and eleven and for y_h between zero and twenty. Considering the two first driving strategies, this results in 440 combinations that are enumerated.

7.3. Numerical Examples

In this section we present several results based on the estimates discussed above. We assume a basic scenario for a typical container terminal. When parameter values differ from those of the basic scenario we explicitly redefine them. For the basic scenario we assume a starting terminal length of $Y^L = 450$ m and a starting terminal depth of $Y^D = 250$ m. The length and width of a ground lot is defined by $L = 6.25$ m and $W = 3.5$ m. The maximal velocity of a SC can be up to 8 meters per second (Stahlbock and Voß 2008). Nevertheless, we assume a velocity of SCs with $v = 5$ meters per second as we consider the average travel speed. We also assume that $\gamma = 0.6$. The rehandle time is assumed to be $t^r = 105$ seconds and lifting time to be $t^l = 30$ seconds. In the parallel case is $\delta_h = 4$ bays which results in a driving lane width of 25 m. In the perpendicular case is $\delta_h = 7$ rows which results in a driving lane width of 24.5 m and we define $\delta_v = 4$ bays. We define the capacity for the storage yard C by using an initial average stacking height $\lambda = 1.75$, and we assume that Y^L and Y^D are solely used for stacking: $C = G \times \lambda$ with $x_e = 0$. We assume in general a maximal average stacking height of $\chi = 3$ containers. The parameter α is assumed to be zero.

7.3.1. The Impact of Different Compensation Strategies

When implementing a driving lane compensation has to be made for loss of ground space. The problem defined by the model (7.47)-(7.50) gives the possibility of using either a greater terminal area or increasing the average stacking height for this purpose. In the following we want to analyze if one compensation strategy is more favorable than another. We use a starting yard length of $Y^L = 300$ m, and

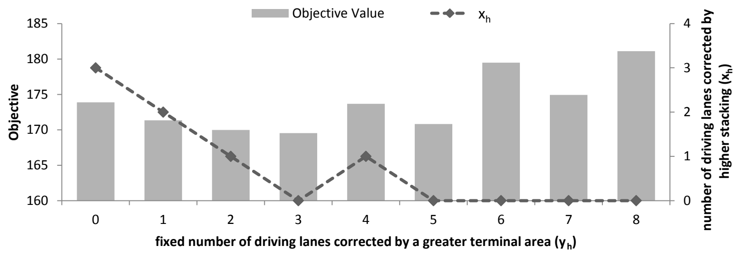


Figure 7.19.: Influence of vertical driving lanes compensated by a greater terminal area (y_h) on the cycle time estimate for the parallel case with $Y^L = 300$ and a TSA in the middle of the yard

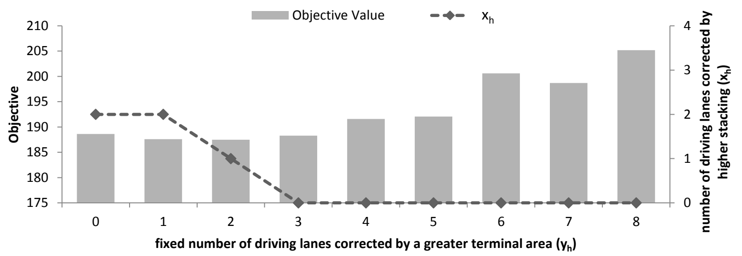


Figure 7.20.: Influence of vertical driving lanes compensated by a greater terminal area (y_h) on the cycle time estimate for the parallel case with $Y^L = 300$ and a TSA on the left edge of the yard

we assume a TSA position in the middle of the yard ($H = HM$) unless otherwise stated.

Figure 7.19 shows for a parallel layout the development of the cycle times and of variable x_h when y_h is fixed at a specific value. The cycle times are based on the derived optimal value of x_h with a fixed value of y_h. The results show that until about three driving lanes (y_h) the cycle times as well as the number of secondary driving lanes x_h decrease. Thus compensation secured by a wider terminal area outweighs the compensation by higher stacking until three driving lanes. The slight increase of AY^L of 75 m in this scenario does not outweigh the decrease of D_h and I_o due to a higher number of driving lanes. From about three driving lanes the cycle times increase. When the TSA is on the left edge of the yard (Figure 7.20) ($H = HL$) this effect occurs earlier. Figure 7.20 shows that the cycle time increases for increased values of $y_h > 2$ and achieves only a slight decrease for $y_h = 1$ and $y_h = 2$ compared to the decrease achieved when the TSA is in the middle. In the case of a TSA on the left edge of the yard the landside cycle times are more sensitive to changes in the total yard length.

Figure 7.21 shows the influence of the different vertical driving lanes on a

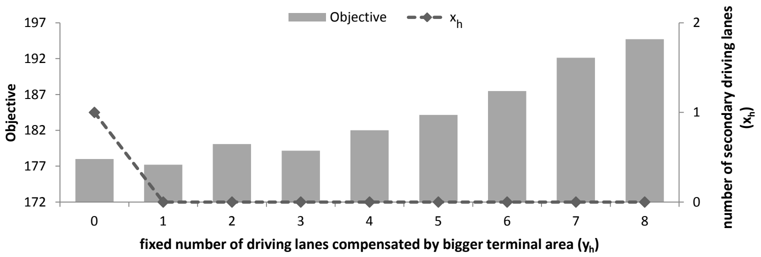


Figure 7.21.: Influence of vertical driving lanes compensated by more terminal area (y_h) on the cycle time estimation for the perpendicular case with $Y^L = 300$

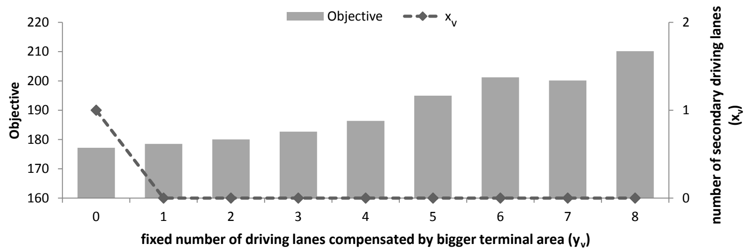


Figure 7.22.: Influence of horizontal driving lanes compensated by more terminal area (y_v) on the cycle time estimation for the perpendicular case with $Y^L = 300$

perpendicular layout. The results are similar to those of the parallel layout. The solution with a value of $y_h = 1$ results in a lower cycle time. For values of $y_h > 1$ the cycle times increase. Figure 7.22 shows the results for horizontal driving lanes with a fixed variable y_v. In this case the cycle times increase for higher values of y_v.

To summarize, none of the compensation strategies is clearly preferable to another. A terminal planner should carefully consider whether additional space is available to build a wider terminal. In the following we assume that $Y^L = MY^L$ and $Y^D = MY^L$, which means that there is no space available to increase the terminal area. This leads to fixed variables $y_e = 0$.

7.3.2. The Impact of the TSA Position

Above we derived estimates for expected landside cycles assuming two possible TSA positions. In this section we analyze the impacts of both TSA positions on the solutions. We therefore calculate the optimal solution for different values of Y^L. The results for the parallel layouts are given in Table 7.1 and for the perpendicular layouts in Table 7.2. In the case of the perpendicular layout is $x_v = 1$ for all values of Y^L.

The results show that the cycle times (values of z in Table 7.1 and 7.2) are

Table 7.1.: Results for different values of Y^L assuming a TSA in the middle of the yard (mid) and on the left edge of the yard (left) for a parallel layout

	Y^L	300	400	500	600	700	800	900	1000	1100	1200
left	x_h	2	3	5	4	5	5	6	8	9	9
	l	13	13	10	16	15	18	17	14	14	15
	z	188.6	204.2	221.7	237.9	254.7	271.7	287.9	304.1	320.2	338.0
mid	x_h	3	3	5	5	5	5	7	7	9	9
	l	9	13	10	12	15	18	14	16	14	15
	z	173.9	184.2	196.7	209.3	219.7	231.7	243.1	254.8	265.2	278.0

Table 7.2.: Results for different values of Y^L assuming a TSA in the middle of the yard (mid) and on the left edge of the yard (left) for a perpendicular layout

	Y^L	300	400	500	600	700	800	900	1000	1100	1200
left	x_h	1	1	2	2	2	3	3	3	4	5
	r	39	53	42	52	62	51	59	66	57	51
	z	193.0	210.6	227.0	242.8	259.1	276.1	291.8	308.4	325.0	341.8
mid	x_h	1	1	1	3	3	3	3	3	3	5
	r	39	53	67	37	44	51	59	66	73	51
	z	178.0	190.6	203.1	213.9	225.0	236.1	246.8	258.4	270.2	281.8

higher if the TSA is on the left edge of the yard than when it is in the middle of the yard. This is obvious as the possible maximal distance for the SCs is greater when $H = HL$. Interestingly, when the TSA is positioned in the middle of the yard the results in Table 7.1 and Table 7.2 show a structure in which solutions are preferred which have an even number of blocks (x_h is odd and thus b_h is even). In the case of an odd number of blocks (b_h is odd) the SCs have to travel around the block which is located above the TSA (see Figure 7.16 or 7.12). When the number of blocks is even we assume that the SCs can directly enter the driving lane above the TSA (see Figure 7.11 and 7.15). For this reason solutions with an even number of blocks might achieve lower cycle times. To avoid this effect we assume in the following that the TSA is positioned in the left corner of the yard ($H = HL$).

7.3.3. The Impact of Different Parameter Settings

In this section the influences of different parameter values on the solution are discussed. Table 7.3 shows results for different parameter values for Y^L,γ, t^r, λ, χ, and α for the parallel layouts. In every case only the values of the con-

Table 7.3.: Influence of different parameter settings on the solution for a parallel layout

Y^L		300	400	500	600	700	800	900	1000	1100	1200
	l	13	13	10	16	15	18	17	14	14	15
	x_h	2	3	5	4	5	5	6	8	9	9
	z	188.6	204.2	221.7	237.9	254.7	271.7	287.9	304.1	320.2	338.0
γ		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	l	6	8	11	11	11	15	15	15	15	21
	x_h	6	5	4	4	4	3	3	3	3	2
	z	288.1	251.0	235.1	225.5	218.4	212.9	208.2	204.6	201.8	199.5
t^r		75	95	115	135	155	175	195	215	235	255
	l	11	11	15	15	15	15	15	15	15	15
	x_h	4	4	3	3	3	3	3	3	3	3
	z	199.4	208.7	217.1	225.3	233.6	241.8	250.1	258.4	266.6	274.9
λ		1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2
	l	11	11	11	11	15	15	15	15	15	15
	x_h	4	4	4	4	3	3	3	3	3	3
	z	197.6	201.1	204.6	208.1	211.3	214.5	217.7	220.9	224.1	227.4
χ		2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	l	15	15	15	15	15	15	15	15	15	15
	x_h	3	3	3	3	3	3	3	3	3	3
	z	212.9	212.9	212.9	212.9	212.9	212.9	212.9	212.9	212.9	212.9
α		0	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	l	15	15	15	15	15	15	15	15	15	15
	x_h	3	3	3	3	3	3	3	3	3	3
	z	212.9	210.7	209.6	208.3	207.1	205.8	204.6	203.3	202.0	200.8

sidered parameter are changed, the other parameter values remain unchanged. Consequently the values of the basic scenario hold for the unchanged parameters. In Table 7.3 we exclude the consideration of different yard depth values Y^D as this only influences the solution value not the solution itself because we do not consider vertical driving lanes in the parallel case.

Changing the values of Y^L leads to differences in the values of l. A greater terminal length Y^L, however, does not lead to longer blocks (higher values of l). By contrast, the block length stays on a level between 10 and 18 bays. Naturally, the cycle times z increase for higher values of Y^L.

The parameter γ influences the time a SC spends driving within a storage block in the way that a lower speed, lower value of γ, increases the travel times. Shorter block lengths are, therefore, preferable for lower values of γ. Consequently a decrease in the values of the parameter γ leads to a decrease in the block length l and to higher cycle times z.

Increasing the parameters t^r and λ leads to increased values of l up to 15 TEUs. Increasing the rehandle times leads to longer blocks as a higher average stacking height is more costly. In addition, a higher starting stacking density leads to longer blocks. In general, more dense stacking will result in longer blocks as additional driving lanes become more costly. Moreover, reducing the value of χ has no influence in the parallel case as the optimal solution is not restricted by any of the used values for the maximal average stacking height χ. Changing the transhipment ratio weight α does not influence the solution structure. Only the cycle times z decrease for higher transhipment ratios (higher values of α). This is due to the higher landside cycles than quayside cycle times.

Table 7.4 shows the results for the perpendicular layout for different parameter values. In the perpendicular case the problem is extended as vertical and horizontal driving lanes have now to be planned. The influence of parameter Y^L on the block width is similar to that of the parallel case. The block width ranges between 39 and 66 rows. Moreover, the results for different values of Y^L show that the block length is identical for all different yard lengths. Obviously the block length l is not influenced by the yard length Y^L but by the yard depth Y^D. Up to a yard depth of 200 m the whole yard is used for stacking ($x_v = 0, x_h = 0$). For a yard length of 250 m or more vertical and horizontal driving lanes are used. Overall the block length ranges for different values of Y^D between 8 and 32 bays.

The results in Table 7.4 for different values of γ are identical with those for the parallel layout. Lower values of γ lead to shorter block length. Where $\gamma \geq 0.7$ the whole yard is used for stacking as the SCs can move nearly as quickly within as outside the blocks. Thus all containers can be reached quickly without driving lanes.

For values of $t^r \geq 155$ seconds again the whole yard is used for stacking. Thus for high rehandle times the loss of stacking space is not favorable as the container can still be reached efficiently using the first driving strategy. We could show that obviously this behavior changes if the value of γ decreases. For low values of γ a solution with a block length of 40 bays would simply result in too high in-block travel times. Moreover, the results in Table 7.4 show that more dense stacking settings (higher values of λ) lead to solutions with higher cycle times. The maximal stacking height (χ) has a similar impact on solutions for the perpendicular layout as on solutions for the parallel layout. Due to the restriction of the maximal stacking height fewer driving lanes are allowed and thus the values

Table 7.4.: Influence of different parameter settings on the solution for a perpendicular layout

Y^L		300	400	500	600	700	800	900	1000	1100	1200
	l	18	18	18	18	18	18	18	18	18	18
	x_v	1	1	1	1	1	1	1	1	1	1
	r	39	53	42	52	62	51	59	66	57	51
	x_h	1	1	2	2	2	3	3	3	4	5
	z	193.0	210.6	227.0	242.8	259.1	276.1	291.8	308.4	325.0	341.8
Y^D		50	100	150	200	250	300	350	400	450	500
	l	8	16	24	32	18	22	16	13	15	17
	x_v	0	0	0	0	1	1	2	3	3	3
	r	128	128	128	128	38	38	38	38	38	38
	x_h	0	0	0	0	2	2	2	2	2	2
	z	158.1	173.7	190.0	206.4	218.1	230.1	239.8	251.2	261.0	271.2
γ		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	l	7	7	7	10	18	18	40	40	40	40
	x_v	3	3	3	2	1	1	0	0	0	0
	r	38	38	38	38	38	38	128	128	128	128
	x_h	2	2	2	2	2	2	0	0	0	0
	z	296.7	257.4	244.3	235.0	226.0	218.1	210.8	201.6	194.5	188.8
t^r		75	95	115	135	155	175	195	215	235	255
	l	18	18	18	18	40	40	40	40	40	40
	x_v	1	1	1	1	0	0	0	0	0	0
	r	38	38	38	38	128	128	128	128	128	128
	x_h	2	2	2	2	0	0	0	0	0	0
	z	205.1	213.8	222.4	231.0	238.8	245.2	251.5	257.8	264.2	270.5
λ		1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2
	l	18	18	18	18	18	18	18	18	18	18
	x_v	1	1	1	1	1	1	1	1	1	1
	r	38	38	38	38	38	38	38	38	38	38
	x_h	2	2	2	2	2	2	2	2	2	2
	z	203.1	206.5	209.8	213.1	216.4	219.7	223.1	226.4	229.7	233.0
χ		2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	l	40	18	18	18	18	18	18	18	18	18
	x_v	0	1	1	1	1	1	1	1	1	1
	r	128	60	38	38	38	38	38	38	38	38
	x_h	0	1	2	2	2	2	2	2	2	2
	z	223.0	219.3	218.1	218.1	218.1	218.1	218.1	218.1	218.1	218.1
α		0	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	l	18	18	18	18	18	18	18	18	18	18
	x_v	1	1	1	1	1	1	1	1	1	1
	r	38	38	38	38	38	38	38	38	38	38
	x_h	2	2	2	2	2	2	2	2	2	2
	z	218.1	215.7	214.5	213.3	212.1	211.0	209.8	208.6	207.4	206.2

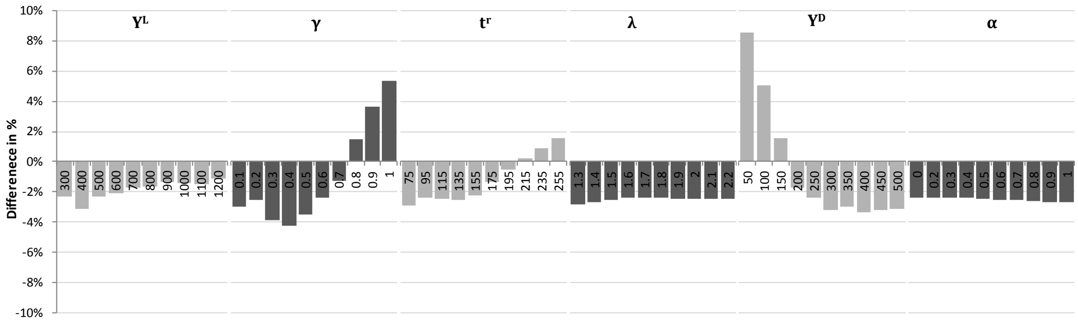


Figure 7.23.: Difference $((z^{pa} - z^{pe})/z^{pa})$ between the parallel and perpendicular layouts with a default yard depth of $Y^D = 250$ m

of l and r increase. For values of $\chi \geq 2.3$ the solutions are not restricted by the maximal stacking height. Similar to the results for the parallel layout, the transhipment ratio weight α has no impact on the solution structure. Again, only the cycle time decreases for higher values of α.

In summary, the results show that each scenario has to be considered individually. The main factors determining block length on the perpendicular layout are terminal depth, rehandle times, and in-block travel velocity of SCs. In the case of the parallel layout the block length is influenced mainly by in-block travel velocity and rehandle times.

7.3.4. The Vertical vs. the Parallel Case

A remaining question is whether one of the orientation options is preferable. Accordingly the results presented above for parameter settings (Y^L, γ, t^r, λ, Y^D, and α) for the perpendicular and parallel cases are compared. We define z^{pa} as solution values z for the parallel layout and z^{pe} as solution values z for the perpendicular layout. Figure 7.23 shows the differences (in percentage terms $(z^{pa} - z^{pe})/z^{pa}$) between the parallel and perpendicular layouts for the different parameters and for the 10 parameter values listed in Table 7.3 and Table 7.4. Consequently, positive values in Figure 7.23 represent the advantage in percentage terms of the perpendicular layout and negative values the advantage of the parallel layout.

As shown in Figure 7.23 the parallel layout is superior to the perpendicular case for all values of the parameters Y^L, λ, and α. The advantage of the parallel layout in those cases is on average 2.3 %. Moreover, the parallel layout dominates the perpendicular layout for most values of the remaining parameters γ, t^r, and Y^D. Please note that we assume no horizontal driving lanes for the parallel layout. In the case that an additional horizontal driving lane is used for the parallel layout,

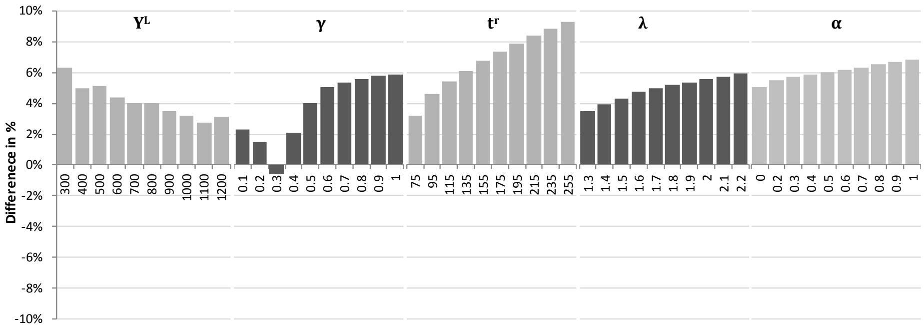


Figure 7.24.: Difference $((z^{pa} - z^{pe})/z^{pa})$ between the parallel and perpendicular layouts with a fixed yard depth of $Y^D = 100$ m

e.g. to avoid traffic jams, the advantage of the parallel layout diminishes. The perpendicular layout, however, achieves lower cycle times than the parallel layout for high in-block velocities (γ), for high rehandle times (t^r), and for short yard depth (Y^D). As yard depth seems greatly to influence the results we calculate the difference $((z^{pa} - z^{pe})/z^{pa})$ between the parallel and perpendicular cases for different values of Y^L, γ, t^r, λ, and α for a yard depth of $Y^D = 100$ m. The results are shown in Figure 7.24.

The results in Figure 7.24 show that in the case of $Y^D = 100$ m the advantage of the parallel layout becomes an advantage of the perpendicular layout. For all values of the parameters Y^L, t^r, λ, and α the perpendicular layout achieves a lower cycle time. The parallel layout is preferable to the perpendicular layout solely for a low in-block velocity of $\gamma = 0.3$. On average the perpendicular layout achieves 5.1 % lower cycle times. In case of the deeper yard depth ($Y^D = 250$ m) the parallel layout achieves on average about 1.8 % lower cycle times. The advantage of the perpendicular layout for shorter yard depth seems to lie in its ability to use (nearly) the whole yard for stacking (a yard without driving lanes). A similar advantage occurs for higher values of t^r and λ. In both cases the storage space becomes more costly and therefore a solution without driving lanes is to be favored. Consequently, the difference between the perpendicular and parallel layouts increases for higher values of t^r and λ.

Above we assume that all three driving strategies can be used for both layout options. When only the third driving strategy is possible for the parallel layout the difference between both layout options will change. Figure 7.25 illustrates the differences between the parallel and perpendicular layouts when only the third driving strategy can be used for the parallel layout ($o = 3$). For the perpendicular layout all three driving strategies are still possible. In this case the perpendicular layout achieves lower cycle times for all parameter values.

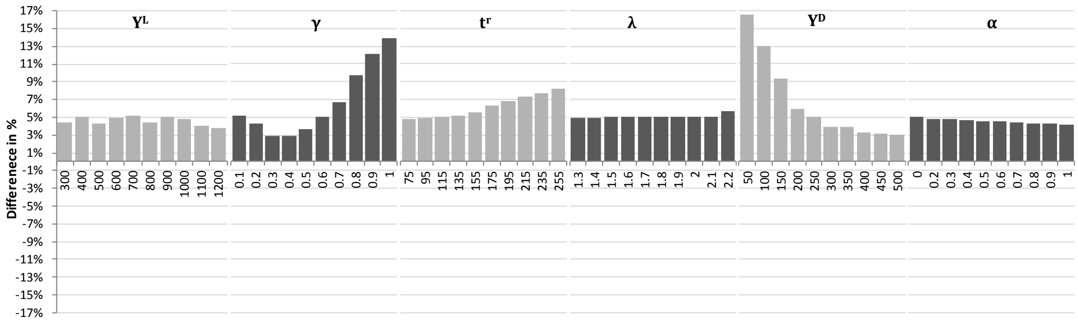


Figure 7.25.: Difference $((z^{pa} - z^{pe})/z^{pa})$ between the parallel and perpendicular layouts in case that the driving strategy is fixated to $o = 3$ in the parallel case (default $Y^D = 250$ m)

Generally, it cannot be concluded that one kind of layout is better than the other. The above results show that each case has to be considered carefully. In particular, the values of γ, Y^D and the possible driving strategies greatly influence the preference of a layout. The results indicate that for high in-block travel velocities of the SCs or for short yard depth the perpendicular layout seems to be preferable to the parallel layout, and vice versa.

7.3.5. Comparison of the Driving Strategies

In above sections we consider three driving strategies. The third, however, is mostly ignored as it is inferior to the first and second. In this section we compare the results for the first and second driving strategy. Which driving strategy is preferable depends greatly on the possible in-block velocities. Figure 7.26 illustrates the difference between the optimal solution using the first driving strategy and that using the second driving strategy ($z^{o=1} - z^{o=2}$). Positive values indicate the advantage of the second driving strategy and negative values the advantage of the first. Naturally the first driving strategy is to be favored for high in-block velocities as the longer in-block distances can be compensated by the high velocities. Thus the second driving strategy is advantageous for lower in-block velocities. The first driving strategy is advantageous for the parallel layout for an in-block velocity of $\gamma \geq 0.5$, as shown by Figure 7.26. For the perpendicular layout the first driving strategy results in lower cycle times for an in-block velocity of $\gamma \geq 0.4$.

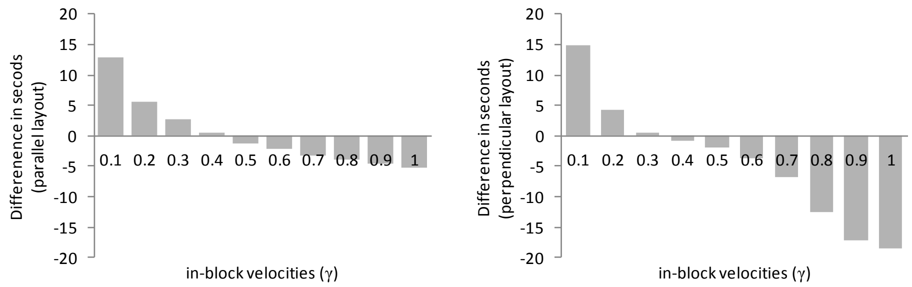


Figure 7.26.: Difference in seconds between first and second driving strategy

7.4. Summary

In this chapter we have considered the yard layout design problem for container terminals operated by SCs. We derive estimates for the expected cycle times of SCs considering a parallel and a perpendicular layout, various driving and compensation strategies. Different estimates are derived which distinguish between horizontal and vertical travel, free travel outside blocks and travel within blocks, and seaside and hinterland cycles. These estimates have been used to model the problem. As only a few configurations are feasible the problem could be solved by an enumeration of all possible values. The results show that for driving strategies, compensation options and layout orientations it cannot be concluded that one option is superior to another. For each layout option situations might exist in which this particular option works best. Thus all different situations with their specific restrictions and parameter values have to be carefully considered. Nevertheless, the results showed that for certain combinations of parameter values a superior layout option could be identified. Perpendicular layouts, for instance, seemed favorable in situations where the straddle carriers achieve a high velocity when traveling within a block and where the terminal has a short depth.

8. Adequacy of Layout Categories for Different Terminal Scenarios

In the preceding chapters we have presented several methods to support the design of yard layouts distinguishing different layout categories. These yard layout categories have differing characteristics which might have advantages in certain situations. In this chapter we analyze the adequacy of layout categories for specific scenarios. Possible scenarios are different modal splits, e.g. different transhipment ratios or scenarios which consider different ratios of reefer containers. We analyze the performance of the considered yard layout categories with varying configurations for several scenarios. To evaluate the performance of different yard layout categories and designs we use a newly developed simulation model.

More precisely, we here consider the common layout categories parallel layouts with transfer lanes and perpendicular layouts with transfer points. Both categories are described in Section 2.4.3. Specific layout configurations of both categories are simulated for different scenarios with varying transhipment and reefer rates. From the simulation results, we determine whether layouts of a specific category are suitable for every scenario simulated; whether for instance, both categories can provide suitable layouts for a terminal with high transhipment rates.

The remainder of this chapter is structured as follows: Section 8.1 illustrates the simulation model used to evaluate different layouts. In Section 8.2 the layout categories and configurations considered in the study are described. Section 8.3 introduces the different scenarios that are simulated and defines groups of scenarios. Section 8.4 shows the results of the simulation study. Finally, Section 8.5 summarizes the main results of this chapter.

8.1. Description of the Simulation Model

As in Chapter 4 we use means of simulation to measure the performance of specific terminal configurations. The simulation model in this chapter shares features with that described in Section 4.2. Nevertheless, several new implementations have to be done. For instance, we need a more detailed implementation of the

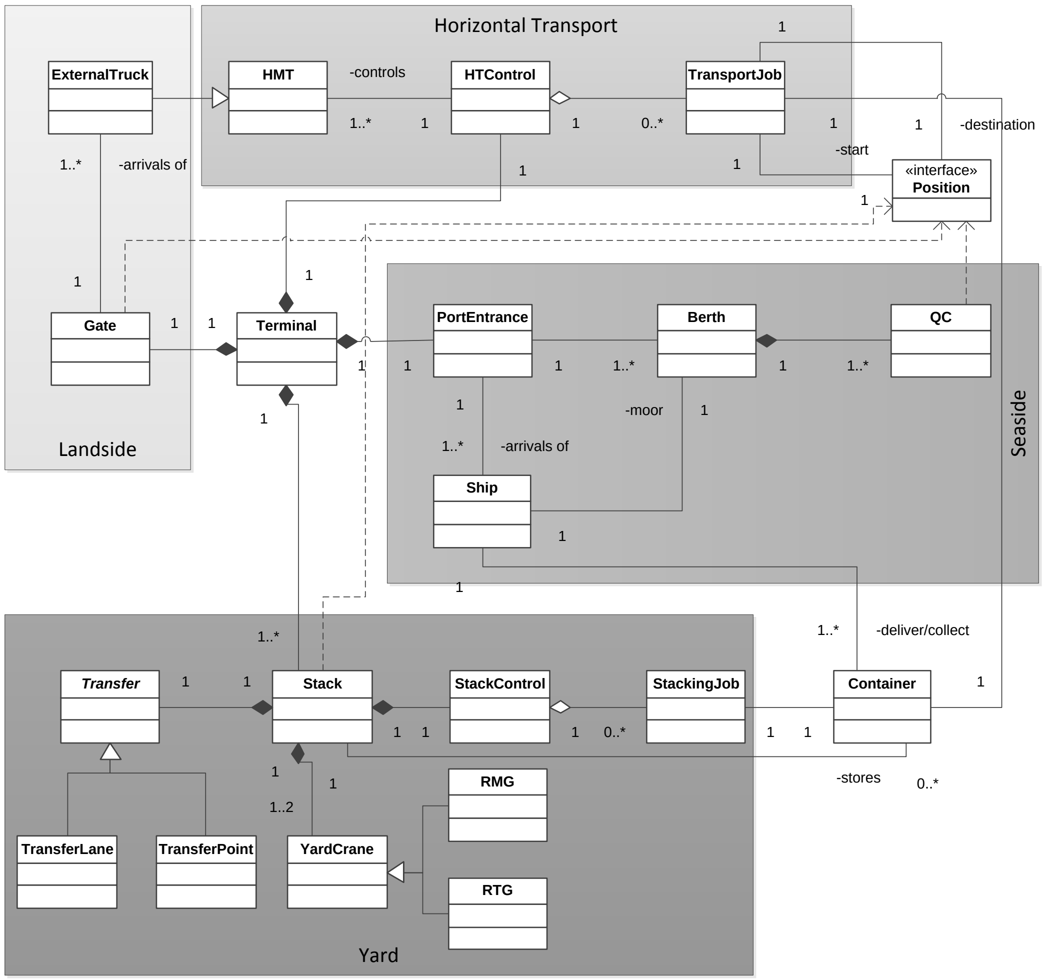


Figure 8.1.: Structure of the simulation model visualized as UML class diagram

storage blocks and of the RMG-based crane types for the perpendicular layout. In the following important details of the simulation model are described. The simulation model has been implemented using the software Plant Simulation 8.1 (see UGS Tecnomatix 2007).

8.1.1. Structure and Elements of the Simulation Model

The simulation model has to be designed in a way that allows us to simulate different layout categories. We, for instance, have to simulate a parallel RTG-based layout with transfer lanes and a perpendicular RMG-based yard layout with transfer points. In consequence, we need a generic stack implementation that provides the functionalities of both, transfer lanes and transfer points.

Figure 8.1 shows a UML[1] diagram which illustrates the structure of the simula-

[1]For information about the Unified modeling language (UML) we refer to Booch et al. (2005)

tion model. We structured the simulation model by the main parts of the terminal (see Figure 8.1). The landside part is modeled by the gate through which external trucks enter the terminal to collect or deliver containers. A train connection is not considered in our simulation. The horizontal transport system consists of the horizontal means of transport (HMT) class and a control class (HTControl). The control class collects the transport jobs and assigns them to idle HMT. The movements of external trucks and HMT are modeled by calculating the distances between different positions in the terminal. Thus the different terminal elements (Gate, QC, etc.), to which a HMT or external truck has to travel, implement the position interface, which is used for the calculation of distances.

The seaside is modeled by a port entrance where the arrival of ships is simulated. We also model berths where the ships moor and QCs which operate at a berth. The central element of the yard is the stack where the containers are temporarily stored. Up to two YCs operate at a stack and each YC is always assigned to a single stack. Hence gantry moves to other storage blocks are not modeled in case of RTGs. The stack either has a transfer lane or transfer points for the transfer of containers between HMT and YCs. YCs are either RTGs or RMGs and the dispatching of stacking jobs is done by the stack control object.

8.1.2. Simulation Features and Limitations

As described in Chapter 2 several processes take place at a container terminal. In this section we describe which elements of the terminal operations are modeled and which parts are neglected in the simulation.

The first process we simulate at the seaside is the mooring of vessels. The arrival of ships is given by the scenario which is simulated and we assume that arrival times are known. After a ship is moored at a berth the unloading process starts. During the unloading process the QCs assigned to the berth begin to unload the containers from the ship. When all containers have been unloaded the charging of the ship starts. The unloading and loading processes proceed sequentially, not simultaneously. That is, the loading of a ship starts only when all QCs finished the unloading of containers. For the loading of containers we consider a fixed load sequence. In this case a QC has to wait for the container that is scheduled next. Interchanges of containers in the sequence are not considered in our simulation. The QCs are modeled as standard QCs with a single trolley and standard spreader that can lift a single container (see Section 2.2.1).

A further simulated process is the transport of containers from the quayside to the yard and vice versa. Accordingly, the horizontal means of transport are used. After a QC has unloaded a container onto a HMT, the HMT conveys the container to a stack. The driving times for the HMT are derived from the calculated distances considering the travel speed of the equipment. Acceleration and deceleration of HMT is not modeled in the simulation; nor do we distinguish between travel speeds for loaded or unloaded HMT. The distance is calculated considering the corresponding layout structure and available driving lanes. Driving lanes are not explicitly modeled in the simulation: they are only considered for the distance calculation. In consequence we do not model delays for HMT at driving lanes due to, e.g. traffic jams. Nevertheless, to consider stochastic driving times of the HMT we alter the driving times calculated by a random time which we assume to be triangularly distributed.

The yard processes are concerned with the operations of the yard cranes. The movements of the YCs are modeled as gantry, lifting, letdown and trolley movements; the latter are either done concurrently with the gantry movements in case of RMGs or sequentially in the case of RTGs. The letdown and lifting movements are modeled using a triangular distribution. The position of a container in the stack is recorded by the assigned ground slots on which the container is stacked. The exact vertical position of the container in the concrete pile is not recorded. Consequently we do not simulate rehandles as we do not know which containers are stacked on other containers. We thus assume that every container can be retrieved directly from the stack without rehandling other containers. The probabilities of rehandles should be similar for the compared layouts of the same category, as the probabilities depend mainly on the average stacking height (available TGS), implemented stacking strategy, and data accuracy. We assume therefore that rehandles can be neglected for the analysis in this chapter. Nevertheless, the trolley and gantry movements of the crane for simple storages and retrievals of containers without rehandles are simulated accurately as the ground slot is recorded. Therefore the gantry and trolley times depend on the actual position of the YC at the stack and the final position of the corresponding stacking job. As with the HMT movements we derive the gantry and trolley times from the calculated distances; acceleration and deceleration are not considered. Nor do we distinguish between travel speeds for loaded or unloaded YCs. For simplification we assume that the average distance to the transfer lane or to the transfer points corresponds to the width of one row or the length of one bay. Containers are stacked only in a bay with available capacity. When no capacity is available, the container is still stacked in the yard so that the simulation can be continued. A storage that exceeds the capacity is counted as over-storage in the statistical evaluation.

As mentioned in Section 2.2, several container types are available. In the simulation, however, we only consider standard twenty-foot containers and reefer containers. Empty and forty-foot containers, for instance, are not modeled. The difference between standard and reefer containers is that reefer containers can only be stored in the reefer racks of a block. For all other tasks reefer containers are treated similarly to standard containers.

The final process modeled in the simulation is the service of external trucks. External trucks arrive at the gate and travel to a stack at which they have to deliver or collect a container. At the stack the external truck is serviced by a YC similar to an HMT. After an external truck has been serviced, it leaves the terminal again through the gate.

8.1.3. Control Algorithms Used in the Simulation

During the simulation of the container terminal operations several logistic problems have to be solved. An overview of these problems is given in Section 2.3.1. In this section the implemented procedures to control the terminal operations during the simulation are described. As we do not focus on the evaluation of solution procedures for the different decision problems but on the suitability of layout categories for specific situations, we mainly use simple greedy approaches in our simulation model to solve decision problems arising. Nevertheless, the solution procedures obviously influence the performance of the terminal system. We have therefore implemented different approaches for important decisions like the dispatching of the YCs to be able to evaluate the influence of the solution procedures.

A first problem is the assignment of arriving vessels and feeders to berths. We use a simple first-come, first-served procedure that assigns vessels in order of their arrival to the first berth available. For the assignment of berths we do not consider preferred berths for a specific vessel or feeder. If all berths are occupied, newly arriving ships have to wait in the port entrance until a berth becomes available.

For the yard management we make all decisions in real-time using a procedure similar to that described in Petering and Murty (2009), which tries to distribute the current and expected future workload among the stacks. A similar procedure is also described in Section 4.2.1, but there are some differences. When preferred berths are considered, export containers can be placed in stacks that are somewhat close to the preferred berth to avoid long travel distances for HMT. As we do not consider preferred berths for vessels and feeders, we do not distinguish between import and export containers for the assignment of storage blocks. The implemented assignment procedure is illustrated in Figure 8.2. First of all, a set of blocks is built which contains all blocks of the yard that have remaining capacity for the corresponding type of container. When no capacity is available, all blocks capable of storing containers of the needed type are considered. Among the blocks in the set, the container is assigned to the block with the lowest total workload, which is a weighted combination of the expected and current workload.

The current workload of a stack is defined by the number of HMT and external trucks that are currently traveling to this stack or are currently waiting at the stack. For the expected workload of a stack the expected departure time of the container to be stored is calculated. Thus the expected workload is computed by the number of containers that have an expected departure time similar to that of the container for storage. For import containers (which are collected by trucks) the expected departure time is hard to determine as the truck arrivals are mostly unknown (see Dekker et al. 2006). We simply calculate the expected departure times for import containers by adding the average dwell time to the arrival time. In contrast, for transhipment or export containers the expected departure time is calculated using the known arrival times of the vessels and feeders. Due to the data inaccuracy of the expected departure times, we count all containers with an expected departure time similar to the expected departure of the container to be stored, for the calculation of the expected workload. Containers have a similar expected departure if the expected departure time lies in a given time period defined around the departure time of the container to be stored.

Where a layout is simulated for scenarios with different transhipment rates, the effect occurs that for higher transhipment rates the information detail about the expected departure times becomes increasingly accurate as fewer import containers have to be handled at the terminal. Thus the expected workload can be calculated in a more accurately way when more transhipment containers are handled at a terminal.

The assignment of containers to storage slots within the assigned block is conducted randomly. We use a random procedure to ensure that the whole block is used for stacking and not just a part of it, especially in cases of low use of the storage space. If the randomly generated bay has no free capacity, a new one is computed until a free bay is found or the random generation has been conducted as often as the block has bays. When no free bay is found a random bay is selected and the storage is counted as over-storage. Again, the container type is considered when generating the slot position. Thus only reefer racks are considered as valid storage positions for reefer containers. A second implementation of the slot assignment works similarly to the procedure just described. The difference is that the second procedure tries to store export or transhipment containers next to the seaside end of the block and import containers next to the landside end. Clearly this procedure is only applicable for a perpendicular yard layout with transfer

```
input  : S: Set of stacks in the yard, t: container
output : Stack b to store container t
foreach s ∈ S do
    if s has free capacity for t then
        F ← F ∪ s;
    end if
end foreach
if F = ∅ then
    over-storage ← over-storage +1;
    foreach s ∈ S do
        if s has the ability to store containers of the type of container t then
            F ← F ∪ s;
        end if
    end foreach
end if
b ← ∅;
bVal ← ∞;
foreach f ∈ F do
    if bVal > ExpectedWorkload(f,ExpectedDeparture(t)) ×w +
    CurrentWorkload(f) ×(1 − w) then
        b ← f;
        bVal ← ExpectedWorkload(f,ExpectedDeparture(t)) ×w +
        CurrentWorkload(f) ×(1 − w);
    end if
end foreach
return b;
```

Figure 8.2.: Assignment of arriving containers to a stack

points. The first procedure is called random assignment and the second split random assignment.

The dispatching of transport jobs to available HMT is implemented similarly to the system described in Section 4.2.1 (see also Petering and Murty 2009). The trucks are all centrally controlled by a single control class and are not assigned to a specific berth or QC. Once a HMT becomes idle the control class assigns the most urgent transport job to the idle HMT. To choose the most urgent transport job we use a system which stores all unassigned transport jobs distinguishing the corresponding QCs. The most urgent transport job is that corresponding to the QC which has waited longest for the assignment of a HMT to a job.

For the dispatching of stacking and retrieval jobs to the YCs we have implemented two procedures: one which prioritizes retrievals of seaside containers to support the loading process of QCs and the other without such priorities. Both procedures have to distinguish the cases in which one or two cranes operate at the same stack. We call the procedure without priorities the YCS1 procedure and the procedure with priorities of seaside retrievals the YCS2 procedure. When two YCs operate on a block in a perpendicular layout, we distinguish in the following between the seaside and landside YC: For the cross-over RMGs system the seaside crane is the larger and the landside crane the smaller. For the twin RMG system the seaside crane is that which can reach the seaside end of the block.

The YCS1 is a first-come, first-served procedure. That is, the earliest job is assigned to the next available YC. If two YCs that can cross each other are available, we assign the nearest crane to the earliest job. In case that two YCs are available that cannot cross each other, we assign the earliest job to the seaside or landside crane depending on the type of job.

The YCS2 procedure is a priority rule-based algorithm which is similar to that proposed in Petering et al. (2008). Some differences occur, however, as in Petering et al. (2008) no external trucks are serviced. Moreover, we have to consider the case in which two cranes operate at a single block. In this case we have to decide which of the cranes is assigned to a job. Figure 8.3 illustrates the dispatching algorithm YCS2. In case of a single crane, the YCS2 procedure assigns the most urgent seaside retrieval; otherwise the nearest seaside storage to the YC. When no seaside job exists, the nearest landside storage or retrieval is assigned to the YC. The nearest storage or retrieval job is that which has the shortest gantry distance for the YC. The most urgent job is that with the closest due date. The due date of a retrieval job is calculated based on the expected loading time of the needed container by a QC and the expected travel time for the HMT between the stack and the corresponding QC.

Where two YCs operate on a stack and they are not able to cross each other, we have to distinguish which YC is able to perform the next job. It is possible to consider a buffer area (see Stahlbock and Voß 2010) in which containers between the landside and the seaside YCs can be exchanged. Using a buffer area allows the spilt up of a job into two consecutive moves performed by both YCs (see Saanen and Valkengoed 2005). We do not consider the possibility of splitting up a job in two consecutive moves and assume that a job (retrieval or storage) is completed by only one YC. Therefore the seaside YC can only be used for seaside jobs and the landside YC only for landside jobs. Thus the most urgent seaside retrieval or otherwise the nearest seaside storage is assigned to the seaside YC. Correspondingly, the nearest landside storage or retrieval is assigned to the landside YC (see Figure 8.3).

In situations where a new job is assigned to a stack and both YCs are idle the YCS2 procedure works as follows: When the YCs can cross each other the

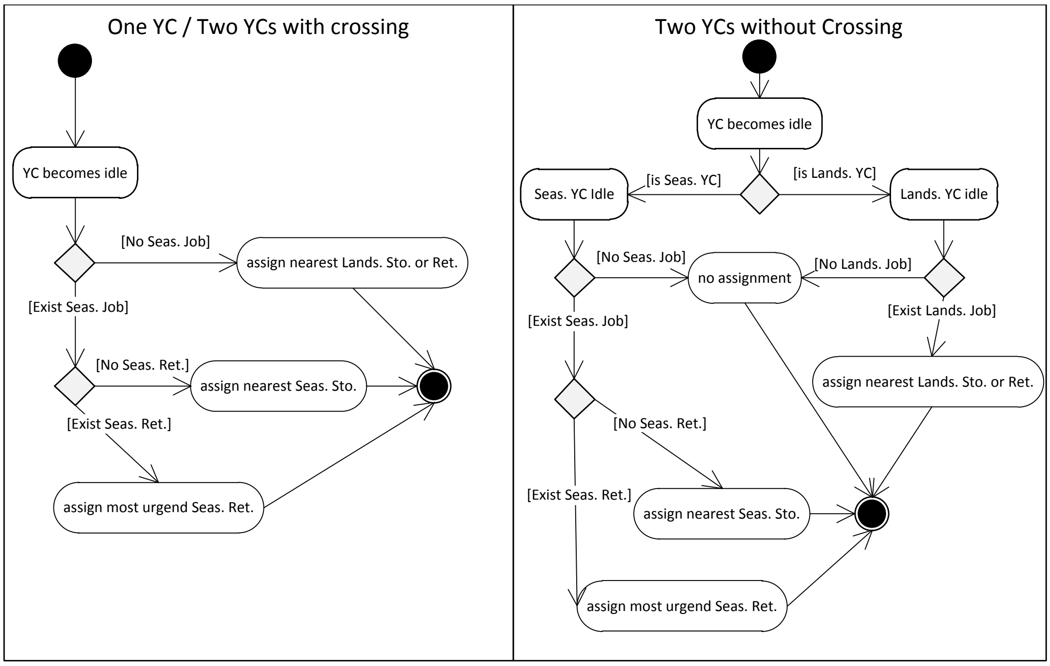


Figure 8.3.: Dispatching procedures YCS2 considering due dates

most urgent seaside retrieval is assigned to the seaside YC, otherwise the nearest seaside storage is assigned to the landside or seaside YC. For the calculation of the nearest seaside storage the distances for both cranes are considered. If no seaside job is available, the nearest landside storage or retrieval is assigned to the YC with the shortest distance. When the YCs cannot cross each other and both cranes are idle, we first try to assign a seaside job to the seaside crane and afterwards landside jobs to the landside crane. In summary, the YCS2 procedure prioritizes seaside retrievals over seaside storages and seaside jobs over landside jobs.

During the operation of two YCs on a single block two types of conflict are considered in our simulation model as illustrated in Figure 8.4: one for YCs of the same size and one for YCs of a different size. Conflicts for cranes of the same size can occur when a YC wants to enter the area behind the other YC. Figure 8.4(a) shows an example in which the landside YC performs a gantry move in the seaside direction and the seaside crane has to gantry to the marked gray slot. This situation obviously leads to a conflict. This is resolved as follows: the YC which starts its gantry move first finishes its gantry move and the other YC waits until the blocking YC moves away. In the example of Figure 8.4(a) the seaside crane waits at the black line for the landside crane to finish its move.

Conflicts of two cranes of differing size are considered in the case where the two cranes need to cross each other and the larger seaside crane cannot move its

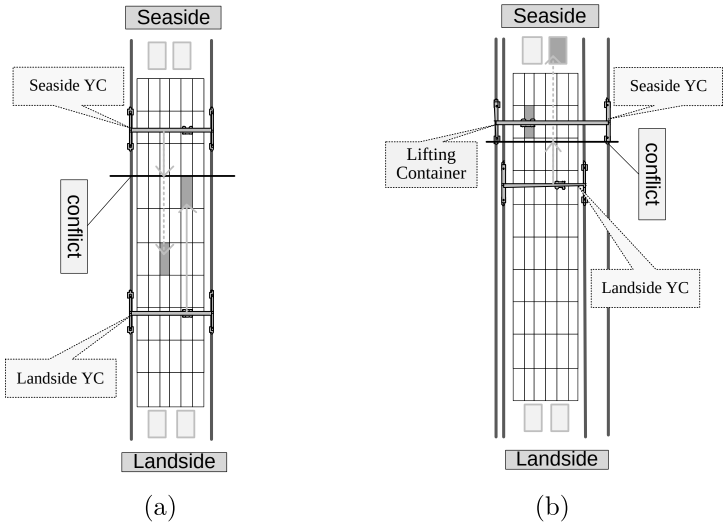


Figure 8.4.: Possible conflicts during the operation of two YCs on a single stack, distinguishing YCs with crossing ability (b) and without (a)

trolley to the rightmost position in time. The example in Figure 8.4(b) illustrates a conflict which occurs when the larger seaside crane is lifting a container and the smaller landside crane needs to get to a position behind the current position of the larger crane. To consider these conflicts we calculate the expected point at which both cranes have to cross each other. No conflict occurs if the time needed for the landside crane to perform a gantry travel to this position is greater than the time needed by the seaside crane to move its trolley to the rightmost position. Where the gantry time is smaller than the trolley time, we simply add the additional time needed to move the trolley in the rightmost position to the gantry times of both moving cranes. Another type of conflict occurs when two YCs operate within a safety clearance (see Stahlbock and Voß 2010). However, conflicts due to safety clearances are not considered in our simulation model.

8.2. Simulated Layout Configurations

In this section we describe the layout categories and configurations which we consider for the study in this chapter. We discuss parallel RTG-based layouts with transfer lanes and perpendicular RMG-based layouts with transfer points. Both layout categories are illustrated in Figure 2.12 in Chapter 2. In addition we consider different possible crane configurations for the perpendicular layouts as described in Section 2.2.3. The first configuration is a system with a single RMG per block, and the second is a system with two RMGs of the same size and

Table 8.1.: Different layout configurations

	Block Length		Block Width		#Blocks	Term. Length	#Tiers	Capacity
	#Bays	meter	#Rows	meter		(meter)		(TEUs)
1RMG	39	253.5	11	32.5	16	600	4	27456
1RMG-W8	43	279.5	8	25.0	20	600	4	27520
2RMG	39	253.5	11	32.5	16	600	4	27456
2RMGs-Cr	48	253.5	11	40.5	13	600	4	27456
1RTG	42	273.0	6	23.0	24	600	4	24192

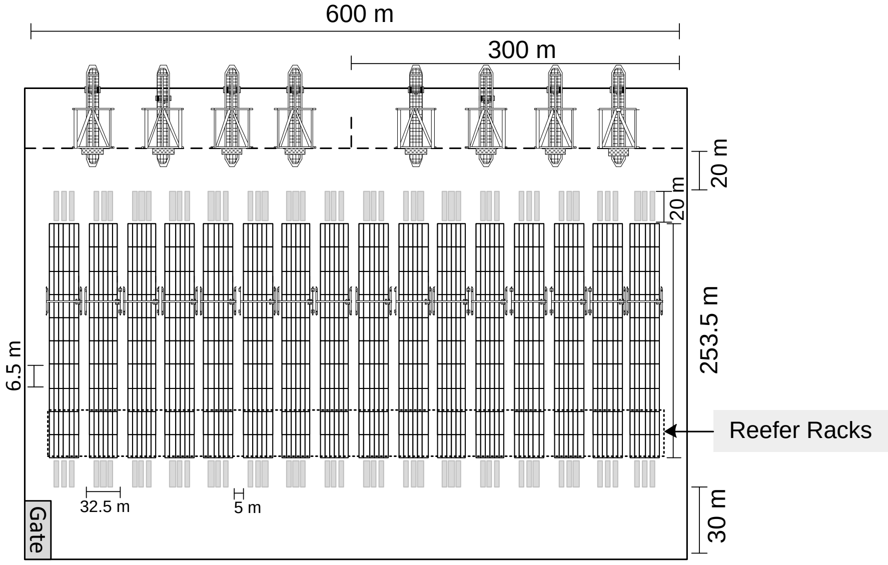


Figure 8.5.: Basic perpendicular yard layout with transfer points

both operating on identical rail tracks (twin RMGs). The third configuration is a system with two RMGs of different size which operate on independent rail tracks (cross-over RMGs). A system with three cranes is not considered in this chapter. In total we consider five different layout configurations: four for the perpendicular RMG-based layouts with transfer points and one for the parallel RTG-based layouts with transfer lanes. Table 8.1 summarizes the different layout configurations considered in the simulation study.

For the layouts considered we assume in the following that a bay has a length of 6.5 m and a row a width of 2.5 m. We assume a container terminal with two berths each of which has a length of 300 m. For all layouts we assume that eight QCs are used, of which four are assigned to a berth. We assume a fixed position of QCs calculated by distributing them equally over the berth.

The basic terminal layout configuration considered for the perpendicular yard layout is shown in Figure 8.5. The distance between the QCs and the start of the yard is assumed to be 20 m. For the configuration depicted in Figure 8.5 we assume that a block has 11 rows, which leads to a block width of 32.5 m (including 2.5 m for each rail track). We also assume a distance between two blocks of 5 m. Consequently a total of 16 blocks fit into the assumed yard length of 600 m. The length of the blocks is assumed to be 253.5 m with a total of 39 bays. Among the 39 bays the last four bays are assumed to contain reefer racks (see Figure 8.5). We assume a length of the transfer points of 20 m. Assuming a maximal stacking height of four tiers, the storage capacity of the yard is 27456 TEUs. In the following this configuration is denoted by 1RMG.

In addition to the configuration depicted in Figure 8.5 we consider a modification of this layout configuration in which we alter the block widths and lengths to a configuration with eight rows, 43 bays (279.5 m) of which five are reefer racks. This configuration leads to a total of 20 blocks with a capacity of 27520 TEUs. In the following we refer to this configuration as 1RMG-W8.

For the configurations with two YCs we distinguish that with twin-RMGs denoted by 2RMG and the cross-over RMG configuration denoted by 2RMG-Cr. The 2RMG configuration uses a layout configuration identical with the 1RMG layout. However, in case of the cross-over RMG system the layout configuration is different as we regard additional space needed for the extra rail tracks of the larger seaside crane (see Figure 2.5). For these additional rail tracks we assume a width of 8 m. Due to this additional space, the overall width of the blocks changes to 40.5 m and only 13 blocks fit into the yard. To achieve a similar storage capacity we change the number of bays to 48 including five bays for reefer racks. This leads to a total capacity of 27456 TEUs.

Figure 8.6 shows the basic terminal layout for the parallel yard layout with transfer lanes. The length of a block is 273 m each having 42 bays, six rows and four tiers. The combination of two blocks each with a transfer lane (4 m) to a module with one bypass lane (4 m) leads to an overall width of a module of 50 m considering 2 m for each yard crane track. Six modules fit into the depth of the yard of 310 m when a space between two modules of 2 m is considered. Thus the yard contains a total of 12 modules and 24 blocks[2]. Overall this leads to a yard capacity of 24192 TEUs. Moreover, we assume that the two blocks at the bottom of the yard solely contain reefer racks (see Figure 8.6). In the following this configuration is denoted by 1RTG.

[2]Please note that for simplification only eight modules are shown in Figure 8.6.

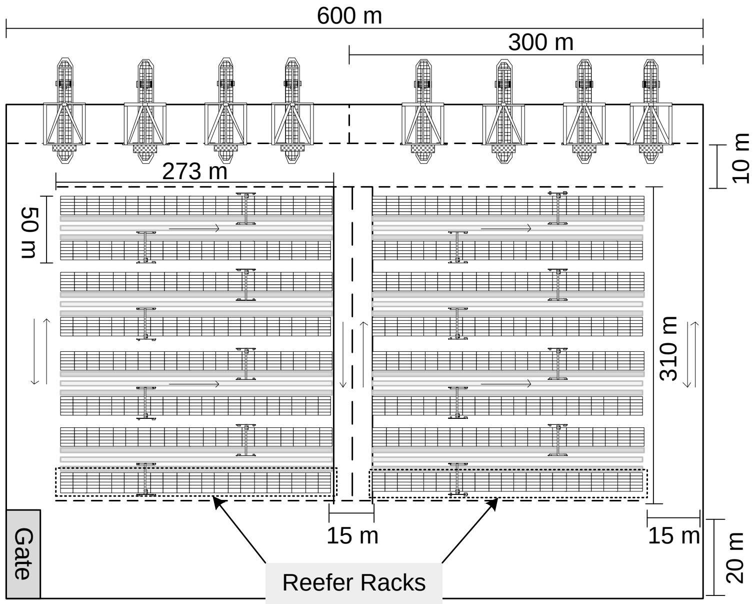


Figure 8.6.: Basic parallel yard layout with transfer points

8.3. Scenarios

As in Chapter 4, we use an implementation of the scenario generator proposed by Hartmann (2004b) for the generation of different scenarios. In this section we describe the different scenarios used for the study in this chapter. Accordingly, we briefly discuss the functionality of the scenario generator which is needed to understand this chapter. For details of the generator we refer to Hartmann (2004b).

The generator can be configured using several input parameters such as the number of containers arriving by the different means of transport, the modal split[3], and the dwell time. The ratios of different types of container can be defined (e.g., the ratio of reefer containers) and the time span when specific means of transport arrive. From the given data the generator computes arrival times for vessels, feeders and trucks[4] and data on the containers that are delivered by or picked up by the corresponding means of transport. Thus the flow of containers through the seaside and landside interfaces of the terminal is defined in advance by a scenario.

For the generation of the scenarios we aim at achieving a similar workload for the storage yard for all scenarios within a group. A group of scenarios consists of those with the same assumed target workload (number of block moves) and the

[3]For each mode of transport the modal split defines the distribution of the containers arriving (e.g., by vessels) among the respective modes of transport for pickup.
[4]Trains are not considered in this study.

Table 8.2.: Scenarios with different transhipment ratios

						Arriving Containers			∅ Containers per Day	
Scenario	D	D-T	B-Mov.	Trans.	Reef.	Vessel	Feeder	Truck	Arriving	Leaving
R5-T0-E	21	3.1	5760	0%	5%	22680	7560	30240	2880.0	2370.1
R5-T25-E	21	3.1	5760	25%	5%	28350	9450	22680	2880.0	2327.9
R5-T50-E	21	3.1	5760	50%	5%	34020	11340	15120	2880.0	2317.6
R5-T75-E	21	3.1	5760	75%	5%	39690	13230	7560	2880.0	2342.4
R5-T100-E	21	3.1	5760	100%	5%	45360	15120	0	2880.0	2257.2
R20-T0-E	21	3.1	5760	0%	20%	22680	7560	30240	2880.0	2370.1
R20-T25-E	21	3.1	5760	25%	20%	28350	9450	22680	2880.0	2327.9
R20-T50-E	21	3.1	5760	50%	20%	34020	11340	15120	2880.0	2317.6
R20-T75-E	21	3.1	5760	75%	20%	39690	13230	7560	2880.0	2342.4
R20-T100-E	21	3.1	5760	100%	20%	45360	15120	0	2880.0	2257.2
R5-T0-H	21	3.1	8640	0%	5%	34020	11340	45360	4320.0	3539.1
R5-T25-H	21	3.1	8640	25%	5%	42525	14175	34020	4320.0	3545.3
R5-T50-H	21	3.1	8640	50%	5%	51030	17010	22680	4320.0	3524.9
R5-T75-H	21	3.1	8640	75%	5%	59535	19845	11340	4320.0	3528.5
R5-T100-H	21	3.1	8640	100%	5%	68040	22680	0	4320.0	3447.5

same reefer rate. We therefore construct the scenarios in a way that ensures a similar number of storages or retrievals at the blocks in the yard during one day. From this assumed number of block moves, we calculate the numbers of containers arriving per vessel, feeder, or truck depending on the assumed transhipment ratio. We define the transhipment ratio as the proportion of containers that arrives at the seaside and depart from the seaside to the total number of containers arriving at the seaside. From this procedure we generate different scenario groups. In total we consider three scenario groups each having five scenarios with different transhipment rates.

For each assumed scenario we generate 30 distinct instances. Details of the scenarios considered can be found in Table 8.2. Column D-T shows the average dwell-time in days, B-Mov the assumed number of block moves per day, Trans. the transhipment ratio, and Reef. the reefer ratio. These values and also those of the arriving containers are input parameters for the generator. The average numbers of containers arriving or leaving per day in Table 8.2 show average values of the 30 instances. The accuracy of the output is at a sufficient level. For instance, the transhipment rate for the R5-T25-E instances is on average 25.003%. Two scenario groups have a yard workload of 5760 block moves per day, where one group has a reefer rate of 5% and the other a high reefer rate of 20%. The third scenario group has again a reefer rate of 5% but a higher yard workload of 8640 block moves per day.

As shown in Table 8.2 the average number of containers arriving is higher than

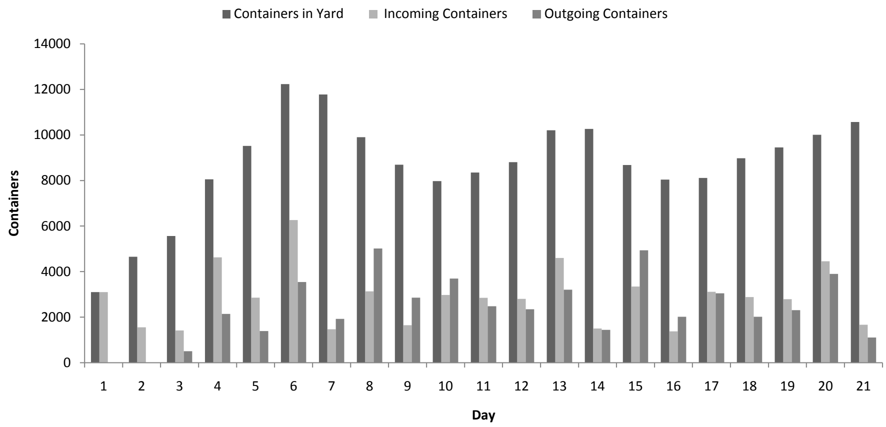


Figure 8.7.: Daily container flows of one instance of the scenario R5-T25-E

the average number of containers leaving, since on the first days of the horizon no container leaves the terminal. Figure 8.7 illustrates the flow of containers as well as the resulting number of containers in the yard for one instance of scenario R5-T25-E. The first containers leave the terminal on day three. During days one and two of the horizon containers arrive at the terminal but none departs, which is due to the dwell time configuration of 3.1 days on average. The yard fills up in the first week, and the first decrease in the number of containers in the yard occurs on day seven. We therefore use the first week as warm-up for the simulation and start to collect data on day eight. When we consider the horizon in which data is collected (day eight to day 21), the average number of leaving containers is 2885 for the instance shown in Figure 8.7.

Figure 8.8 exemplifies the arrivals per day of vessels, feeders and trucks of one instance of the scenario R5-T25-E. During days two and seven of a week only feeders and no vessels arrive. The rate of arrivals of feeders is quite constant, as on each day either four or five feeders arrive. A peak of truck arrivals occurs during the horizon on the first day of a week (days eight and fifteen). The arrival patterns[5] which are definable for each mode of transport (see Hartmann 2004b) are set equally for all different scenarios. Therefore the arrivals of other scenarios have a pattern similar to that illustrated in Figure 8.8.

[5]The arrival patterns define for each mode of transport the distribution of the arrivals over a week. These values are defined by the fraction of the arrivals of a mode of transport per day.

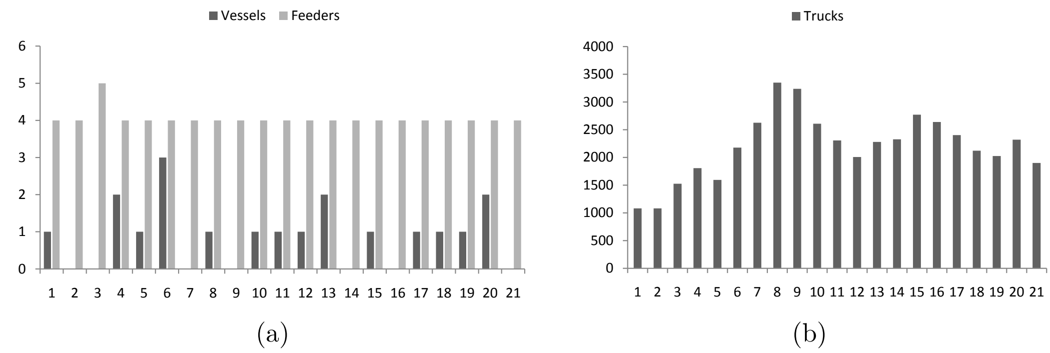


Figure 8.8.: Arrivals of the different modes of transport for one instance of scenario R5-T25-E: (a) arrivals of vessels and feeders per day, (b) arrivals of trucks per day

8.4. Simulation Results

The simulation model described in Section 8.1 has been used to simulate the different layout configurations and scenarios described in Sections 8.2 and 8.3. In this section the results of the simulation study are discussed. The structure of this section is as follows: Section 8.4.1 gives an overview of the combinations of layouts, parameter values and control algorithms simulated. Section 8.4.2 shows the results for the perpendicular RMG-based layouts with transfer points and Section 8.4.3 the results for the parallel RTG-based layouts with transfer lanes. Section 8.4.4 summarizes the results with respect to the adequacy of special layout categories for certain scenarios.

8.4.1. Overview of Different Simulated Settings

In this section the basic parameter settings used in the simulation model are described. The handling times of a QC are modeled as a triangular distribution with an average of 60 seconds, a maximal time of 90 seconds, and a minimal time of 30 seconds (30, 60, 90). In addition, the time needed for a QC to place a container onto a horizontal means of transport or to take a container from a HMT is assumed to be uniformly distributed between five and ten seconds. This leads to an average time of 67.5 seconds per QC move, which defines a maximal possible QCR of about 53.3 moves.

For the movements of the crane we assume an average gantry speed of 3 meters per second and an average speed of 1 meter per second for the trolley movements. The times for lifting a container in the stack or from a HMT and the time for lowering a container are both assumed to be triangularily distributed. The times

Table 8.3.: Overview of the different settings which are simulated

		Layout				
Scenarios	Algorithms	1RMG-W8	1RMG	2RMG	2RMG-Cr	1RTG
R5-T0…100-E	YCS1	•	•	•	•	•
R20-T0…100-E	YCS1		•	•	•	•
R5-T0…100-H	YCS1	•	•	•	•	•
R5-T0…100-E	YCS2		•	•	•	•
R20-T0…100-E	YCS2		•	•	•	•
R5-T0…100-H	YCS2		•	•	•	•
R5-T0…100-E	YCS2/Split		•	•	•	

for lowering are (13, 20, 30) seconds and the times for lifting are (13, 20, 30) seconds.

We need two parameters for the algorithm to assign containers to a stack depicted in Figure 8.2: one which defines the range in which containers are assumed to have the same expected departure time, and the parameter w which is used to weight the expected and the current workload. The range is defined as 15 minutes before and after the expected departure time and the weight w is set to a value of 0.5.

For the calculation of the driving times of HMT we use a triangular distribution for which the average and minimum value of the distribution is set to the driving time calculated based on the actual distances. To use stochastic driving times we set the maximal value of the triangular distribution to the average driving time plus 5%. The mooring process of ships is defined as triangular distribution with (4, 5, 6) minutes. For the HMT (and external trucks) we assume an average travel speed of 6 meters per second. For the basic parameter setting we assume that 24 HMT are available for the horizontal transport of containers.

Table 8.3 shows the different settings, i.e. combinations of different scenarios, layouts and control algorithms which are simulated. In total 145 different settings are simulated each with 30 independent runs, which leads to a total number of 4350 simulation runs. The column "Algorithms" shows which algorithm is used for the YC dispatching and the assignment of storage slots. The entry "Split" indicates that the split random assignment is used for the storage slot assignment (see Section 8.1.3), in all other cases the random assignment is used.

The results for the different simulation runs are presented in the next sections. During the simulation of a scenario we record several performance measures for the evaluation. More details on the performance measures can be found in Appendix B.1. In the following sections an overview of the main results is presented which focuses on the main performance measures. The detailed results for all performance measures can be found in Appendix B.2.

8.4.2. Results for the Perpendicular RMG-Based Layouts with Transfer Points

In this section the results for the different layout configurations for the perpendicular RMG-based layouts are given. The aim of the study in this chapter is to analyze the suitability of certain yard layout categories for different scenarios. We thus focus on the change in the yard performance for the different scenarios within a scenario group. Accordingly, we compare the stack moves per hour (StaMov) and the average gantry time of a crane per movement (AVG-GanT). The influence of the yard performance on the quay crane rate (QCR) and the turnaround time of external trucks (Truck-TAT) is discussed afterwards. For more details on the performance measures we refer to Appendix B.1.

Figure 8.9 shows the results for the scenario group with a reefer rate of 5% and 5760 block moves a day (R5-T0…100-E). The error bars show the confidence intervals for the average values with an approximately 95% confidence (see Law 2007, p. 495). The results for the yard performance for the layout with eight rows and a single crane (1RMG-W8) show a tendency in the average gantry times to decrease for higher transhipment rates. The stack moves increase accordingly for higher transhipment rates. Similar behavior can be observed from the results of the other layout with a single RMG and 11 rows (1RMG). A possible explanation for the decreasing gantry times for higher transhipment rates is that 95% of the containers (the standard containers) have to be stored in the block range without reefer racks. In case of high transhipment rates most containers are stored in the block from the seaside end of the block as well as retrieved from the seaside end. This might lead to shorter movements within the standard container area of a block (see Figure 8.5). In contrast, long movements occur when reefer containers have to be stacked from the seaside end. For low transhipment rates, however, both sides of the block have to be serviced and containers have to be moved across the reefer racks. Another possible effect of low transhipment rates on the average gantry times is the following: where a landside storage follows a seaside retrieval (or vice versa), the crane has to move empty from one side of the block to the other. These side changes occur more often in the case of low transhipment rates. This might lead to the higher empty travel times for lower transhipment rates (see Table B.3 in Appendix B.2). The results might change when a different control algorithm is used for the YC dispatching.

As to the effect of the yard operations on the landside or seaside performance

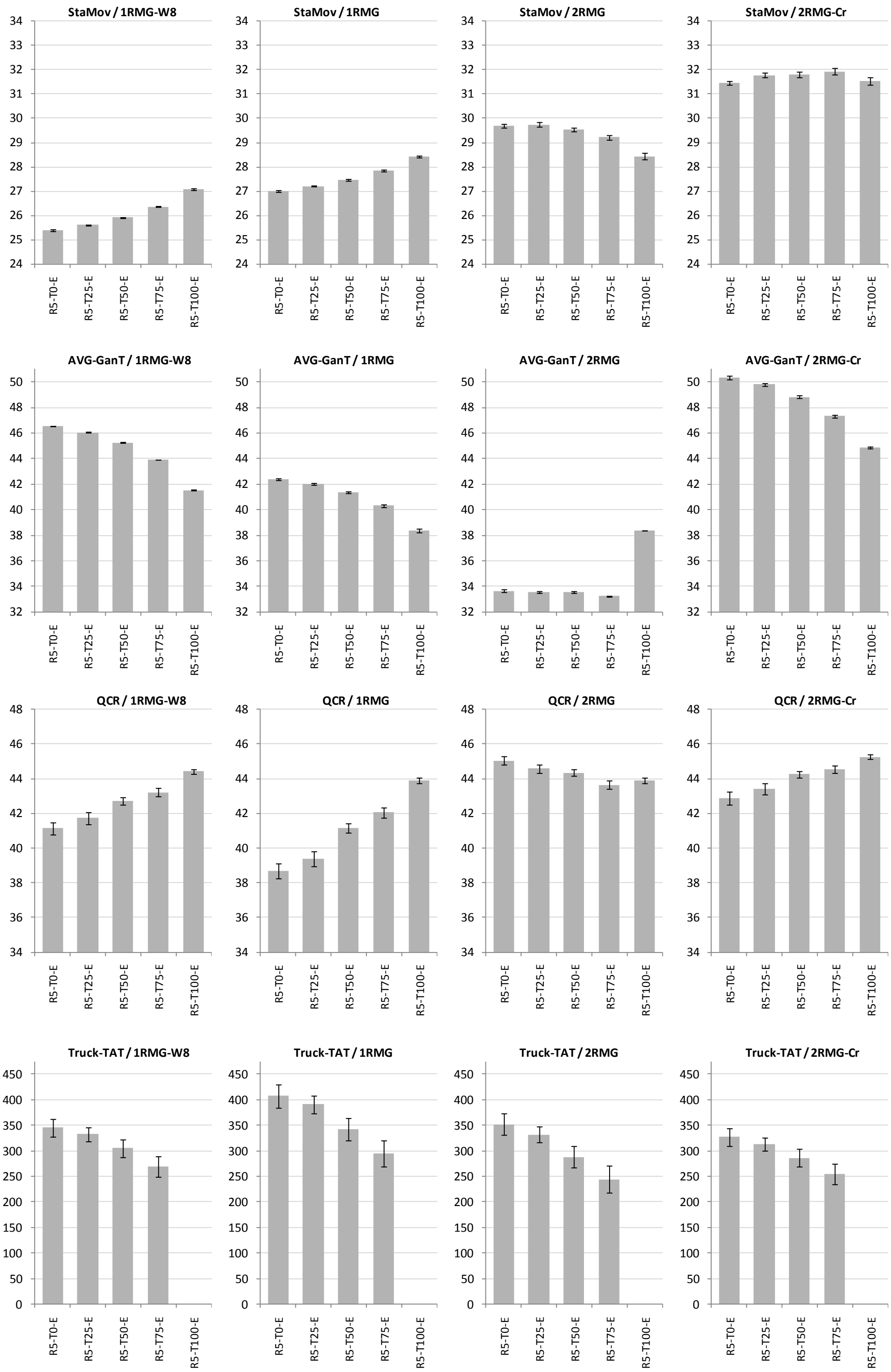


Figure 8.9.: Results for different RMG layouts for the scenarios with a reefer rate of 5% using the YCS1 procedure assuming 5760 block moves per day

it has to be noted that there are several other factors that influence these performances. For instance, the seaside performance might get worse due to bottlenecks in the horizontal transport system. When the transhipment rate increases the workload for the horizontal transport system increases as more containers arrive at and depart from the seaside. Moreover, in the case of import/export terminals a trade-off between the priority of seaside and landside moves of YCs can lead to a higher QCR at the expense of higher turnaround times of external trucks. In a pure transhipment terminal there is no such a trade-off and the whole block performance can be used to facilitate the seaside processes. Furthermore, we assume that the arrival times of vessels are known, whereas the arrival times of external trucks are not known in detail. As described above, this leads to a more accurate calculation of the expected workload and also influences the overall system performance. In consequence, it is hard to isolate the effects of the yard performance on the sea- and landside performance. Nevertheless, we discuss the results for the landside performance (truck turnaround time) and seaside performance (QCR) in the following.

The results in Figure 8.9 for the 1RMG layouts show that the QCR increases for higher transhipment rates, whereas the turnaround time of external trucks decreases. As just mentioned, one reason might be the higher stack moves in the case of higher transhipment rates. This impact of the yard performance, however, cannot be isolated. The results for the layout 1RMG and 1RMG-W8 also show that the layout 1RMG-W8 achieves a higher QCR and lower truck turnaround times for all scenarios. These results are consistent with the results presented in Chapter 6.

In the case of the layouts with two RMGs per block the results change. As shown in Figure 8.9 the stack moves decrease with higher transhipment rates for the 2RMG layout. In particular the results for the pure transhipment scenario (R5-T100-E) are identical with the results for the 1RMG configuration, which means that the second crane does not improve the performance at all. This is obvious, as we assume that the landside crane can only perform landside jobs and does not support the seaside crane (see Section 8.1.3). Thus the landside crane is not used in the case of a pure transhipment setting. As the block is split by the two cranes the average gantry time for each crane is lower than that of the layout with one crane (1RMG). The effect of the yard performance on the QCR is smaller than that of the 1RMG results. However, the highest QCR is achieved for the pure import/export scenario (R5-T0-E). The truck turnaround times again decrease for lower transhipment rates.

For the 2RMG-Cr layout the number of stack moves is similar for each scenario, even though the average gantry times differ. Accordingly, the average gantry time seems not greatly to affect the stack moves in the case of the 2RMG-Cr layout. Perhaps the yard cranes have to wait for HMT to deliver or collect containers. We have not, however, simulated scenarios with different numbers of HMT and thus could not verify this assumption. As with all other layout configurations, the average truck turnaround times decreases for higher transhipment ratios. Moreover, the QCR increases for higher transhipment rates. As mentioned above, the effect of the yard performance on the sea and landside performance cannot be isolated. Thus the changes in the QCR and in the Truck-TAT are due to different effects that also occur in the other layout configurations. For instance, in the case of a pure transhipment terminal every block move supports the seaside process, whereas with import/export settings seaside moves might be delayed due to a landside move. This is obviously a natural effect that occurs with different transhipment rates and does not allow any statement about the adequacy of a layout for certain scenarios.

Comparing the results for the 2RMG and the 2RMG-Cr configuration it can be observed that the 2RMG layout outperforms the 2RMG-Cr layout for the import/export scenarios R5-T0-E and R5-T25-E with respect to the QCR and truck turnaround times. In these scenarios the drawback of the 2RMG-Cr configuration that it needs additional space for the rail tracks of the bigger crane becomes noticeable. In consequence fewer blocks fit into the yard than on the 2RMG configuration (see Section 8.2). Thus in the case of import/export scenarios the workload seems to be better distributed among the cranes of the 2RMG configuration.

In summary, the different transhipment rates affect yard performance of each considered layout configuration. These impacts, however, might be different for other scenario groups. The results for the scenarios with a higher workload of 8640 block moves per day and an identical reefer rate of 5% are shown by Figure 8.10. Results similar to the effects just described occur, however, with a higher intensity due to the higher workload in the system. For instance, the difference between the QCR of scenario R5-T0-H and R5-T100-H is 10.69 moves, whereas the difference between the QCR of R5-T0-E and R5-T100-E is 5.2 moves.

Figure 8.11 shows the results for the scenario group with 5760 block moves and a higher reefer rate of 20% (R20-T0...100-E) together with the results for the scenario group with a reefer rate of 5% (R5-T0...100-E). The results show the effect discussed above: in case of transhipment terminals long moves are needed to store reefer containers. For instance, in the case of the 1RMG layout the average gantry times increase slightly for higher transhipment rates which leads to a slightly decreasing number of stack moves. Nevertheless, the QCR increases for higher transhipment rates. This increase, however, is lower as in case of a

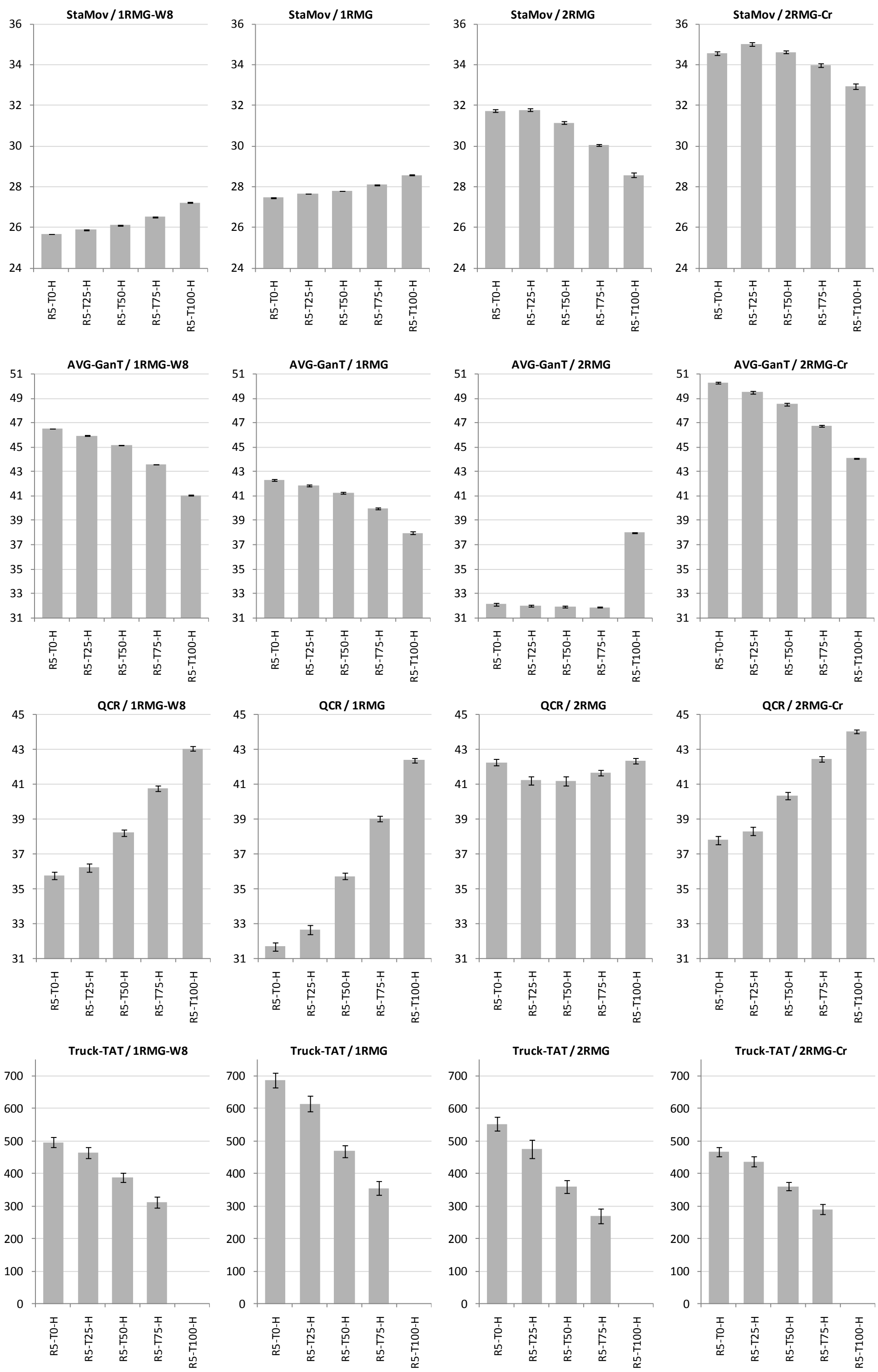


Figure 8.10.: Results for different RMG layouts for the scenarios with a reefer rate of 5% using the YCS1 procedure assuming 8640 block moves per day

reefer rate of 5%. Overall, the results in Figure 8.11 show that the performance of all considered systems is worse in the case of a higher reefer rate. Only the truck turnaround time is lower in the case of a higher reefer rate. A possible explanation is that the retrieval of a reefer container at the seaside induces a long gantry travel, whereas the retrieval of a reefer container at the landside causes a short gantry travel. Thus the average truck turnaround time reduces compared to the results for the scenarios with a reefer rate of 5%. Again, the longer gantry travel distances for reefer containers occur under the assumption that the reefer racks are situated at the end of each storage block. Another distribution with a higher concentration of the reefer racks at fewer blocks might allow shorter gantry distances for the reefer containers, but on the other hand limit the ability to distribute the workload (see also Section 6.2.1). Moreover, a change of the positions of racks within the block could have an impact on the performance.

Figure 8.12 gives the results for the different RMG layout configurations for scenarios R5-T0. . . 100-E comparing the YCS1 procedure with the YCS2 procedure. The influence of the transhipment rate on the yard performance is similar to that described above for the R5-T0. . . 100-E scenarios using the YCS1 procedure. Nevertheless, the results show that there are small differences between the YCS1 and the YCS2 procedures concerning yard performance. For all layout configurations and scenarios the YCS2 procedure achieves lower or at least equal average gantry times. Moreover, despite the results for the R5-T100-E scenario in case of the 2RMG-Cr layout, all stack moves are slightly higher or at least equal under the YCS2 than the YCS1 procedure.

For the operational problem of YCs dispatching, the results in Figure 8.12 show that the prioritization of the seaside retrievals leads to a higher QCR for all layout configurations and scenarios. The large improvements of the QCR in the case of the 1RMG layout for the R5-T0-E scenario can be achieved due to the low prioritization of landside jobs, which leads to high truck turnaround times. In the case of the 2RMG-Cr layout the increase of the QCR for the R5-T0-E scenario can be achieved with just a slight increase of the truck turnaround times. The results for the YCS2 procedure for the other scenarios (R20-T0. . . 100-E, R5-T0. . . 100-H) can be found in Appendix B.2.

Figure 8.13 shows the results of the scenario group (R5-T0. . . 100-E) using the YCS2 procedure and comparing the two different slot assignment strategies, namely the random assignment (denoted by YCS2) and the split random assignment (denoted by YCS2/Split). It is obvious that the split assignment achieves a much higher yard performance in the case of transhipment terminals, as in this case mainly the first half of the block is used for stacking. The other half is only used for stacking when the first half has reached capacity. Thus with

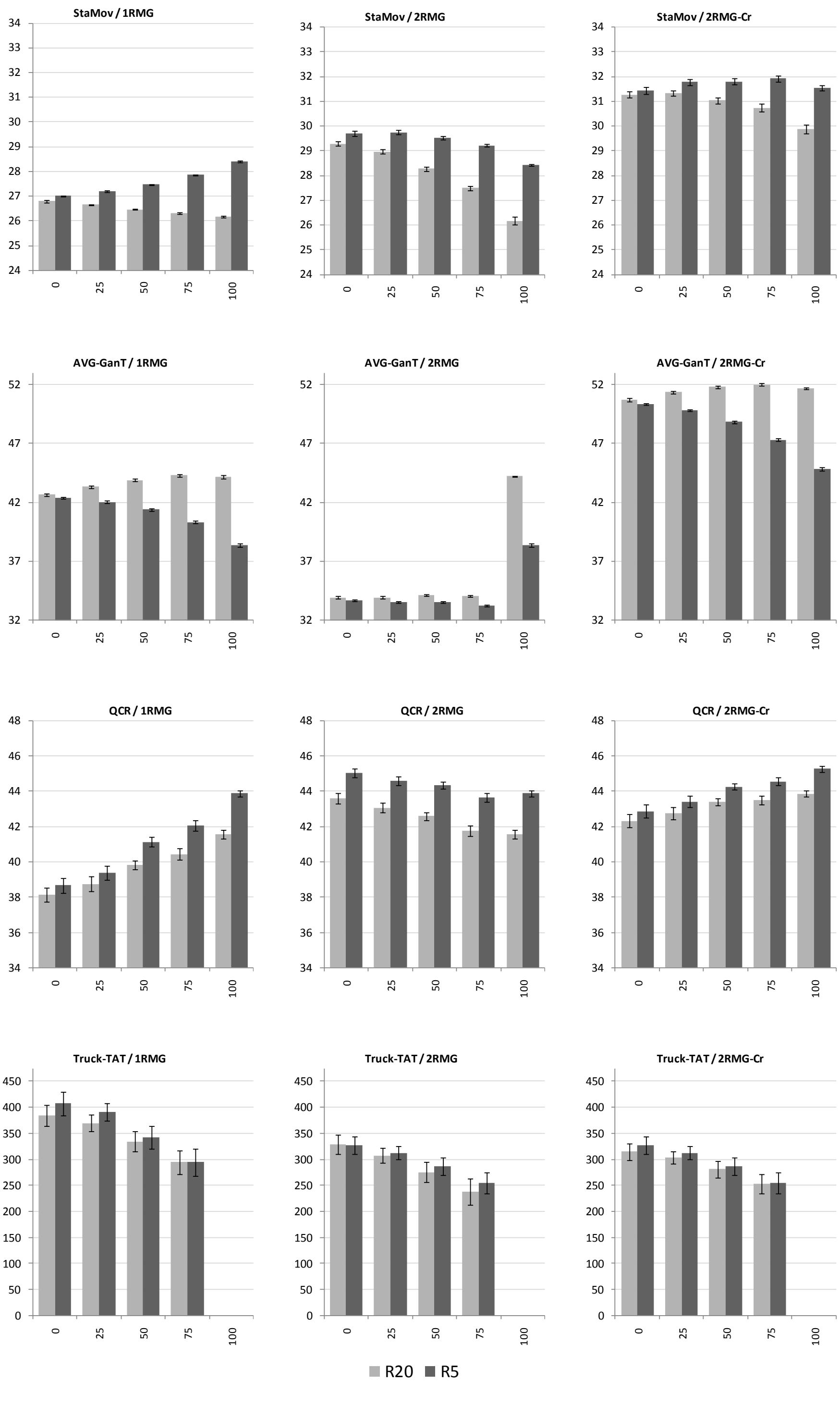


Figure 8.11.: Results for different RMG layouts for the scenarios with a reefer rate of 20% (R20) and for the scenarios with a reefer rate of 5% (R5) using the YCS1 procedure assuming 5760 block moves per day

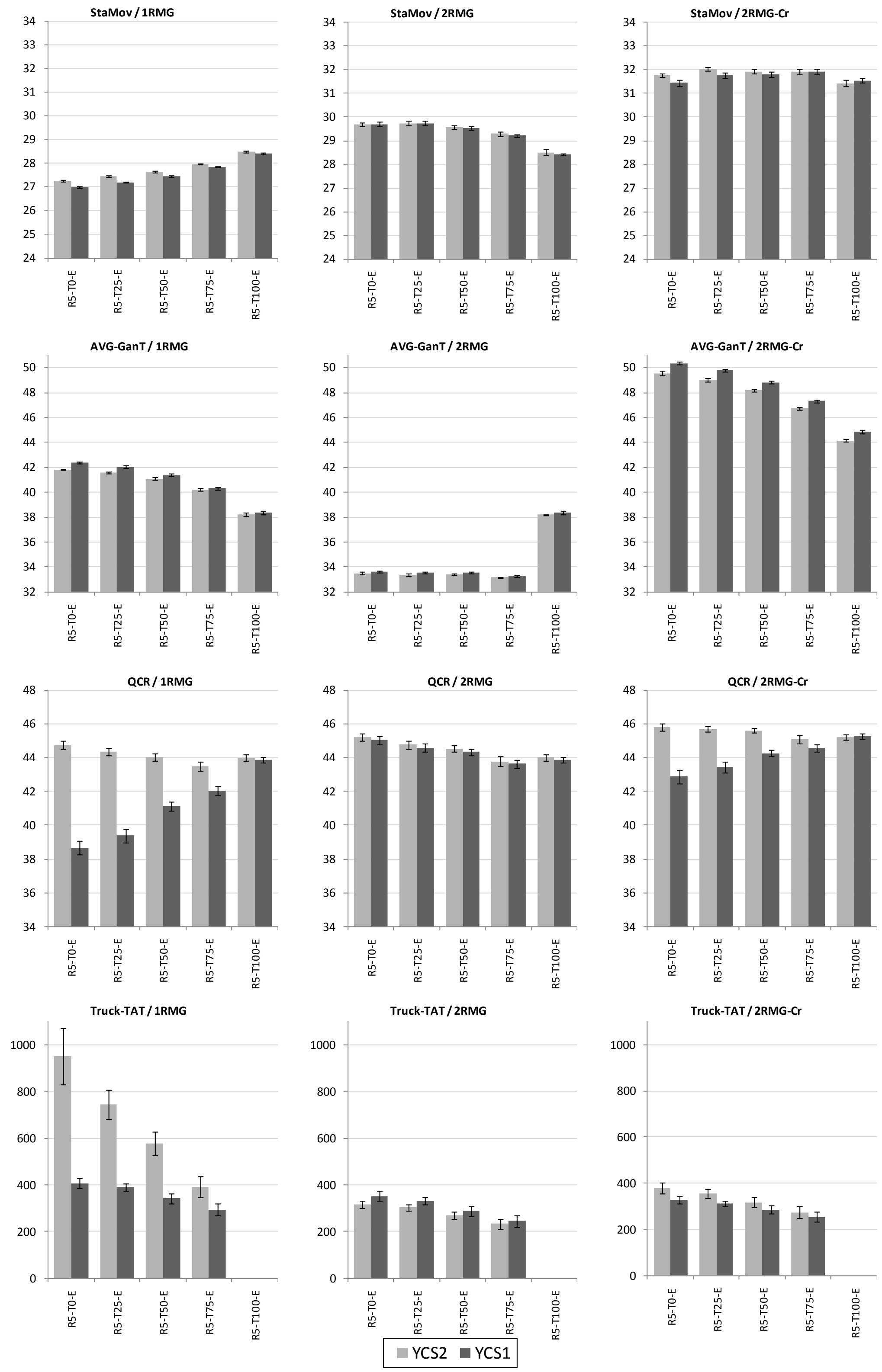


Figure 8.12.: Results for different RMG layouts for the scenario with a reefer rate of 5% using the YCS1 or YCS2 procedure assuming 5760 block moves per day

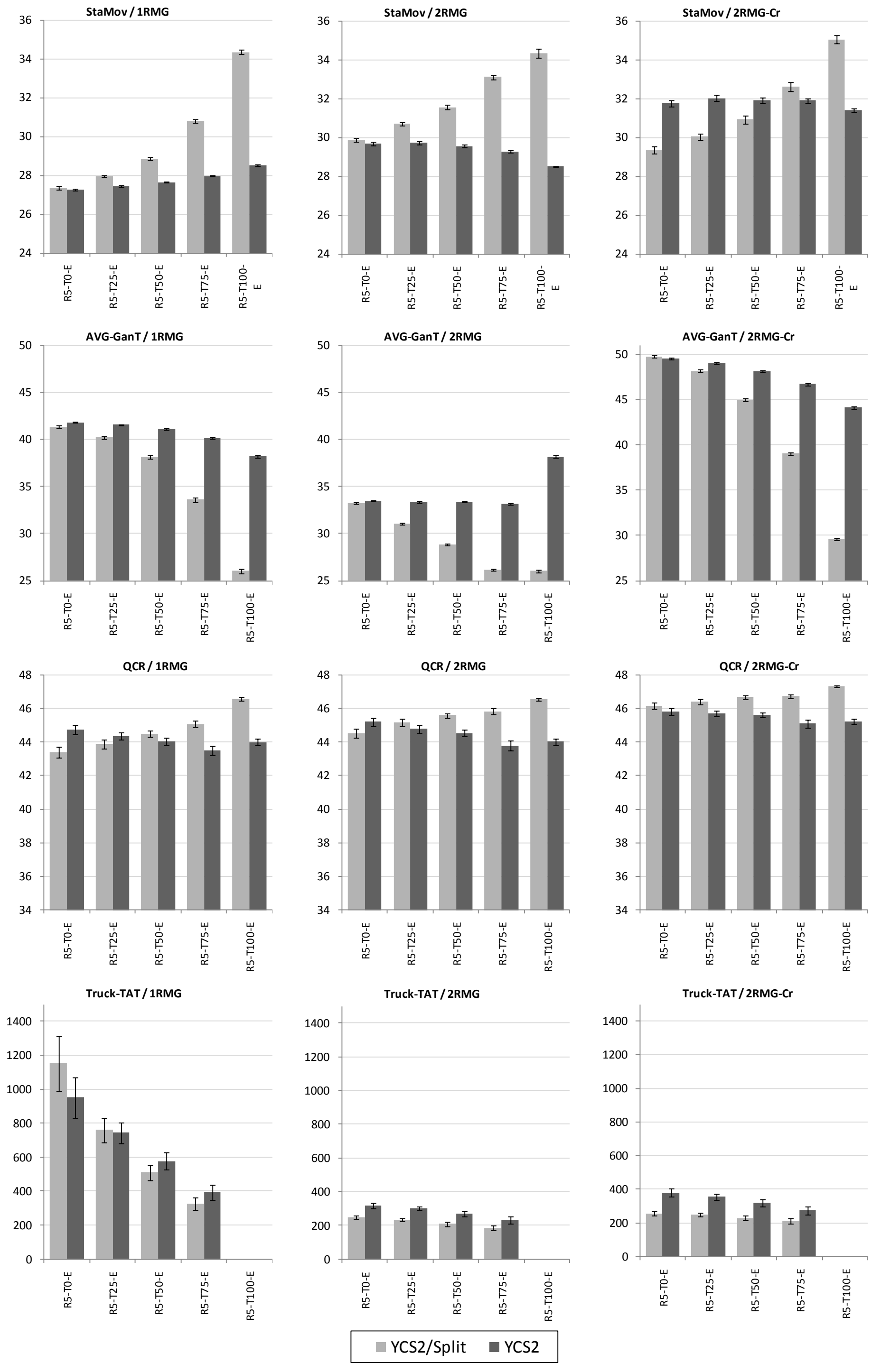


Figure 8.13.: Results for different RMG layouts for the scenario with a reefer rate of 5% using the YCS2 procedure with the random or the split random assignment of storage slots assuming 5760 block moves per day

high transhipment rates a high reduction of the average gantry times can be observed (see Figure 8.13). With the YCS2/Split procedure, most scenarios and layouts which have lower average gantry times achieve a higher number of stack moves. Concerning the 2RMG-Cr layout the lower or equal gantry time leads to a reduction of the stack moves. Nevertheless, in the case of the split random assignment the QCRs are higher and the truck turnaround times are lower for all scenarios than with the random assignment. This might be due to the decrease in the number of conflicts and of the blocked time in the case of the split random assignment (see Table B.3).

Concerning the operational question of where to store incoming export, import or transhipment containers, the results can be interpreted in the following way: Transhipment containers should be positioned at the seaside end to achieve short gantry distances, as they are stored and retrieved from this end. For import and export containers no such clear statement can be given. In the case of the 1RMG layout the split assignment leads to lower QCRs and higher truck turnaround times for the scenarios with a high rate of import and export containers (R5-T0...25-E). This might be due to the long distances of gantry travel which occur when an arriving import container has to be stored at the landside end or an arriving export container at the seaside end. During these time-consuming movements of the crane, a newly assigned job with a higher priority might have to wait (e.g., a seaside retrieval). Nevertheless, the differences between the spilt random assignment and the random assignment for the R5-T25-E scenario are quite small, especially in case of the truck turnaround times. For the 2RMG layout in the case of the R5-T0-E scenario with the split random assignment the QCR is lower than with the standard random assignment, despite lower blocked times and number of conflicts (see Table B.3). The truck turnaround time, however, is lower in the case of the split random assignment. For the 2RMG-Cr layout the split random assignment achieves a higher QCR and lower truck turnaround times for all scenarios. In summary, these results might indicate that in the case of two YCs which can cross each other import containers should primarily be stored at the landside end of the block and export containers primarily at the seaside end. This finding should, however, be validated in further simulation studies which for example also consider the impact of housekeeping.

8.4.3. Results for the Parallel RTG-Based Layouts with Transfer Lanes

Figure 8.14 shows the results for the RTG-based layout concerning both YC dispatching procedures (YCS1 and YCS2) and the scenarios with a reefer rate

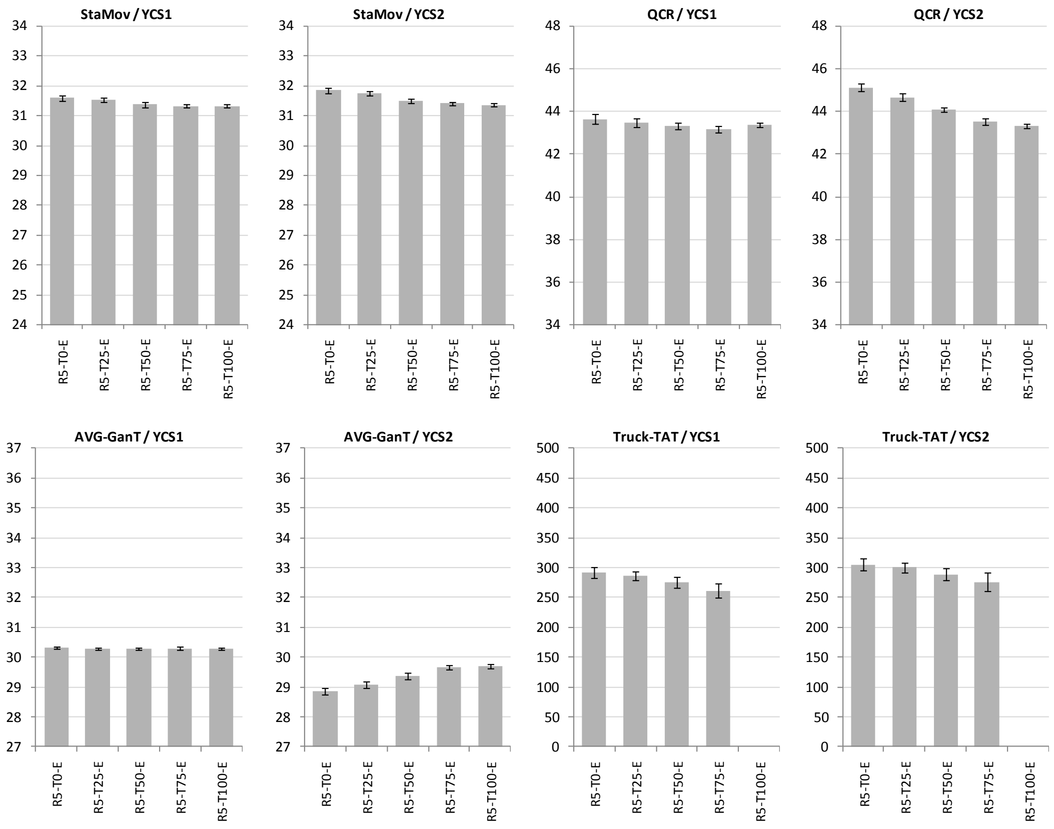


Figure 8.14.: Results for the RTG layout for the scenario with a reefer rate of 5% using the YCS1 or YCS2 procedure assuming 5760 block moves per day

of 5%. The results show that in the case of YCS1 the average gantry times and the number of stack moves are on an identical level for all scenarios. Moreover, the different QCRs are quite similar. Only the truck turnaround times show some small differences. This behavior changes with the YCS2 procedure. The scenarios with lower transhipment rates achieve slightly lower average gantry times and higher stack moves values. Concerning the seaside and landside performance the YCS2 procedure leads to increased turnaround times of trucks and achieves therefore a higher QCR.

Figure 8.15 shows the results for the RTG-based layout concerning the scenarios with a high yard workload. The results are similar to those in Figure 8.14 for the scenario group with a lower workload. The average gantry times are similar for all scenarios. The results for stack moves, however, differ from those results for the scenario group with a lower workload. The number of stack moves decreases with higher transhipment rates. A possible explanation is the greater use of the horizontal transport system in the case of higher transhipment rates. This might lead to waiting or idle times for the YCs and QCs, as they have to wait for an

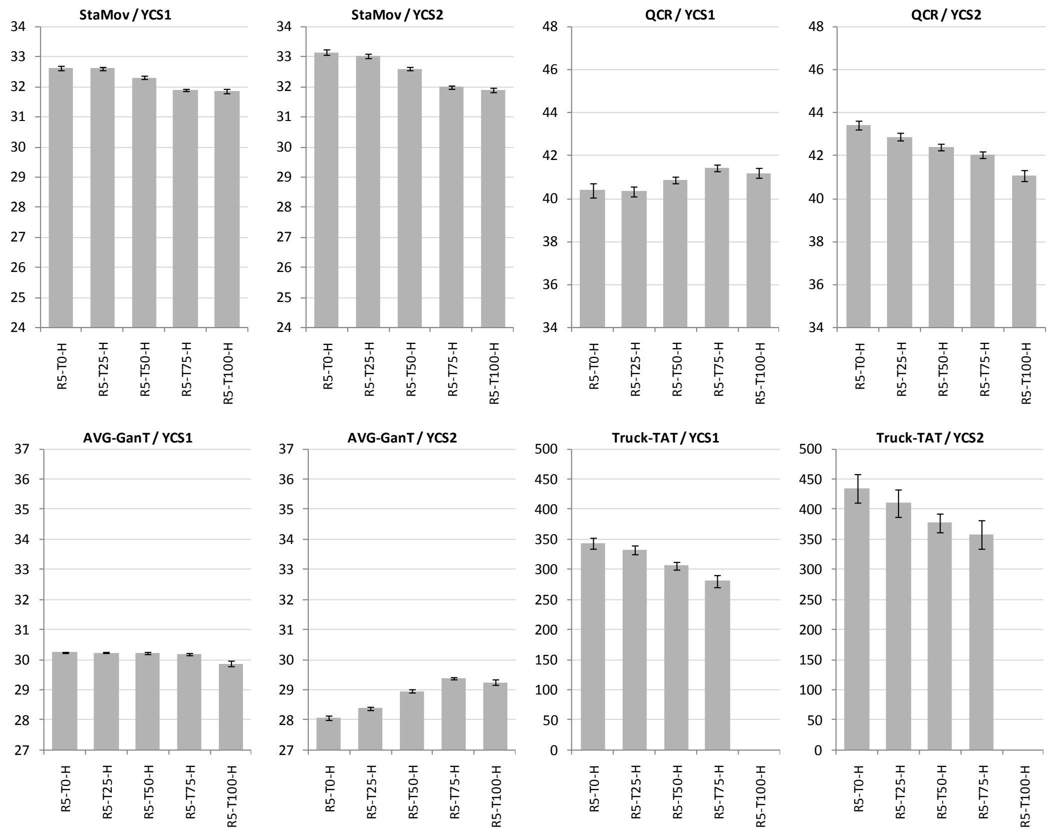


Figure 8.15.: Results for the RTG layout for the scenario with a reefer rate of 5% using the YCS1 or YCS2 procedure assuming 8640 block moves per day

arrival of the HMT. For instance, for the R5-T100-H scenario the YC idle times are higher than is the case for the other scenarios and the occupancy of the HMT is higher (see Table B.6 and Table B.7).

Figure 8.16 shows the results for the scenarios with a high reefer rate of 20%. Again the results for the stack moves and the average gantry times are quite similar to those for the low and high yard workload scenario groups. The difference is that in the case of the scenarios with a high reefer rate the QCRs are lower and the truck turnaround times are higher than for both other scenario groups. This is obviously due to the two blocks equipped with reefer racks having a very high workload. Moreover, we do not consider gantry moves of YCs between different blocks. Thus the two YCs on the reefer blocks have to handle a high amount of the overall container traffic. This leads to blocked times for the QCs and to higher turnaround times for external trucks. The YCS2 procedure is again able to achieve higher QCRs by prioritizing the seaside jobs, which again leads to high turnaround times for external trucks.

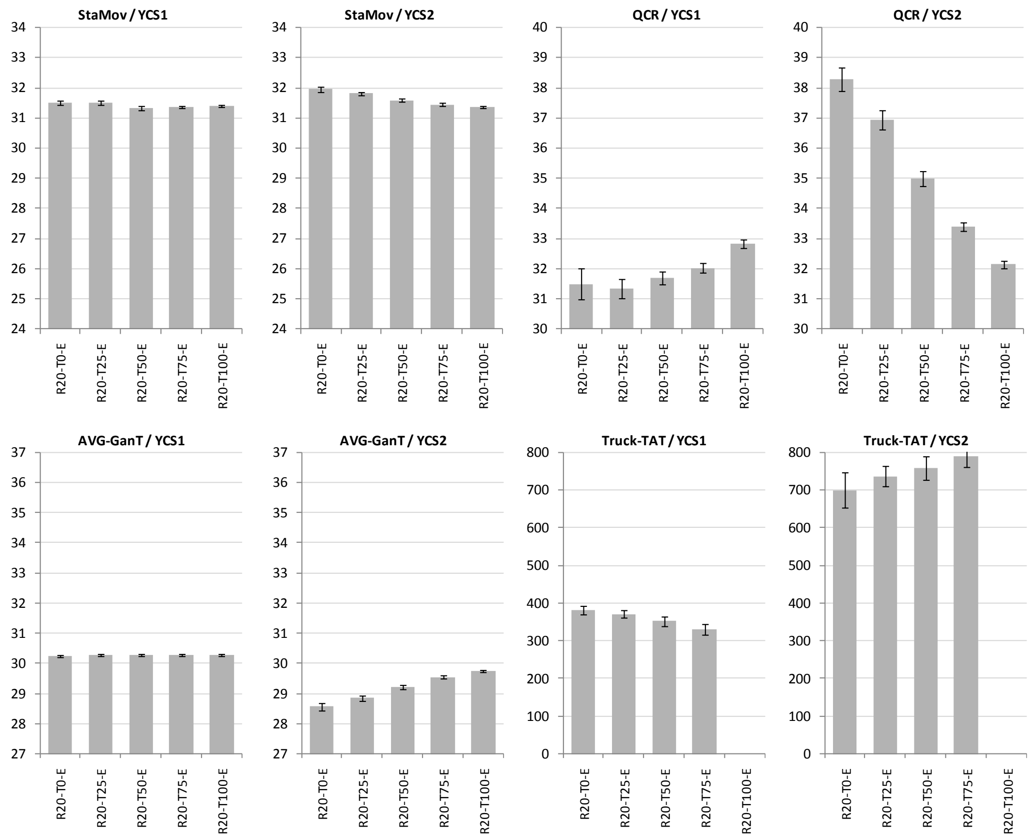


Figure 8.16.: Results for the RTG layout for the scenario with a reefer rate of 20% using the YCS1 or YCS2 procedure assuming 5760 block moves per day

8.4.4. Summary and Interpretation of the Results

It is important to be aware that the results presented above only hold on the given assumptions of the simulation model. Thus the results might change for instance when rehandles, acceleration and deceleration of equipment, and different travel speeds for loaded and unloaded equipment are considered.

The results for the RTG and RMG-based layouts are described individually in the sections above. The remaining question is whether, from the results, conclusions about the adequacy of certain layouts for specific scenarios can be drawn. Comparing the results for the RMG and the RTG-based layouts the following observations can be made: the RTG layout has more stable results with respect to QCR, truck turnaround time, stack moves and average gantry times for the scenarios with different transhipment rates in contrast to the values observed for the RMG layouts. The RMG layouts show higher differences in the above-mentioned values for the scenarios with different transhipment rates. Moreover, the results indicate that the control algorithms used also influence the results. Thus it might be useful to design algorithms specific to the individual layout configuration and to likely scenarios. Such specialized algorithms might improve the results for certain layouts in specific situations.

The results show that most layout configurations are adequate for all scenarios, especially when the control algorithms are designed for the individual situation. An exception might be the 2RMG layout for high transhipment rates, as in this case the landside YC is useless given the underlying assumptions of our simulation model. This leads to a clear reduction in yard performance (average number of stack moves) for higher transhipment rates. In practice the landside crane can be used to support the operations of the seaside crane. Nevertheless, it is questionable whether this support will improve significantly performance. The results for the scenarios with a very high reefer rate of 20% show that the long storage moves in the case of transhipped reefer containers reduce performance. In this case another distribution of the reefer racks might achieve a better performance (see Section 8.4.2). The same can be observed for the RTG-based layout. In summary, the results show that the parallel RTG-based layouts are more robust to changes in the transhipment rate than perpendicular RMG-based layouts. Nevertheless, it cannot be concluded that one of the two considered terminal layout categories is not in general adequate for a specific scenario.

In addition to the analysis of the adequacy of layout categories for certain transhipment scenarios, the simulation results were used to compare several layout configurations. For instance, the results for the different crane configurations or the different block widths have been compared. The results show that the layout configuration with smaller block widths (allowing more blocks within the yard width) but longer blocks achieves a higher QCR and lower truck turnaround times than does the configuration with wider blocks.

Comparison of the different crane configurations suggests that the systems with two cranes secures greater improvement in terminal performance with respect to the QCR and truck turnaround times than does a system with a single RMG for most scenarios. Which is the better system, a twin RMG or a cross-over RMG system, depends on the scenario considered. The drawback of the cross-over RMG system is that it needs additional space for the additional rail tracks, leading to fewer blocks in the yard. The advantage of crossing, however, becomes noticeable in the case of high transhipment rates. For the scenarios with high transhipment rates the terminal performance is higher for the cross-over RMG system in most cases (for instance, see results in Figure 8.9). In the case of low transhipment rates, the twin RMG system can distribute the workload more easily to both available cranes making the advantage of crossing less attractive. By contrast, with high transhipment rates the workload has mainly to be handled by the seaside crane, which leads to poorer performance in most cases. Consequently, the expected transhipment rate influences the decision on which crane system to use. In practice, however, it should be considered that even for moderate long-term transhipment ratios there might be peak phases in which a lot of seaside traffic has to be handled. In such cases the cross-over RMG system can again make use of its crossing abilities.

8.5. Summary

In this chapter we presented a simulation study in which we have analyzed the adequacy of two layout categories, namely parallel RTG-based layouts with transfer lanes and perpendicular RMG-based layouts with transfer points, for different scenarios. We have considered different scenario groups in which all scenarios have a similar workload for the storage yard with varying transhipment rates. Thus we aimed to analyze the performance differences for a specific layout category in different transhipment scenarios. For this analysis we have proposed a simulation model which is capable of simulating different layout categories for different transhipment scenarios. Using the simulation model we have conducted a study with 4350 simulated instances. The results showed that most layouts achieve an adequate performance for all different transhipment scenarios. An exception is the perpendicular layout with twin RMGs (2RMG), where the performance of the YCs reduces with higher transhipment rates. Overall, the results for the parallel RTG-based layouts are more robust to changing transhipment rates than the perpendicular RMG-based layouts. Nevertheless, we have not been able to identify a layout category in general that is not adequate for a scenario.

The results show that some effects are not yet considered in our simulation study. The effect of different numbers of HMT deployed and different distributions of reefer racks, for instance, could be analyzed in a further simulation study. Moreover, the simulation model could be extended to a more realistic environment by considering, for instance, acceleration and deceleration as well as different travel speeds for loaded and unloaded equipment.

9. Summary and Conclusion

In this thesis we addressed the problem of layout planning of container terminals. The main research objective of this thesis was in particular to extend the basis of existing operations research methods which are concerned with decision support for container terminal layout planning problems. Designing the layout is a crucial step in the construction phase of a terminal as the layout directly affects performance.

In Chapter 2 we introduced the processes and equipment of a container terminal and described the layout planning problem. We also identified the yard layout planning problem, which is concerned with the layout planning of the storage yard. A storage yard can be categorized according to the stacking equipment used and the transfer options. The following three main yard layout categories were identified: the RTG-based layout with transfer lanes, the RMG-based layout with transfer points, and the SC-based layout with direct transfer. We consequently distinguished three yard layout problems common to the three categories.

The literature review in Chapter 3 showed that there are already approaches related to the layout planning of container terminals. We reviewed these approaches and classified them according to the yard layout category and the options considered in the approach. An overview of the existing approaches showed that there are still remaining topics where operations research methods provide useful help in planning a container terminal layout. Thus we developed the following summarized research objectives of the thesis: to develop novel analytic approaches for the layout design considering the three different yard layout categories; to analyze the adequacy of different layout categories for different transhipment scenarios; and to analyze the influence of the positions of storage areas for non-standard containers on the terminal performance.

In Chapter 4 we analyzed the influence of the positions of storage areas for non-standard containers on terminal performance. We proposed a new mixed-integer program which is based on models for the facility layout problem, to optimize the block positions within a given terminal area. To assess the influence of the block positions on the terminal performance we developed a simulation model. The simulation model was used to simulate different layouts found by the mixed-integer program. The results showed that the block positions affect terminal performance, especially the distances traveled by the horizontal transport equipment. Nevertheless, handmade layout solutions which have been constructed using rules of thumbs achieved quite competitive results.

Chapters 5, 6 and 7 addressed the objective to develop new approaches for the three different layout categories. In Chapter 5 we dealt with RTG-based layouts with transfer lanes. For this layout category two approaches were proposed: The first treated the problem of finding optimal block lengths, or more precisely finding an optimal number of driving lanes and their positions in the storage yard. A new integer program was proposed for rectangular yards. It can be shown that the linear relaxation of the program has at least one optimal integer solution. For non-rectangularly shaped yards the model is non-linear, and we therefore proposed a special variable neighborhood descent heuristic. The results showed that this heuristic is able to achieve competitive results. The second approach was devoted to the influence of different block widths on the terminal performance. This approach is based on estimates which can be used to determine approximately the terminal performance for different block widths. The method could be used to identify quickly promising block widths as shown by the numerical example presented in Chapter 5.

The problem of designing yard layouts with transfer points was addressed in Chapter 6. We proposed a new approach to plan perpendicular yards with transfer points, assuming that the width of the yard is limited. The depth of the yard, however, is assumed to be flexible. The model used approximate estimates for the average gantry distance of the yard cranes. Besides the design of the yard, the distribution of reefer racks over the yard was considered. The results showed that thinner but longer blocks lead to a higher overall performance of the yard than wider, but smaller blocks. In case of thinner blocks, more blocks fitted into the available width of the yard, which increased the potential to distribute the workload. However, these solutions also require more land and a higher number of cranes which in consequence lead to higher cost than that of a layout with wider blocks. Finally, we showed how a terminal planner can use the results of the model to identify promising perpendicular yard layout configurations.

In Chapter 7 we developed a new model to design straddle carrier-based storage yards with direct transfer. This model is based on approximate estimates of the different movements of straddle carriers within a terminal. Thus estimates have been derived for the horizontal and vertical movements of straddle carriers performing seaside cycles between the quay and the storage yard, for the movements of straddle carriers within a storage block, and for horizontal and vertical movements of straddle carriers performing landside cycles between a truck service area and the storage yard. The estimates were used for the definition of the objective function of a model which determines the optimal number of vertical and horizontal driving lanes within a yard. We presented numerical examples for different parameter values, comparing driving lane types, orientation options and driving strategies. The results showed that none of the options is clearly superior for all parameter values. In consequence, each option should be considered when planning a layout of a container terminal.

Finally, in Chapter 8 the adequacy of layout categories for certain scenarios was analyzed by means of simulation. The layout categories considered were parallel RTG-based layouts and perpendicular RMG-based layouts. Different scenario groups have been proposed with a similar workload for the yard for each scenario within a group. The transhipment rate, however, was changed for each scenario within a group. A simulation study was carried out in which different layouts of each considered layout category were simulated for the scenario groups. The results of the simulation study were used to analyze the adequacy of the layout categories for the scenarios. In brief, the results showed that most layouts of both layout categories achieved an adequate performance for all scenarios. The results showed, however, RTG-based layouts to be more robust to changing transhipment rates than the perpendicular RMG-based layouts.

In summary, the main research objective of this thesis, namely to extend the basis of operations research methods for the decision support of the layout design of container terminals has been achieved. We proposed new methods which can be used for the planning of storage yards considering each of the three main layout categories. Moreover, we studied the effect of the positions of storage areas for non-standard containers on the performance of a terminal and the adequacy of different layout categories for different scenarios.

In the following we want to suggest topics for future research in the field of container terminal layout planning with respect to OR methods. In this thesis we provided several analytical methods to support the planning of storage yards. These methods, however, are not able to consider effects that occur in real-time operations. They do not, for instance, consider the effect of traffic jams in the yard or in the case of SC-based layouts with direct transfer, the impact of blocking of SCs. A first step for further research should be to measure the accuracy of the methods proposed in this thesis comparing the results of the models proposed with results gained from a more detailed simulation model. A more detailed simulation model is thus needed that considers effects such as traffic jams in the yard. So far, however, we are not aware of any simulation model in the literature that considers traffic jams of horizontal transport equipment within the yard (see also Petering and Murty 2009). Clearly, another research step could be devoted to extending the methods proposed in this thesis, e.g. by using techniques known from queueing theory.

Another topic for future research could be the development of a model for SC-based layouts with direct transfer which considers a possible impact of the positions of driving lanes as well as non-rectangularly shaped yards. In this context the use or the extension of the model which we proposed in Chapter 5 for the RTG-based layouts with transfer lanes for SC-based yards could be analyzed.

A further interesting research topic which is not related to the storage yard of a container terminal, is the design of the seaside layout. Additional research is needed concerning the determination of the size of the area between the quay and the storage yard: that is, the number of driving lanes at the quay and the number of waiting or parking positions have to be defined. These elements have to be designed properly, so that costly obstructions of the traffic at the seaside are avoided. On the other hand, the design of the seaside layout should be as compact as possible to avoid a waste of land that could be used for stacking. An important factor in this research is the consideration of obstructions such as traffic jams of horizontal transport equipment.

Recently, new equipment technology has been considered for use in container terminals. For instance, new transport technologies such as the grid rail system or new stacking technology like AS/R systems are under consideration for use in a container terminal. An interesting future research topic might be the analysis of the influence of new technology on the layout of a container terminal. With the help of such analysis new methods can be developed which support terminal planners in designing layouts for container terminals where these new technologies are used.

Generally, the results of this thesis demonstrate that several planning tasks can be supported by OR methods. Moreover, the possible further research topics show that several aspects can and should be investigated in future. These methods can all be implemented in a decision support system which assists planners in the design of a container terminal layout.

Appendix A.

Proofs

This chapter of the appendix contains a proof of inequality (5.11) and of proposition 5.1 which are stated in Section 5.1.

Proof of Inequality (5.11)

The inequality (5.11): $c^d_{ij} > c^d_{ik} + c^d_{kj}$, is valid $\forall i, j, k \in N$ with $i < k < j$:

Proof. For simplification we reduce the distance costs solely to the distances d_{qij} multiplied by the flow f_{qij}. Obviously the factors v^d and c^d can be neglected. We know that $f_{qij} > 0$ as we assume $f_q > 0$ and $b^{\min} \geq 1$. We show for an arbitrary stream point q that $f_{qij}d_{qij} > f_{qik}d_{qik} + f_{qkj}d_{qkj}$ with $i < k < j$. We know that $f_{qik} + f_{qkj} = f_{qij}$. The stream point q has an arbitrary but fixed position. As the vertical distance can be neglected we split the distances d_{qij},d_{qik} and d_{qkj} into the following single horizontal distances d^s:

$$d_{qij} = d^s_{qi} + d^s_{ij} + d^s_{jq}$$
$$d_{qik} = d^s_{qi} + d^s_{ik} + d^s_{kq}$$
$$d_{qkj} = d^s_{qk} + d^s_{kj} + d^s_{jq}$$

It can be easily seen that $d^s_{ij} = d^s_{ik} + d^s_{kj}$. Thus $d_{qij} = d^s_{qi} + d^s_{ik} + d^s_{kj} + d^s_{jq}$. This leads to the following distance differences:

$$\Delta d^s_1 = d_{qij} - d_{qik} = d^s_{kj} + d^s_{jq} - d^s_{kq}$$
$$\Delta d^s_2 = d_{qij} - d_{qkj} = d^s_{qi} + d^s_{ik} - d^s_{qk}$$

The different distances are illustrated in Figure A.1. In the illustration a position of stream point q with $i < j \leq q$ is assumed. The other possibilities are $i < q < j$

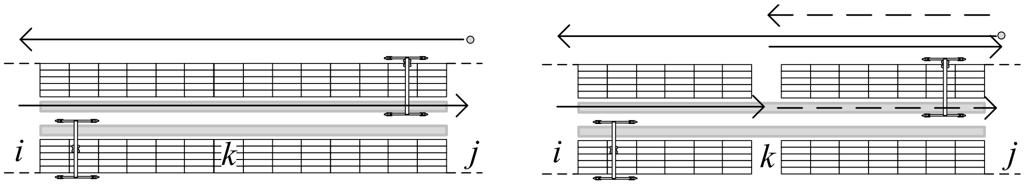


Figure A.1.: Different distances without and with driving lane k for a stream point q with $i < j \leq q$

and $q \leq i < j$. To show that $c^d_{ij} > c^d_{ik} + c^d_{kj}$ is valid we need to show that $f_{qij}d_{qij} > f_{qik}d_{qik} + f_{qkj}d_{qkj}$. Replacing f_{qij} with $f_{qik} + f_{qkj}$ it reduces to

$$f_{qik}d_{qij} + f_{qkj}d_{qij} > f_{qik}d_{qik} + f_{qkj}d_{qkj}. \quad \text{(A.1)}$$

In case that $i < q < j$ the cases $i < q \leq k < j$ and $i < k \leq q < j$ can be distinguished. For both cases it is obvious that $\Delta d^s_1 > 0$ and $\Delta d^s_2 > 0$ and therefore that $d_{qij} > d_{qik}$ as well as $d_{qij} > d_{qkj}$ and it follows that (A.1) is valid. For the case $i < j \leq q$ ($i < k < j \leq q$) it is obvious that $d^s_{kj} + d^s_{jq} = d^s_{kq}$ and thus that $\Delta d^s_1 = 0$. Moreover, it is obvious that $d^s_{qi} + d^s_{ik} > d^s_{qk}$ and that therefore $\Delta d^s_2 > 0$. In sum it follows that (A.1) is valid. The proof for the case $q \leq i < j$ is similar to the opposite case $i < j \leq q$. □

Proof of Proposition 5.1

Proposition 5.1: The LP relaxation of the NYLM has at least one integral optimal solution.

Proof. First of all we need to introduce some notation: Let x^s be the solution vector of solution s. We define a function $\text{frac}(x) = x - \lfloor x \rfloor$. Let $r^o_i = \sum_{j:(i,j)\in A} \text{frac}(x^s_{ij})$ be the sum of fractional flows going out of vertex i and $r^p_j = \sum_{i:(i,j)\in A} \text{frac}(x^s_{ij})$ be the sum of fractional flows going into vertex j. Let u^o_i be the number of edges with fractional flow going out of vertex i and u^p_i the number of fractional edges going into vertex i. Let l be an arbitrary vertex with $r^o_l > 0$, $r^p_l = 0$ and $\sum_{i:(i,l)\in A} x^s_{il} = 1$. We know that there exists a vertex m after l (at least n) with $r^o_m = 0$, $r^p_m > 0$ and $\sum_{j:(m,j)\in A} x^s_{mj} = 1$. Thus we know that the inflow of vertex l and the outflow of vertex m is integral. We assume that until vertex l α driving lanes are used. We define a fractional path ρ_g as a subgraph of G consisting of an ordered set of vertices $(w, k, k+1, \ldots, m-1, m)$ satisfying the properties that for all vertices k with $w \leq k \leq m-1$ an edge $(k, k+1) \in A$ exists and for all vertices k with $w < k \leq m-1$ we require $u^p_k \geq u^o_k$. Let $\mu(\rho_g)$ define the set of edges $(k, k+1) \in A$ of a fractional path ρ_g, thus

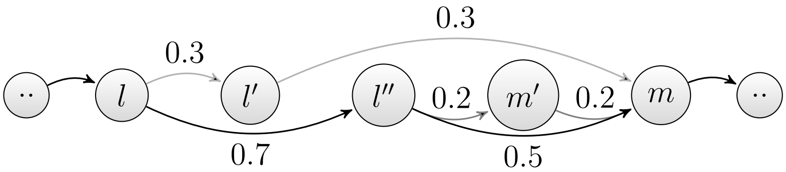


Figure A.2.: Sample network structure of a solution s with fractional flow values

$\mu(\rho_g) = \{(k, k+1) \in A | k, k+1 \in \rho_g\}$. Please note that for a fractional path the last vertex is always m. The length of fraction path ρ_g^L is defined as the number of edges. ρ_g^i defines the vertex at the i-th position of the fractional path ρ_g $(i = 1 \dots \tau)$ with $\tau = \rho_g^L + 1$. Let $f(\rho_g)$ define the fractional flow going over a fractional path ρ_g by $f(\rho_g) = r^o_{\rho_g^1}$.

Figure A.2 illustrates a fractional solution s. To clarify the introduced notation we provide some examples using the sample network in Figure A.2. The notation is used to define fractional parts of a solution s. Thus we have three fractional paths. The first is $\rho_1 = (l, l', m)$ with $\rho_1^L = 2$,$f(\rho_1) = 0.3$ and $\mu(\rho_1) = \{(l, l'), (l', m)\}$. The remaining ones are $\rho_2 = (l'', m', m)$ and $\rho_3 = (l'', m)$. The path (l, l'', m) is not a fractional path as $u^p_{l''} = 1 < u^o_{l''} = 2$.

Now we assume that s is an optimal solution with fractional flow values. Using the above defined notation we show by contradiction that s cannot be optimal or that there is at least an optimal integer solution with the same solution value. An arbitrary fractional part of the solution s starts at vertex l. As the fractional flow ends at node m, we know that among all fractional paths at least two fractional paths with identical start vertexes $\rho_k^1 = \rho_{k+1}^1$ have to exist. We show algorithmically that pairs of fractional paths can be selected and joint to one fractional path. Considering the fractional paths ρ_k, ρ_{k+1}, by definition of a fractional path we know that for ρ_k and ρ_{k+1} the last vertex is m. Thus both have the same start and end vertex. Therefore solution s can be replaced by a new solution where ρ_k and ρ_{k+1} are replaced by the fractional path σ with either $\sigma = \rho_k$ or $\sigma = \rho_{k+1}$ and flow $f(\sigma) = f(\rho_k) + f(\rho_{k+1})$ without influencing other parts of the solution. We distinguish the two cases $\rho_k^L = \rho_{k+1}^L$ and $\rho_k^L \neq \rho_{k+1}^L$:

(i) $\rho_k^L = \rho_{k+1}^L$:
As both fractional paths are of identical length we know that the same number of edges are used in both paths. The rehandle costs caused by the considered fractional paths are induced by the number of used edges or more precisely by the sum of flows going over each of the edges which can be expressed by $\lambda = \rho_k^L \times (f(\rho_k) + f(\rho_{k+1}))$. Thus the sum of rehandle costs caused together by ρ_k and ρ_{k+1} is $\sum_{h=\alpha}^{\alpha+\lambda-\text{frac}(\lambda)} c_h^r + \text{frac}(\lambda) c^r_{\alpha+\lambda-\text{frac}(\lambda)+1}$.

Obviously, the new fractional path σ has the same rehandle costs due to the same flow ($f(\sigma) = f(\rho_k) + f(\rho_{k+1})$) and the same length.

Considering the distance cost we know that $\sum_{(j,j+1)\in\mu(\rho_k)} f(\rho_k)c^d_{j,j+1}$ are the distance costs of ρ_k and $\sum_{(j,j+1)\in\mu(\rho_{k+1})} f(\rho_{k+1})c^d_{j,j+1}$ are the distance costs of ρ_{k+1}. To show that σ would lead to a better or at least identical solution value as s we need to show that either $\sum_{(j,j+1)\in\mu(\rho_{k+1})} c^d_{j,j+1} \leq \sum_{(j,j+1)\in\mu(\rho_k)} c^d_{j,j+1}$ or $\sum_{(j,j+1)\in\mu(\rho_{k+1})} c^d_{j,j+1} \geq \sum_{(j,j+1)\in\mu(\rho_k)} c^d_{j,j+1}$. Let $\Delta c^d = \sum_{(j,j+1)\in\mu(\rho_k)} c^d_{j,j+1} - \sum_{(j,j+1)\in\mu(\rho_{k+1})} c^d_{j,j+1}$ be the distance cost differences of the fractional paths ρ_k and ρ_{k+1}. Thus in the case that $\Delta c^d > 0$ then $\sigma = \rho_{k+1}$ would lead to a lower objective value as $\sigma = \rho_{k+1}$ has identical rehandle costs but lower distance costs than s. In the case that $\Delta c^d < 0$ then $\sigma = \rho_k$ would lead to a lower objective value and s cannot be optimal. In the case that $\Delta c^d = 0$ then $\sigma = \rho_{k+1}$ or $\sigma = \rho_k$ would lead to the same solution value as s.

(ii) $\rho^L_k \neq \rho^L_{k+1}$:
Without loss of generality we assume that $\rho^L_k < \rho^L_{k+1}$. Again, we can calculate the different distance difference values of Δc^d as in case (i). The difference to case (i) is that the rehandle costs for σ are either increased ($\sigma = \rho_{k+1}$) or decreased ($\sigma = \rho_k$) as we know that $\rho^L_k < \rho^L_{k+1}$. We define $\lambda_\rho = f(\rho_k)\rho^L_k + f(\rho_{k+1})\rho^L_{k+1}$. The original rehandle costs of ρ_k and ρ_{k+1} are $\sum_{h=\alpha}^{\alpha+\lambda_\rho-\mathrm{frac}(\lambda_\rho)} c^r_h + \mathrm{frac}(\lambda_\rho)c^r_{\alpha+\lambda_\rho+1-\mathrm{frac}(\lambda_\rho)}$. If $\sigma = \rho_k$ then $\lambda_\sigma = (f(\rho_k) + f(\rho_{k+1}))\rho^L_k$ and if $\sigma = \rho_{k+1}$ then $\lambda_\sigma = (f(\rho_k) + f(\rho_{k+1}))\rho^L_{k+1}$. We define $\Delta\lambda = \lambda_{\sigma=\rho_k} - \lambda_{\sigma=\rho_k+1}$ as the difference between λ_σ for $\sigma = \rho_k$ and $\sigma = \rho_{k+1}$. Obviously, $\rho^L_k < \rho^L_{k+1}$ leads to $\Delta\lambda < 0$. Now considering again the possible values of Δc^d: if $\Delta c^d < 0$ or $\Delta c^d = 0$ and $\Delta\lambda < 0$ it is obvious that $\sigma = \rho_k$ leads to a lower objective value than that of the original solution s. It might be favorable to choose $\sigma = \rho_{k+1}$, if $\Delta c^d > 0$. However, as shown before, the rehandle costs are increased for $\sigma = \rho_{k+1}$. Nevertheless, if the additional rehandle costs are smaller than the saved distance cost, $\sigma = \rho_{k+1}$ leads to a lower objective value than that of the original solution s. If the additional rehandle costs are greater than the saved distance cost, $\sigma = \rho_k$ leads to a lower objective value than that of the original solution s. And again, if the additional rehandle costs equal the saved distance cost, $\sigma = \rho_k$ or $\sigma = \rho_{k+1}$ lead to the same objective value than that of the original solution s.

In all cases we show that by replacing pairwise fractional path ρ_k and ρ_{k+1} with a path σ we are able to delete a fractional path ensuring a lower or at least identical solution value than that of the original solution value. Thus we can replace iteratively all pairs of fractional path until an integral flow is achieved. □

Appendix B.

Detailed Simulation Results

In this chapter of the appendix the detailed results are presented for the simulation study of Chapter 8. In Section B.1 the different performance measures are described. Section B.2 contains the detailed results.

B.1. Definition of Performance Measures

In this section the different performance measures are described which are used for the evaluation of the simulation runs. We define the busy time of an item of equipment as the time a job is assigned to the equipment. For instance, the busy time of a truck is the time it waits at a QC or Stack to collect or deliver a container and the time it travels from a place to another place. A truck is idle when no job is assigned to it and it is waiting for the assignment of another task. A stack is busy when at least one job is assigned to any yard crane working at the stack. A QC is busy when a ship is moored at the corresponding berth of the QC. When two yard cranes are deployed at one stack, one yard crane may still be idle even when the stack is busy. These busy times are used for the calculation of the following occupancy values of the equipment.

The following performance measures are related to seaside operations of the terminal.

QCR	Quay crane rate: average number of moves per hour of a QC. For the QCR only the time is considered in which a ship is moored at the corresponding berth.
AVG-BlockT	Average blocked time: average time a QC is blocked, i.e. the average time a QC waits for a horizontal means of transport.
TerOcc	Terminal occupancy: proportion of the simulation horizon in which at least one berth is occupied.
BerOcc	Berth occupancy: average occupancy of berths.

2BerOcc	Two berth occupancy: proportion of the simulation horizon in which both berths are occupied at the same time.
CtMoves	Total container moves: total number of container moves performed by all QCs during the simulation horizon.

The following performance measures are related to the landside operations and the horizontal transport of containers.

TruckTAT	Turnaround time for external trucks: average time external trucks spend in the terminal to collect or deliver a container.
HMTDist	Total HMT distance: average of the total distances traveled by a horizontal means of transport.
AvgHMTDist	Average HMT distance: average of the distances per journey of a horizontal means of transport.
HMTOcc	HMT occupancy: occupancy of the HMT during the simulation horizon.
HMTOcc2	HMT occupancy relative to the terminal occupancy: occupancy of the HMT during the simulation horizon in which at least one ship docks at the terminal.

The following performance measures are related to the stacks in the yard of a terminal.

StaMov	Number of moved containers at a stack: average number of container moves (retrievals & storages) in one hour of operation of a storage block.
StaOcc	Stack occupancy: average occupancy during the simulation horizon. Please note that the occupancy is not related to the occupancy of the storage space but to the time the block has to perform storage or retrieval jobs. Thus the stack occupancy is the proportion of time that a job is assigned to a stack at the overall simulation time.
StaOcc2	Stack occupancy relative to terminal occupancy: average occupancy of the block (related to equipment) during the simulation horizon in which at least one ship docks at the terminal. Please note that this ratio may be greater than 100% as the activities of a stack processing external trucks are considered even if no ship is docked at a berth.
AvgGanT	Average gantry time: average time needed for a yard crane to perform a gantry move.

GanT	Gantry time: average of the total times yard cranes perform gantry movements.
AVG-TroT	Average trolley time: average time needed for a yard crane to perform movements of the trolley. For the RMG-based layouts only trolley movements are considered if they exceed the concurrently gantry time.
TroT	Trolley time: average of the total time yard cranes perform trolley movements.
YCIdleT	YC idle times: average time a YC is idle.
NumRetr	Number of retrievals: number of containers that are retrieved from any block in the yard.
NumSto	Number of storages: number of containers that are stacked into an arbitrary block in the yard.
NumOver	Number of over-storages: number of containers that are stacked into a block even if the block has no free capacity. This only occurs when no free stacking capacity is available.
RatioStaMov	Ratio of total stack moves: the ratio of the total number of retrievals and storages during the simulation run to the maximal number of storages and retrievals achieved by another simulation run within the related scenario group.

The following performance measures are only related to RMG-based layouts.

AVG-EmptyT	Empty time per job: average time per storage or retrieval job that a YC performs a gantry movement without a lifted container.
BlTim	Blocked time: time a yard crane is blocked by another yard crane. In other words the time a yard crane has to wait for another yard crane at the same block to finish its operation.
NumConfs	Number of conflicts: number of conflicts between the two cranes at a block, in which one crane has to wait for another crane to finish its job.

In the case of an RTG-based layout we do not consider the operation of two YCs on the same block. Thus BlTim and NumConfs are not listed in the results. Moreover, the empty travel time in case of an RTG is similar to its gantry time and hence it is not listed in the results for RTG-based layouts. Please note that CtMoves, NumRetr, and NumSto are given by the scenario. Nevertheless, the values may be dissimilar for different layout configurations as different events take place during the time horizon in which the statistical data is collected.

B.2. Summary of the Simulation Results

In this section the detailed simulation results are listed in several tables. Given the large number of performance measures recorded for each simulation run we have to split up the results for a simulation run into separate tables. We therefore categorize the performance measures according to performance measures concerning the seaside and landside turnover of containers, the horizontal means of transport and the stacks in the yard.

The results for the different RMG-based layouts are presented in Tables B.1, B.2, B.3, and B.4. Table B.1 shows the results of the seaside performance measures (e.g., QCR and AVG-BlockT) and the landside performance measures (e.g,Truck-TAT) for the different combinations of scenario, algorithm used and layout configuration. Table B.2 shows the results of the HMT performance measures (e.g., AVG-HMT-Dist) for the different combinations of scenario, algorithm used and layout configuration. The results concerning the yard are split up into two tables: Table B.3 shows the results of the stack performance measures (e.g., StaMov) for the different combinations of scenario, algorithm used and layout configuration, and Table B.4 the results of the yard performance measures.

The results for the RTG-based layouts are presented in Tables B.5, B.6 and B.7. Table B.5 shows the results of the seaside performance measures (e.g., QCR and AVG-BlockT) and the landside performance measures (e.g., Truck-TAT) for the different combinations of scenario and algorithm used. Table B.6 shows the results of the HMT performance measures (e.g., AVG-HMT-Dist) for the different combinations of scenario and algorithm used. Table B.7 shows the results of the stack and yard performance measures (e.g., StaMov) for the different combinations of scenario and algorithm used.

Table B.1.: Results concerning seaside and landside turnover of containers for different RMG-based layouts with transfer points

Scenarios	Algorithms	Layout	QCR	AVG-BlockT	TerOcc	2BerOcc	BerOcc	CtMoves	Truck-TAT
R5-T0-E	YCS1	1RMG-W8	41.14	17.26	53%	17%	43%	36166.77	345.55
R5-T25-E	YCS1	1RMG-W8	41.74	15.90	61%	22%	48%	43240.83	332.36
R5-T50-E	YCS1	1RMG-W8	42.72	13.98	65%	29%	52%	49883.43	305.08
R5-T75-E	YCS1	1RMG-W8	43.21	13.31	74%	42%	61%	62099.47	269.24
R5-T100-E	YCS1	1RMG-W8	44.41	11.32	80%	52%	67%	72342.90	0.00
R5-T0-H	YCS1	1RMG-W8	35.75	30.03	79%	46%	70%	55939.73	495.91
R5-T25-H	YCS1	1RMG-W8	36.22	28.76	86%	60%	77%	65836.07	464.09
R5-T50-H	YCS1	1RMG-W8	38.22	23.74	90%	69%	81%	76737.93	387.22
R5-T75-H	YCS1	1RMG-W8	40.76	18.24	97%	83%	88%	93203.43	311.29
R5-T100-H	YCS1	1RMG-W8	43.05	13.99	100%	96%	93%	115496.66	0.00
R5-T0-E	YCS1	1RMG	38.68	22.64	56%	20%	46%	36325.80	407.43
R5-T25-E	YCS1	1RMG	39.38	20.79	64%	25%	51%	43388.67	390.64
R5-T50-E	YCS1	1RMG	41.14	17.07	67%	31%	54%	50003.47	342.41
R5-T75-E	YCS1	1RMG	42.05	15.49	75%	44%	63%	62235.60	294.25
R5-T100-E	YCS1	1RMG	43.88	12.24	80%	53%	68%	72369.87	0.00
R20-T0-E	YCS1	1RMG	38.12	23.97	56%	20%	47%	36292.03	384.02
R20-T25-E	YCS1	1RMG	38.75	22.26	64%	26%	53%	43362.90	369.42
R20-T50-E	YCS1	1RMG	39.82	19.84	68%	33%	56%	50033.37	334.20
R20-T75-E	YCS1	1RMG	40.42	18.83	77%	47%	66%	62356.13	294.39
R20-T100-E	YCS1	1RMG	41.57	16.67	83%	57%	72%	72575.40	0.00
R5-T0-H	YCS1	1RMG	31.69	42.56	86%	55%	78%	56397.53	687.55
R5-T25-H	YCS1	1RMG	32.67	39.25	92%	70%	85%	66499.97	614.55
R5-T50-H	YCS1	1RMG	35.74	30.13	94%	77%	87%	77539.60	468.39
R5-T75-H	YCS1	1RMG	39.03	22.05	99%	89%	92%	93926.80	354.97
R5-T100-H	YCS1	1RMG	42.38	15.22	100%	96%	93%	115790.3	0.00
R5-T0-E	YCS2	1RMG	44.75	10.76	49%	15%	39%	35851.93	951.51
R5-T25-E	YCS2	1RMG	44.35	11.31	58%	20%	45%	42968.60	744.50
R5-T50-E	YCS2	1RMG	44.05	11.80	63%	27%	51%	49718.23	577.93
R5-T75-E	YCS2	1RMG	43.50	12.95	73%	42%	61%	62012.80	392.11
R5-T100-E	YCS2	1RMG	44.00	12.10	80%	53%	68%	72360.90	0.00
R20-T0-E	YCS2	1RMG	43.62	12.77	50%	16%	40%	35860.37	974.02
R20-T25-E	YCS2	1RMG	43.05	13.63	59%	21%	47%	42987.07	776.44

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Table B.1.: (continued)

Scenarios	Algorithms	Layout	QCR	AVG-BlockT	TerOcc	2BerOcc	BerOcc	CtMoves	Truck-TAT
R20-T50-E	YCS2	1RMG	42.45	14.71	65%	29%	53%	49759.13	615.78
R20-T75-E	YCS2	1RMG	41.77	16.24	75%	44%	64%	62150.93	429.17
R20-T100-E	YCS2	1RMG	41.79	16.29	83%	57%	72%	72556.97	0.00
R5-T0-H	YCS2	1RMG	41.96	15.96	70%	35%	60%	55129.00	3801.50
R5-T25-H	YCS2	1RMG	40.87	18.13	78%	49%	69%	64794.10	3682.69
R5-T50-H	YCS2	1RMG	40.52	18.85	86%	63%	77%	75970.73	1919.20
R5-T75-H	YCS2	1RMG	41.27	17.35	96%	81%	88%	92955.70	670.46
R5-T100-H	YCS2	1RMG	42.44	15.18	100%	96%	93%	115684.83	0.00
R5-T0-E	YCS2/Split	1RMG	43.39	13.14	50%	16%	40%	35865.90	1153.96
R5-T25-E	YCS2/Split	1RMG	43.87	12.14	58%	21%	46%	42968.50	758.97
R5-T50-E	YCS2/Split	1RMG	44.48	11.03	63%	27%	50%	49681.90	508.91
R5-T75-E	YCS2/Split	1RMG	45.08	10.20	71%	39%	58%	61902.70	324.71
R5-T100-E	YCS2/Split	1RMG	46.55	7.93	77%	48%	64%	72230.50	0.00
R5-T0-E	YCS1	2RMG	45.03	10.13	49%	15%	38%	35871.33	352.17
R5-T25-E	YCS1	2RMG	44.58	10.72	58%	20%	44%	42988.53	331.75
R5-T50-E	YCS1	2RMG	44.35	11.09	63%	27%	50%	49710.73	287.96
R5-T75-E	YCS1	2RMG	43.64	12.54	73%	41%	60%	61985.70	244.04
R5-T100-E	YCS1	2RMG	43.88	12.23	80%	53%	68%	72365.03	0.00
R20-T0-E	YCS1	2RMG	43.59	12.65	50%	15%	40%	35882.50	328.78
R20-T25-E	YCS1	2RMG	43.07	13.40	59%	21%	46%	43016.93	307.06
R20-T50-E	YCS1	2RMG	42.59	14.27	65%	29%	52%	49768.57	275.41
R20-T75-E	YCS1	2RMG	41.78	16.07	75%	44%	63%	62127.53	237.53
R20-T100-E	YCS1	2RMG	41.56	16.67	83%	57%	72%	72594.53	0.00
R5-T0-H	YCS1	2RMG	42.26	15.23	70%	34%	59%	55201.47	552.69
R5-T25-H	YCS1	2RMG	41.23	17.18	78%	49%	67%	64962.37	475.08
R5-T50-H	YCS1	2RMG	41.20	17.28	85%	62%	75%	76016.37	358.64
R5-T75-H	YCS1	2RMG	41.68	16.39	96%	80%	86%	92801.77	270.63
R5-T100-H	YCS1	2RMG	42.35	15.28	100%	96%	93%	115762.6	0.00
R5-T0-E	YCS2	2RMG	45.20	9.91	49%	14%	38%	35867.77	316.54
R5-T25-E	YCS2	2RMG	44.77	10.51	58%	19%	44%	42987.27	302.49
R5-T50-E	YCS2	2RMG	44.53	10.87	63%	27%	49%	49705.87	268.28
R5-T75-E	YCS2	2RMG	43.78	12.40	73%	41%	60%	61966.90	233.67

Continued on next page

Table B.1.: (continued)

Scenarios	Algorithms	Layout	QCR	AVG-BlockT	TerOcc	2BerOcc	BerOcc	CtMoves	Truck-TAT
R5-T100-E	YCS2	2RMG	44.02	12.09	80%	52%	68%	72362.57	0.00
R20-T0-E	YCS2	2RMG	43.79	12.37	50%	15%	39%	35875.70	292.81
R20-T25-E	YCS2	2RMG	43.31	13.11	59%	21%	46%	43012.50	278.64
R20-T50-E	YCS2	2RMG	42.84	13.89	64%	29%	52%	49765.63	254.40
R20-T75-E	YCS2	2RMG	41.90	15.93	75%	44%	63%	62105.80	226.38
R20-T100-E	YCS2	2RMG	41.76	16.35	83%	57%	72%	72571.10	0.00
R5-T0-H	YCS2	2RMG	42.45	14.90	70%	34%	58%	55175.03	460.61
R5-T25-H	YCS2	2RMG	41.53	16.65	77%	48%	66%	64911.53	409.83
R5-T50-H	YCS2	2RMG	41.39	16.95	85%	62%	75%	75976.53	324.69
R5-T75-H	YCS2	2RMG	41.81	16.18	96%	79%	86%	92747.50	255.85
R5-T100-H	YCS2	2RMG	42.44	15.17	100%	96%	93%	115720.93	0.00
R5-T0-E	YCS2/Split	2RMG	44.49	11.05	50%	15%	39%	35863.47	249.17
R5-T25-E	YCS2/Split	2RMG	45.16	9.84	57%	19%	44%	42947.27	233.66
R5-T50-E	YCS2/Split	2RMG	45.58	9.12	62%	25%	48%	49635.73	208.04
R5-T75-E	YCS2/Split	2RMG	45.83	8.93	70%	38%	57%	61835.57	185.15
R5-T100-E	YCS2/Split	2RMG	46.54	7.93	77%	48%	64%	72228.20	0.00
R5-T0-E	YCS1	2RMG-Cr	42.88	14.02	52%	16%	41%	36118.13	327.47
R5-T25-E	YCS1	2RMG-Cr	43.42	12.81	59%	21%	46%	43182.77	312.48
R5-T50-E	YCS1	2RMG-Cr	44.26	11.30	63%	27%	50%	49815.03	286.51
R5-T75-E	YCS1	2RMG-Cr	44.56	11.00	72%	40%	58%	62027.70	254.81
R5-T100-E	YCS1	2RMG-Cr	45.26	9.95	79%	50%	65%	72302.70	0.00
R20-T0-E	YCS1	2RMG-Cr	42.32	15.06	52%	16%	42%	36103.17	314.74
R20-T25-E	YCS1	2RMG-Cr	42.75	14.05	60%	21%	47%	43172.87	303.55
R20-T50-E	YCS1	2RMG-Cr	43.40	12.82	64%	28%	51%	49827.90	280.87
R20-T75-E	YCS1	2RMG-Cr	43.49	12.87	73%	42%	60%	62095.37	252.95
R20-T100-E	YCS1	2RMG-Cr	43.85	12.36	80%	53%	68%	72403.20	0.00
R5-T0-H	YCS1	2RMG-Cr	37.80	24.93	76%	41%	66%	55827.90	467.07
R5-T25-H	YCS1	2RMG-Cr	38.30	23.64	82%	55%	72%	65684.70	436.44
R5-T50-H	YCS1	2RMG-Cr	40.35	19.06	87%	64%	76%	76492.27	360.10
R5-T75-H	YCS1	2RMG-Cr	42.47	14.93	95%	78%	84%	92819.13	290.62
R5-T100-H	YCS1	2RMG-Cr	44.02	12.28	100%	95%	91%	115159.9	0.00
R5-T0-E	YCS2	2RMG-Cr	45.82	8.91	49%	14%	38%	35858.20	379.52

Continued on next page

Table B.1.: (continued)

Scenarios	Algorithms	Layout	QCR	AVG-BlockT	TerOcc	2BerOcc	BerOcc	CtMoves	Truck-TAT
R5-T25-E	YCS2	2RMG-Cr	45.69	8.97	57%	19%	43%	42958.60	355.78
R5-T50-E	YCS2	2RMG-Cr	45.60	9.10	62%	26%	48%	49674.07	318.02
R5-T75-E	YCS2	2RMG-Cr	45.08	10.14	71%	39%	57%	61928.50	273.40
R5-T100-E	YCS2	2RMG-Cr	45.21	10.04	79%	50%	65%	72299.70	0.00
R20-T0-E	YCS2	2RMG-Cr	45.08	10.14	49%	15%	39%	35862.40	375.95
R20-T25-E	YCS2	2RMG-Cr	44.92	10.24	58%	19%	44%	42971.73	351.89
R20-T50-E	YCS2	2RMG-Cr	44.67	10.65	63%	27%	49%	49701.23	315.61
R20-T75-E	YCS2	2RMG-Cr	44.00	11.98	72%	41%	60%	61995.97	276.08
R20-T100-E	YCS2	2RMG-Cr	43.88	12.31	80%	53%	68%	72383.90	0.00
R5-T0-H	YCS2	2RMG-Cr	43.43	13.14	69%	33%	58%	55132.50	893.93
R5-T25-H	YCS2	2RMG-Cr	42.88	14.09	75%	45%	64%	64755.27	813.80
R5-T50-H	YCS2	2RMG-Cr	43.03	13.80	83%	58%	72%	75815.43	518.62
R5-T75-H	YCS2	2RMG-Cr	43.48	13.07	94%	75%	82%	92472.47	341.21
R5-T100-H	YCS2	2RMG-Cr	43.98	12.35	100%	95%	91%	115144.73	0.00
R5-T0-E	YCS2/Split	2RMG-Cr	46.15	8.34	49%	14%	38%	35854.90	256.42
R5-T25-E	YCS2/Split	2RMG-Cr	46.39	7.83	56%	18%	42%	42937.63	248.72
R5-T50-E	YCS2/Split	2RMG-Cr	46.68	7.37	61%	24%	47%	49626.60	229.37
R5-T75-E	YCS2/Split	2RMG-Cr	46.72	7.50	69%	37%	55%	61834.07	211.11
R5-T100-E	YCS2/Split	2RMG-Cr	47.30	6.77	77%	47%	62%	72205.07	0.00

Table B.2.: Results concerning HMT performance measures for different RMG-based layouts with transfer points

Scenarios	Algorithms	Layout	HMT-Dist	AVG-HMT-Dist	HMT-Occ	HMT-Occ2
R5-T0-E	YCS1	1RMG-W8	708114.30	235.02	43%	81%
R5-T25-E	YCS1	1RMG-W8	847942.27	235.33	48%	79%
R5-T50-E	YCS1	1RMG-W8	975122.71	234.63	52%	80%
R5-T75-E	YCS1	1RMG-W8	1216466.96	235.09	61%	83%
R5-T100-E	YCS1	1RMG-W8	1413974.13	234.56	67%	85%
R5-T0-H	YCS1	1RMG-W8	1095219.54	234.95	70%	88%
R5-T25-H	YCS1	1RMG-W8	1289144.80	234.97	76%	89%
R5-T50-H	YCS1	1RMG-W8	1498387.41	234.31	81%	90%
R5-T75-H	YCS1	1RMG-W8	1818938.99	234.20	88%	91%
R5-T100-H	YCS1	1RMG-W8	2250703.10	233.86	93%	93%
R5-T0-E	YCS1	1RMG	713297.72	235.66	46%	83%
R5-T25-E	YCS1	1RMG	851691.91	235.55	51%	81%
R5-T50-E	YCS1	1RMG	975125.27	234.04	54%	82%
R5-T75-E	YCS1	1RMG	1218121.10	234.91	63%	84%
R5-T100-E	YCS1	1RMG	1415976.77	234.81	68%	85%
R20-T0-E	YCS1	1RMG	712904.62	235.74	47%	83%
R20-T25-E	YCS1	1RMG	848974.12	234.94	53%	82%
R20-T50-E	YCS1	1RMG	977675.57	234.51	56%	83%
R20-T75-E	YCS1	1RMG	1218365.42	234.50	66%	85%
R20-T100-E	YCS1	1RMG	1422098.29	235.15	72%	87%
R5-T0-H	YCS1	1RMG	1104816.97	235.08	78%	91%
R5-T25-H	YCS1	1RMG	1301593.91	234.87	85%	92%
R5-T50-H	YCS1	1RMG	1515736.28	234.57	87%	92%
R5-T75-H	YCS1	1RMG	1834855.19	234.43	92%	93%
R5-T100-H	YCS1	1RMG	2255243.74	233.74	93%	93%
R5-T0-E	YCS2	1RMG	702400.64	235.16	39%	79%
R5-T25-E	YCS2	1RMG	842443.76	235.31	45%	78%
R5-T50-E	YCS2	1RMG	972964.91	234.88	51%	80%
R5-T75-E	YCS2	1RMG	1214733.01	235.08	61%	83%
R5-T100-E	YCS2	1RMG	1412919.35	234.33	68%	85%
R20-T0-E	YCS2	1RMG	701833.22	234.93	40%	80%
R20-T25-E	YCS2	1RMG	841298.06	234.90	47%	80%
R20-T50-E	YCS2	1RMG	973515.01	234.81	53%	82%
R20-T75-E	YCS2	1RMG	1214223.48	234.46	64%	85%
R20-T100-E	YCS2	1RMG	1418530.41	234.63	72%	87%
R5-T0-H	YCS2	1RMG	1082362.34	235.63	60%	86%
R5-T25-H	YCS2	1RMG	1269742.42	235.18	69%	88%
R5-T50-H	YCS2	1RMG	1487950.86	235.05	77%	90%
R5-T75-H	YCS2	1RMG	1817071.01	234.59	88%	91%
R5-T100-H	YCS2	1RMG	2253369.40	233.76	93%	93%
R5-T0-E	YCS2/Split	1RMG	704778.56	235.86	40%	80%
R5-T25-E	YCS2/Split	1RMG	844473.89	235.89	46%	79%
R5-T50-E	YCS2/Split	1RMG	971161.28	234.62	50%	80%
R5-T75-E	YCS2/Split	1RMG	1214370.60	235.43	58%	82%
R5-T100-E	YCS2/Split	1RMG	1411445.81	234.52	64%	82%
R5-T0-E	YCS1	2RMG	702506.04	235.07	38%	77%
R5-T25-E	YCS1	2RMG	840329.53	234.63	44%	76%
R5-T50-E	YCS1	2RMG	968099.55	233.72	50%	79%
R5-T75-E	YCS1	2RMG	1213450.59	234.95	60%	82%
R5-T100-E	YCS1	2RMG	1409723.90	233.80	68%	85%
R20-T0-E	YCS1	2RMG	701763.42	234.77	40%	79%
R20-T25-E	YCS1	2RMG	841636.54	234.81	46%	78%

Continued on next page

Table B.2.: (continued)

Scenarios	Algorithms	Layout	HMT-Dist	AVG-HMT-Dist	HMT-Occ	HMT-Occ2
R20-T50-E	YCS1	2RMG	970615.77	234.09	52%	81%
R20-T75-E	YCS1	2RMG	1215252.34	234.76	63%	84%
R20-T100-E	YCS1	2RMG	1421459.66	234.99	72%	87%
R5-T0-H	YCS1	2RMG	1077630.70	234.28	59%	84%
R5-T25-H	YCS1	2RMG	1271651.55	234.91	67%	86%
R5-T50-H	YCS1	2RMG	1483551.97	234.21	75%	88%
R5-T75-H	YCS1	2RMG	1808121.72	233.82	86%	90%
R5-T100-H	YCS1	2RMG	2255085.48	233.78	93%	93%
R5-T0-E	YCS2	2RMG	702273.99	235.02	38%	77%
R5-T25-E	YCS2	2RMG	840637.8	234.73	44%	76%
R5-T50-E	YCS2	2RMG	972469.30	234.80	49%	79%
R5-T75-E	YCS2	2RMG	1210448.67	234.43	60%	82%
R5-T100-E	YCS2	2RMG	1413944.57	234.50	68%	85%
R20-T0-E	YCS2	2RMG	701909.38	234.84	39%	78%
R20-T25-E	YCS2	2RMG	838483.56	233.97	46%	78%
R20-T50-E	YCS2	2RMG	972529.20	234.54	52%	81%
R20-T75-E	YCS2	2RMG	1214758.18	234.73	63%	84%
R20-T100-E	YCS2	2RMG	1420981.57	234.99	72%	87%
R5-T0-H	YCS2	2RMG	1077733.40	234.41	58%	84%
R5-T25-H	YCS2	2RMG	1267349.19	234.31	66%	86%
R5-T50-H	YCS2	2RMG	1483603.41	234.35	75%	88%
R5-T75-H	YCS2	2RMG	1807165.86	233.83	86%	90%
R5-T100-H	YCS2	2RMG	2255503.72	233.90	93%	93%
R5-T0-E	YCS2/Split	2RMG	702630.88	235.17	39%	78%
R5-T25-E	YCS2/Split	2RMG	841145.71	235.04	44%	76%
R5-T50-E	YCS2/Split	2RMG	971016.31	234.78	48%	78%
R5-T75-E	YCS2/Split	2RMG	1214202.80	235.67	57%	80%
R5-T100-E	YCS2/Split	2RMG	1413353.15	234.85	64%	82%
R5-T0-E	YCS1	2RMG-Cr	703631.53	233.79	41%	79%
R5-T25-E	YCS1	2RMG-Cr	842708.65	234.17	46%	77%
R5-T50-E	YCS1	2RMG-Cr	964594.75	232.39	50%	78%
R5-T75-E	YCS1	2RMG-Cr	1203377.82	232.82	58%	81%
R5-T100-E	YCS1	2RMG-Cr	1402711.27	232.82	65%	82%
R20-T0-E	YCS1	2RMG-Cr	701798.76	233.30	42%	80%
R20-T25-E	YCS1	2RMG-Cr	842566.00	234.20	47%	78%
R20-T50-E	YCS1	2RMG-Cr	969337.97	233.49	51%	80%
R20-T75-E	YCS1	2RMG-Cr	1207621.43	233.39	60%	82%
R20-T100-E	YCS1	2RMG-Cr	1407772.94	233.34	68%	84%
R5-T0-H	YCS1	2RMG-Cr	1085958.54	233.43	66%	87%
R5-T25-H	YCS1	2RMG-Cr	1277627.40	233.41	72%	87%
R5-T50-H	YCS1	2RMG-Cr	1486084.24	233.14	76%	87%
R5-T75-H	YCS1	2RMG-Cr	1799396.94	232.65	84%	88%
R5-T100-H	YCS1	2RMG-Cr	2229316.63	232.32	91%	91%
R5-T0-E	YCS2	2RMG-Cr	696865.86	233.27	38%	77%
R5-T25-E	YCS2	2RMG-Cr	836301.43	233.64	43%	76%
R5-T50-E	YCS2	2RMG-Cr	964777.80	233.07	48%	78%
R5-T75-E	YCS2	2RMG-Cr	1203065.26	233.13	57%	81%
R5-T100-E	YCS2	2RMG-Cr	1401983.47	232.72	65%	82%
R20-T0-E	YCS2	2RMG-Cr	696384.71	233.08	39%	79%
R20-T25-E	YCS2	2RMG-Cr	837539.28	233.91	44%	77%
R20-T50-E	YCS2	2RMG-Cr	965035.94	233.03	49%	79%
R20-T75-E	YCS2	2RMG-Cr	1203746.35	233.04	60%	82%
R20-T100-E	YCS2	2RMG-Cr	1404641.60	232.90	68%	84%
R5-T0-H	YCS2	2RMG-Cr	1071315.48	233.19	58%	84%

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Table B.2.: (continued)

Scenarios	Algorithms	Layout	HMT-Dist	AVG-HMT-Dist	HMT-Occ	HMT-Occ2
R5-T25-H	YCS2	2RMG-Cr	1257720.38	233.08	64%	85%
R5-T50-H	YCS2	2RMG-Cr	1471824.70	232.97	72%	86%
R5-T75-H	YCS2	2RMG-Cr	1795649.75	233.03	82%	88%
R5-T100-H	YCS2	2RMG-Cr	2228201.20	232.23	91%	91%
R5-T0-E	YCS2/Split	2RMG-Cr	703857.60	235.64	38%	77%
R5-T25-E	YCS2/Split	2RMG-Cr	842847.95	235.57	42%	75%
R5-T50-E	YCS2/Split	2RMG-Cr	970421.85	234.70	47%	77%
R5-T75-E	YCS2/Split	2RMG-Cr	1211202.60	235.08	55%	79%
R5-T100-E	YCS2/Split	2RMG-Cr	1413290.94	234.91	62%	80%

Table B.3.: Results concerning stack performance measures for different RMG-based layouts with transfer points

Scenarios	Algorithms	Layout	StaMov	StaOcc	StaOcc2	AVG-GanT	GanT	AVG-TroT	TroT	AVG-EmptyT-Job	BlTim	YCIdleT	NumConfs
R5-T0-E	YCS1	1RMG-W8	25.39	46%	86%	46.54	338585.01	5.70	2489.79	45.40	0.00	609131.28	0.00
R5-T25-E	YCS1	1RMG-W8	25.61	46%	76%	46.06	339703.81	5.57	2487.99	44.97	0.00	605788.17	0.00
R5-T50-E	YCS1	1RMG-W8	25.91	44%	68%	45.26	324375.89	5.56	2528.52	44.07	0.00	625645.23	0.00
R5-T75-E	YCS1	1RMG-W8	26.37	45%	62%	43.92	327205.06	5.66	2950.40	42.25	0.00	613988.90	0.00
R5-T100-E	YCS1	1RMG-W8	27.07	43%	54%	41.54	300361.01	5.88	3526.56	38.52	0.00	633950.02	0.00
R5-T0-H	YCS1	1RMG-W8	25.68	68%	86%	46.54	512225.92	5.78	3937.37	45.45	0.00	358158.23	0.00
R5-T25-H	YCS1	1RMG-W8	25.89	69%	81%	45.95	514664.90	5.78	4083.14	44.80	0.00	348769.49	0.00
R5-T50-H	YCS1	1RMG-W8	26.11	67%	74%	45.16	496738.51	5.75	4191.77	43.87	0.00	375125.55	0.00
R5-T75-H	YCS1	1RMG-W8	26.53	66%	68%	43.59	486699.74	5.90	4980.55	41.56	0.00	387069.16	0.00
R5-T100-H	YCS1	1RMG-W8	27.23	62%	62%	41.03	473790.71	5.98	6289.82	37.50	0.00	471407.20	0.00
R5-T0-E	YCS1	1RMG	27.01	54%	97%	42.39	386489.17	7.28	5260.84	41.45	0.00	517382.89	0.00
R5-T25-E	YCS1	1RMG	27.21	54%	86%	42.04	388515.41	7.18	5291.69	41.13	0.00	512858.08	0.00
R5-T50-E	YCS1	1RMG	27.47	52%	79%	41.39	371500.92	7.26	5381.91	40.32	0.00	535449.53	0.00
R5-T75-E	YCS1	1RMG	27.86	54%	72%	40.31	376221.67	7.41	6216.04	38.78	0.00	520113.49	0.00
R5-T100-E	YCS1	1RMG	28.41	51%	64%	38.38	347071.45	7.71	7112.87	35.65	0.00	542271.45	0.00
R20-T0-E	YCS1	1RMG	26.80	54%	97%	42.66	388356.07	7.18	6185.82	42.02	0.00	513234.39	0.00
R20-T25-E	YCS1	1RMG	26.65	55%	87%	43.31	399814.39	7.21	6031.12	42.57	0.00	500592.33	0.00
R20-T50-E	YCS1	1RMG	26.47	54%	80%	43.90	393933.55	7.29	5760.39	42.87	0.00	513226.64	0.00
R20-T75-E	YCS1	1RMG	26.32	57%	74%	44.30	413901.73	7.56	6259.72	42.55	0.00	484648.75	0.00
R20-T100-E	YCS1	1RMG	26.17	55%	67%	44.19	400374.93	7.90	6785.70	40.96	0.00	500360.77	0.00
R5-T0-H	YCS1	1RMG	27.46	80%	93%	42.31	585218.55	7.36	8426.36	41.33	0.00	229766.24	0.00
R5-T25-H	YCS1	1RMG	27.66	81%	88%	41.84	589626.21	7.35	8734.49	40.77	0.00	214146.86	0.00
R5-T50-H	YCS1	1RMG	27.80	79%	84%	41.22	571083.03	7.39	8983.10	40.00	0.00	243154.48	0.00
R5-T75-H	YCS1	1RMG	28.10	78%	79%	40.00	562068.97	7.71	10261.35	38.16	0.00	252124.18	0.00
R5-T100-H	YCS1	1RMG	28.59	73%	73%	37.95	549177.07	7.91	12358.22	34.80	0.00	345089.79	0.00
R5-T0-E	YCS2	1RMG	27.26	53%	108%	41.83	380094.31	7.26	5693.15	40.24	0.00	525048.73	0.00
R5-T25-E	YCS2	1RMG	27.45	54%	93%	41.57	382711.51	7.23	5675.85	40.10	0.00	520537.11	0.00
R5-T50-E	YCS2	1RMG	27.66	52%	82%	41.10	367716.79	7.25	5622.06	39.71	0.00	541343.75	0.00
R5-T75-E	YCS2	1RMG	27.98	53%	73%	40.21	374245.67	7.42	6310.53	38.56	0.00	524134.25	0.00
R5-T100-E	YCS2	1RMG	28.51	51%	64%	38.23	345603.84	7.73	7257.43	35.35	0.00	543634.11	0.00
R20-T0-E	YCS2	1RMG	27.04	54%	107%	42.09	382146.81	7.24	6647.39	40.84	0.00	520274.36	0.00
R20-T25-E	YCS2	1RMG	26.90	55%	93%	42.79	393723.06	7.24	6428.79	41.49	0.00	508163.02	0.00

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Table B.3.: (continued)

Scenarios	Algorithms	Layout	StaMov	StaOcc	StaOcc2	AVG-GanT	GanT	AVG-TroT	TroT	AVG-EmptyT-Job	BlTim	YCIdleT	NumConfs
R20-T50-E	YCS2	1RMG	26.65	54%	83%	43.60	389918.62	7.32	5991.65	42.24	0.00	519307.55	0.00
R20-T75-E	YCS2	1RMG	26.44	56%	75%	44.15	411520.24	7.53	6376.26	42.25	0.00	488687.47	0.00
R20-T100-E	YCS2	1RMG	26.29	55%	67%	43.96	398077.20	7.93	7035.06	40.49	0.00	501890.35	0.00
R5-T0-H	YCS2	1RMG	28.02	78%	112%	41.14	566168.08	7.52	10187.74	38.82	0.00	242706.83	0.00
R5-T25-H	YCS2	1RMG	28.25	79%	102%	40.81	571999.38	7.37	10140.84	38.55	0.00	232024.13	0.00
R5-T50-H	YCS2	1RMG	28.23	77%	90%	40.66	558371.10	7.28	9448.84	38.76	0.00	254404.89	0.00
R5-T75-H	YCS2	1RMG	28.31	78%	80%	39.82	555226.75	7.68	10356.92	37.77	0.00	256561.43	0.00
R5-T100-H	YCS2	1RMG	28.70	72%	72%	37.76	545859.38	7.92	12698.86	34.42	0.00	346712.04	0.00
R5-T0-E	YCS2/Split	1RMG	27.36	53%	105%	41.37	375655.79	7.50	5603.30	39.48	0.00	526871.12	0.00
R5-T25-E	YCS2/Split	1RMG	27.95	53%	91%	40.25	370099.68	7.30	5412.13	39.69	0.00	531640.88	0.00
R5-T50-E	YCS2/Split	1RMG	28.86	50%	79%	38.14	340837.24	7.26	5545.21	38.74	0.00	566405.65	0.00
R5-T75-E	YCS2/Split	1RMG	30.81	48%	68%	33.60	312566.48	7.16	6952.23	34.49	0.00	579864.09	0.00
R5-T100-E	YCS2/Split	1RMG	34.35	43%	55%	26.02	235860.85	7.14	9392.72	24.34	0.00	639087.74	0.00
R5-T0-E	YCS1	2RMG	29.71	49%	99%	33.65	185260.37	7.59	4120.31	38.43	15995.83	723695.00	498.09
R5-T25-E	YCS1	2RMG	29.75	49%	85%	33.54	186551.95	7.63	4210.23	38.39	15208.60	707387.25	497.63
R5-T50-E	YCS1	2RMG	29.53	48%	77%	33.53	179184.81	7.66	4088.17	38.17	12085.50	716157.72	420.39
R5-T75-E	YCS1	2RMG	29.22	51%	70%	33.25	183158.54	7.76	4213.06	38.29	8511.55	710160.97	313.96
R5-T100-E	YCS1	2RMG	28.43	51%	64%	38.37	346993.89	7.73	7107.70	35.65	0.00	542397.10	0.00
R20-T0-E	YCS1	2RMG	29.30	49%	98%	33.94	186221.50	7.66	4770.38	39.00	18253.09	721433.11	492.96
R20-T25-E	YCS1	2RMG	28.97	51%	86%	33.94	192280.82	7.72	4737.29	38.97	17718.84	702547.29	496.66
R20-T50-E	YCS1	2RMG	28.28	51%	78%	34.15	190574.54	7.79	4411.89	38.82	14238.22	707445.69	419.91
R20-T75-E	YCS1	2RMG	27.49	54%	72%	34.06	201955.45	7.90	4351.92	38.81	10231.23	701008.52	313.87
R20-T100-E	YCS1	2RMG	26.17	56%	67%	44.21	400565.12	7.89	6777.62	40.98	0.00	499656.42	0.00
R5-T0-H	YCS1	2RMG	31.74	69%	99%	32.14	279264.53	7.72	6604.43	38.36	35365.11	544906.39	960.92
R5-T25-H	YCS1	2RMG	31.79	70%	90%	31.98	281121.37	7.76	6887.17	38.25	34581.56	528458.71	958.09
R5-T50-H	YCS1	2RMG	31.15	70%	82%	31.94	272517.31	7.79	6842.20	38.13	28010.03	540052.54	827.97
R5-T75-H	YCS1	2RMG	30.07	73%	76%	31.86	271342.07	7.89	6959.42	38.14	17763.89	548933.12	580.74
R5-T100-H	YCS1	2RMG	28.57	72%	72%	37.99	549600.09	7.92	12345.04	34.84	0.00	345312.83	0.00
R5-T0-E	YCS2	2RMG	29.69	49%	99%	33.49	184942.45	7.66	4218.57	38.31	16389.43	722107.17	507.81
R5-T25-E	YCS2	2RMG	29.75	49%	86%	33.37	186312.15	7.64	4298.03	38.35	15688.88	704314.21	510.50
R5-T50-E	YCS2	2RMG	29.57	48%	77%	33.40	178792.94	7.69	4173.19	38.09	12302.31	714948.63	427.23
R5-T75-E	YCS2	2RMG	29.30	51%	70%	33.16	182566.83	7.79	4302.74	38.19	8547.71	709809.88	316.51

Continued on next page

Table B.3.: (continued)

Scenarios	Algorithms	Layout	StaMov	StaOcc	StaOcc2	AVG-GanT	GanT	AVG-TroT	TroT	AVG-EmptyT-Job	BlTim	YCIdleT	NumConfs
R5-T100-E	YCS2	2RMG	28.51	51%	64%	38.20	345395.28	7.75	7298.69	35.31	0.00	543999.90	0.00
R20-T0-E	YCS2	2RMG	29.29	49%	98%	33.76	185926.87	7.70	4858.52	38.90	18753.68	719767.35	504.36
R20-T25-E	YCS2	2RMG	28.98	51%	86%	33.78	192072.92	7.74	4824.78	38.92	18153.13	700119.08	509.21
R20-T50-E	YCS2	2RMG	28.34	50%	79%	34.01	190094.53	7.79	4501.27	38.75	14468.67	706903.07	427.30
R20-T75-E	YCS2	2RMG	27.57	54%	72%	33.94	201303.88	7.91	4430.27	38.70	10321.97	700195.97	318.10
R20-T100-E	YCS2	2RMG	26.28	55%	67%	44.00	398486.86	7.91	6978.73	40.56	0.00	501484.19	0.00
R5-T0-H	YCS2	2RMG	31.75	69%	99%	31.85	277882.97	7.76	6877.47	37.98	36520.80	543356.13	982.76
R5-T25-H	YCS2	2RMG	31.83	70%	90%	31.70	280010.47	7.78	7116.89	38.00	35843.63	526828.66	984.53
R5-T50-H	YCS2	2RMG	31.23	70%	82%	31.71	271785.62	7.80	7002.70	38.04	28893.90	537679.62	851.07
R5-T75-H	YCS2	2RMG	30.19	73%	76%	31.70	270068.69	7.90	7134.57	38.02	17971.96	547359.41	589.64
R5-T100-H	YCS2	2RMG	28.69	72%	72%	37.79	546423.22	7.92	12671.48	34.47	0.00	346466.79	0.00
R5-T0-E	YCS2/Split	2RMG	29.88	48%	97%	33.27	182052.13	7.78	4192.57	37.24	9156.41	726422.92	487.50
R5-T25-E	YCS2/Split	2RMG	30.73	48%	83%	31.05	174184.88	7.67	4231.25	33.67	6618.41	725736.06	408.48
R5-T50-E	YCS2/Split	2RMG	31.58	45%	73%	28.88	156060.31	7.63	4189.22	30.10	3817.95	755014.26	270.69
R5-T75-E	YCS2/Split	2RMG	33.13	45%	64%	26.11	141722.69	7.54	4641.93	26.48	1874.32	771383.87	148.09
R5-T100-E	YCS2/Split	2RMG	34.33	43%	55%	26.03	235961.74	7.15	9382.46	24.36	0.00	638858.92	0.00
R5-T0-E	YCS1	2RMG-Cr	31.44	57%	110%	50.37	298029.54	7.60	3266.00	49.80	34967.33	653545.80	518.63
R5-T25-E	YCS1	2RMG-Cr	31.78	57%	96%	49.81	298680.44	7.53	3319.76	49.52	34116.62	651636.48	525.51
R5-T50-E	YCS1	2RMG-Cr	31.80	55%	88%	48.84	284102.75	7.52	3342.77	48.59	31816.68	672287.20	498.61
R5-T75-E	YCS1	2RMG-Cr	31.93	57%	80%	47.32	285781.63	7.63	3817.98	46.68	32303.48	663726.91	506.03
R5-T100-E	YCS1	2RMG-Cr	31.54	57%	72%	44.87	261969.03	7.84	4336.82	42.90	31385.61	680889.49	472.54
R20-T0-E	YCS1	2RMG-Cr	31.27	57%	110%	50.74	300449.05	7.50	3824.93	50.42	36079.44	648081.01	537.66
R20-T25-E	YCS1	2RMG-Cr	31.34	58%	97%	51.36	308104.56	7.47	3722.15	51.28	35134.94	640122.55	537.68
R20-T50-E	YCS1	2RMG-Cr	31.03	57%	89%	51.82	301647.45	7.57	3580.23	51.70	32842.63	653356.23	505.89
R20-T75-E	YCS1	2RMG-Cr	30.75	60%	82%	52.00	314598.59	7.71	3862.02	51.38	33335.01	634286.92	514.56
R20-T100-E	YCS1	2RMG-Cr	29.88	60%	75%	51.68	302434.80	7.97	4208.42	49.50	32288.07	644672.93	480.54
R5-T0-H	YCS1	2RMG-Cr	34.56	78%	102%	50.25	456491.08	7.78	5233.98	50.23	59032.16	407947.19	967.99
R5-T25-H	YCS1	2RMG-Cr	35.02	79%	95%	49.52	457948.04	7.78	5484.49	49.62	57945.03	402410.81	994.22
R5-T50-H	YCS1	2RMG-Cr	34.63	78%	89%	48.52	438941.98	7.73	5550.75	48.61	53714.75	430886.24	929.31
R5-T75-H	YCS1	2RMG-Cr	33.99	80%	84%	46.74	426725.81	7.85	6323.08	46.14	51683.07	449048.65	886.75
R5-T100-H	YCS1	2RMG-Cr	32.95	80%	80%	44.08	412956.48	7.96	7676.56	41.73	52042.98	519667.78	852.82
R5-T0-E	YCS2	2RMG-Cr	31.77	56%	115%	49.55	296224.60	7.61	3364.49	49.20	35983.11	654705.27	569.72

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Table B.3.: (continued)

Scenarios	Algorithms	Layout	StaMov	StaOcc	StaOcc2	AVG-GanT	GanT	AVG-TroT	TroT	AVG-EmptyT-Job	BlTim	YCIdleT	NumConfs
R5-T25-E	YCS2	2RMG-Cr	32.04	56%	99%	49.03	297637.13	7.52	3360.39	49.15	35147.75	652107.67	587.30
R5-T50-E	YCS2	2RMG-Cr	31.93	55%	89%	48.20	284576.73	7.51	3322.60	48.68	32701.16	671286.84	574.22
R5-T75-E	YCS2	2RMG-Cr	31.92	57%	81%	46.73	287238.93	7.65	3770.62	47.11	33006.13	661582.54	606.58
R5-T100-E	YCS2	2RMG-Cr	31.43	57%	72%	44.16	263939.49	7.84	4272.59	43.34	32066.01	678008.12	597.83
R20-T0-E	YCS2	2RMG-Cr	31.61	56%	114%	49.94	298537.81	7.51	3937.21	49.78	37079.78	649272.37	578.88
R20-T25-E	YCS2	2RMG-Cr	31.60	57%	100%	50.63	307218.32	7.54	3791.34	50.93	36163.08	640254.81	594.15
R20-T50-E	YCS2	2RMG-Cr	31.19	56%	90%	51.10	301530.52	7.57	3590.01	51.67	33616.76	652947.06	571.78
R20-T75-E	YCS2	2RMG-Cr	30.76	60%	82%	51.41	315916.39	7.76	3812.44	51.82	33829.49	632666.36	599.25
R20-T100-E	YCS2	2RMG-Cr	29.80	60%	75%	50.91	304220.40	7.98	4135.55	49.93	32828.16	641722.33	595.31
R5-T0-H	YCS2	2RMG-Cr	35.49	76%	111%	49.17	449567.08	7.71	5637.68	48.57	60582.48	412775.48	1026.44
R5-T25-H	YCS2	2RMG-Cr	35.96	76%	101%	48.57	452417.61	7.69	5734.05	48.34	59946.36	407093.07	1068.56
R5-T50-H	YCS2	2RMG-Cr	35.27	76%	92%	47.83	436627.42	7.73	5578.01	48.21	55287.65	431273.28	1028.08
R5-T75-H	YCS2	2RMG-Cr	34.14	79%	85%	46.29	428030.87	7.87	6180.35	46.48	52440.20	446447.31	1012.88
R5-T100-H	YCS2	2RMG-Cr	32.80	80%	80%	43.44	416424.75	7.95	7559.33	42.19	53183.87	515349.10	1057.17
R5-T0-E	YCS2/Split	2RMG-Cr	29.37	49%	101%	49.79	240344.01	7.70	2558.33	48.93	28394.48	741028.66	408.76
R5-T25-E	YCS2/Split	2RMG-Cr	30.05	49%	87%	48.21	235792.63	7.60	2534.13	49.11	26756.23	746308.48	410.89
R5-T50-E	YCS2/Split	2RMG-Cr	30.93	46%	76%	45.01	213395.87	7.49	2641.74	47.10	23854.44	774114.49	374.39
R5-T75-E	YCS2/Split	2RMG-Cr	32.63	45%	66%	39.04	192704.73	7.35	3273.46	41.39	24025.20	787465.88	386.12
R5-T100-E	YCS2/Split	2RMG-Cr	35.07	42%	54%	29.61	144300.12	7.22	4182.02	29.51	27067.11	822051.79	425.65

Table B.4.: Results concerning the yard workload for different RMG-based layouts with transfer points

Scenarios	Algorithms	Layout	NumRetr	NumSto	NumOver	RatioStaMov
R5-T0-E	YCS1	1RMG-W8	36488.27	36260.83	0.00	97.62%
R5-T25-E	YCS1	1RMG-W8	36610.50	37159.03	0.00	98.99%
R5-T50-E	YCS1	1RMG-W8	35286.60	36400.80	0.00	96.19%
R5-T75-E	YCS1	1RMG-W8	37432.07	37092.37	0.00	100.00%
R5-T100-E	YCS1	1RMG-W8	35686.50	36656.50	0.00	97.07%
R5-T0-H	YCS1	1RMG-W8	54632.40	55450.17	0.00	95.31%
R5-T25-H	YCS1	1RMG-W8	55945.07	56072.73	0.00	96.99%
R5-T50-H	YCS1	1RMG-W8	54912.60	55112.03	0.00	95.26%
R5-T75-H	YCS1	1RMG-W8	56252.80	55433.30	0.00	96.70%
R5-T100-H	YCS1	1RMG-W8	57797.23	57700.10	0.00	100.00%
R5-T0-E	YCS1	1RMG	36577.30	36355.87	0.00	97.67%
R5-T25-E	YCS1	1RMG	36679.40	37253.83	0.00	99.01%
R5-T50-E	YCS1	1RMG	35365.70	36454.03	0.00	96.18%
R5-T75-E	YCS1	1RMG	37510.90	37160.07	0.00	100.00%
R5-T100-E	YCS1	1RMG	35706.53	36663.90	0.00	96.92%
R20-T0-E	YCS1	1RMG	36545.87	36342.10	1.67	97.45%
R20-T25-E	YCS1	1RMG	36657.60	37244.23	2.83	98.81%
R20-T50-E	YCS1	1RMG	35388.23	36461.20	5.03	96.06%
R20-T75-E	YCS1	1RMG	37559.57	37233.57	17.80	100.00%
R20-T100-E	YCS1	1RMG	35827.27	36749.63	248.77	97.04%
R5-T0-H	YCS1	1RMG	54894.80	55775.63	0.00	95.58%
R5-T25-H	YCS1	1RMG	56212.87	56541.63	0.00	97.38%
R5-T50-H	YCS1	1RMG	55187.00	55666.37	0.00	95.74%
R5-T75-H	YCS1	1RMG	56559.87	55864.40	0.00	97.09%
R5-T100-H	YCS1	1RMG	57938.10	57853.20	0.00	100.00%
R5-T0-E	YCS2	1RMG	36497.67	36191.20	0.00	97.60%
R5-T25-E	YCS2	1RMG	36569.43	37096.53	0.00	98.91%
R5-T50-E	YCS2	1RMG	35226.47	36357.27	0.00	96.12%
R5-T75-E	YCS2	1RMG	37396.43	37078.10	0.00	100.00%
R5-T100-E	YCS2	1RMG	35700.07	36660.50	0.00	97.16%
R20-T0-E	YCS2	1RMG	36494.77	36189.70	2.03	97.41%
R20-T25-E	YCS2	1RMG	36568.23	37096.90	2.60	98.72%
R20-T50-E	YCS2	1RMG	35247.73	36372.43	4.50	95.98%
R20-T75-E	YCS2	1RMG	37475.33	37145.27	15.50	100.00%
R20-T100-E	YCS2	1RMG	35814.23	36743.70	246.33	97.24%
R5-T0-H	YCS2	1RMG	54873.43	55246.57	0.00	95.19%
R5-T25-H	YCS2	1RMG	56434.40	55693.90	0.00	96.92%
R5-T50-H	YCS2	1RMG	55074.73	54807.20	0.00	94.98%
R5-T75-H	YCS2	1RMG	56234.10	55332.33	0.00	96.44%
R5-T100-H	YCS2	1RMG	57901.10	57785.30	0.00	100.00%
R5-T0-E	YCS2/Split	1RMG	36527.50	36193.53	0.00	97.83%
R5-T25-E	YCS2/Split	1RMG	36535.27	37093.10	0.00	99.05%
R5-T50-E	YCS2/Split	1RMG	35166.33	36343.33	0.00	96.20%
R5-T75-E	YCS2/Split	1RMG	37303.80	37033.80	0.00	100.00%
R5-T100-E	YCS2/Split	1RMG	35586.07	36640.90	0.00	97.16%
R5-T0-E	YCS1	2RMG	36304.00	36156.80	0.00	97.39%
R5-T25-E	YCS1	2RMG	36435.17	37075.43	0.00	98.80%
R5-T50-E	YCS1	2RMG	35160.53	36345.97	0.00	96.11%
R5-T75-E	YCS1	2RMG	37338.60	37061.37	0.00	100.00%
R5-T100-E	YCS1	2RMG	35703.90	36661.13	0.00	97.26%
R20-T0-E	YCS1	2RMG	36303.47	36155.03	2.03	97.20%
R20-T25-E	YCS1	2RMG	36446.07	37084.43	2.67	98.64%

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Table B.4.: (continued)

Scenarios	Algorithms	Layout	NumRetr	NumSto	NumOver	RatioStaMov
R20-T50-E	YCS1	2RMG	35194.80	36364.13	4.67	96.00%
R20-T75-E	YCS1	2RMG	37422.63	37120.93	17.57	100.00%
R20-T100-E	YCS1	2RMG	35827.63	36768.07	249.87	97.39%
R5-T0-H	YCS1	2RMG	54338.40	55105.50	0.00	94.54%
R5-T25-H	YCS1	2RMG	55627.37	55569.63	0.00	96.05%
R5-T50-H	YCS1	2RMG	54535.60	54765.77	0.00	94.42%
R5-T75-H	YCS1	2RMG	56009.57	55260.63	0.00	96.12%
R5-T100-H	YCS1	2RMG	57929.53	57834.90	0.00	100.00%
R5-T0-E	YCS2	2RMG	36269.60	36156.03	0.00	97.38%
R5-T25-E	YCS2	2RMG	36411.47	37075.50	0.00	98.81%
R5-T50-E	YCS2	2RMG	35142.47	36342.23	0.00	96.11%
R5-T75-E	YCS2	2RMG	37318.17	37056.30	0.00	100.00%
R5-T100-E	YCS2	2RMG	35699.90	36662.63	0.00	97.29%
R20-T0-E	YCS2	2RMG	36263.27	36155.03	1.97	97.19%
R20-T25-E	YCS2	2RMG	36418.30	37080.53	2.53	98.64%
R20-T50-E	YCS2	2RMG	35176.33	36361.63	5.20	96.01%
R20-T75-E	YCS2	2RMG	37400.13	37112.97	17.03	100.00%
R20-T100-E	YCS2	2RMG	35818.23	36754.30	246.80	97.40%
R5-T0-H	YCS2	2RMG	54231.70	55090.93	0.00	94.47%
R5-T25-H	YCS2	2RMG	55545.43	55545.00	0.00	96.00%
R5-T50-H	YCS2	2RMG	54492.60	54742.40	0.00	94.39%
R5-T75-H	YCS2	2RMG	55973.90	55230.90	0.00	96.09%
R5-T100-H	YCS2	2RMG	57903.50	57821.20	0.00	100.00%
R5-T0-E	YCS2/Split	2RMG	36245.83	36152.50	0.00	97.54%
R5-T25-E	YCS2/Split	2RMG	36355.23	37070.17	0.00	98.92%
R5-T50-E	YCS2/Split	2RMG	35078.13	36321.57	0.00	96.19%
R5-T75-E	YCS2/Split	2RMG	37215.77	37010.03	0.00	100.00%
R5-T100-E	YCS2/Split	2RMG	35583.57	36641.20	0.00	97.30%
R5-T0-E	YCS1	2RMG-Cr	36451.90	36247.10	0.00	97.65%
R5-T25-E	YCS1	2RMG-Cr	36565.40	37144.10	0.00	99.01%
R5-T50-E	YCS1	2RMG-Cr	35237.43	36378.00	0.00	96.19%
R5-T75-E	YCS1	2RMG-Cr	37377.93	37070.67	0.00	100.00%
R5-T100-E	YCS1	2RMG-Cr	35656.97	36645.77	0.00	97.12%
R20-T0-E	YCS1	2RMG-Cr	36436.63	36242.13	0.40	97.53%
R20-T25-E	YCS1	2RMG-Cr	36557.57	37137.40	1.20	98.89%
R20-T50-E	YCS1	2RMG-Cr	35244.87	36382.77	2.03	96.12%
R20-T75-E	YCS1	2RMG-Cr	37413.50	37105.57	8.87	100.00%
R20-T100-E	YCS1	2RMG-Cr	35727.47	36677.27	195.63	97.16%
R5-T0-H	YCS1	2RMG-Cr	54557.43	55400.63	0.00	95.48%
R5-T25-H	YCS1	2RMG-Cr	55878.20	55983.07	0.00	97.14%
R5-T50-H	YCS1	2RMG-Cr	54775.43	54998.97	0.00	95.32%
R5-T75-H	YCS1	2RMG-Cr	56029.67	55268.60	0.00	96.65%
R5-T100-H	YCS1	2RMG-Cr	57613.33	57546.90	0.00	100.00%
R5-T0-E	YCS2	2RMG-Cr	36307.23	36159.17	0.00	97.46%
R5-T25-E	YCS2	2RMG-Cr	36422.67	37076.90	0.00	98.85%
R5-T50-E	YCS2	2RMG-Cr	35134.90	36336.70	0.00	96.13%
R5-T75-E	YCS2	2RMG-Cr	37313.13	37039.20	0.00	100.00%
R5-T100-E	YCS2	2RMG-Cr	35653.43	36645.87	0.00	97.24%
R20-T0-E	YCS2	2RMG-Cr	36299.43	36158.40	0.43	97.37%
R20-T25-E	YCS2	2RMG-Cr	36424.67	37077.77	0.67	98.77%
R20-T50-E	YCS2	2RMG-Cr	35149.50	36346.23	3.00	96.07%
R20-T75-E	YCS2	2RMG-Cr	37348.17	37069.07	8.13	100.00%
R20-T100-E	YCS2	2RMG-Cr	35716.77	36668.43	197.93	97.27%
R5-T0-H	YCS2	2RMG-Cr	54433.40	55119.07	0.00	95.14%

Continued on next page

Table B.4.: (continued)

Scenarios	Algorithms	Layout	NumRetr	NumSto	NumOver	RatioStaMov
R5-T25-H	YCS2	2RMG-Cr	55843.23	55516.17	0.00	96.71%
R5-T50-H	YCS2	2RMG-Cr	54576.97	54677.30	0.00	94.88%
R5-T75-H	YCS2	2RMG-Cr	55858.67	55108.33	0.00	96.37%
R5-T100-H	YCS2	2RMG-Cr	57613.17	57534.97	0.00	100.00%
R5-T0-E	YCS2/Split	2RMG-Cr	36236.97	36154.67	0.00	97.51%
R5-T25-E	YCS2/Split	2RMG-Cr	36356.10	37070.77	0.00	98.91%
R5-T50-E	YCS2/Split	2RMG-Cr	35080.53	36321.00	0.00	96.18%
R5-T75-E	YCS2/Split	2RMG-Cr	37229.80	37007.30	0.00	100.00%
R5-T100-E	YCS2/Split	2RMG-Cr	35568.80	36634.43	0.00	97.26%

Table B.5.: Results concerning seaside and landside turnover of containers for the RTG-based layout with transfer lanes

Scenarios	Algorithms	QCR	AVG-BlockT	TerOcc	2BerOcc	BerOcc	CtMoves	Truck-TAT
R5-T0-E	YCS1	43.64	12.88	51%	15%	40%	36036.23	292.41
R5-T25-E	YCS1	43.48	13.05	60%	20%	46%	43142.33	285.72
R5-T50-E	YCS1	43.32	13.37	64%	28%	51%	49820.67	274.46
R5-T75-E	YCS1	43.17	13.79	73%	42%	61%	62202.07	261.37
R5-T100-E	YCS1	43.38	13.57	81%	54%	69%	72599.53	0.00
R20-T0-E	YCS1	31.50	44.39	65%	28%	57%	36758.27	380.65
R20-T25-E	YCS1	31.33	44.69	74%	38%	65%	43861.83	370.94
R20-T50-E	YCS1	31.70	43.43	79%	48%	71%	50707.57	351.95
R20-T75-E	YCS1	32.02	42.45	90%	68%	83%	63744.90	330.54
R20-T100-E	YCS1	32.82	39.86	96%	82%	90%	74982.97	0.00
R5-T0-H	YCS1	40.39	19.46	72%	37%	62%	55425.67	343.52
R5-T25-H	YCS1	40.35	19.43	79%	50%	68%	65289.20	332.04
R5-T50-H	YCS1	40.86	18.37	86%	62%	75%	76313.17	306.34
R5-T75-H	YCS1	41.44	17.33	96%	80%	86%	93425.23	280.70
R5-T100-H	YCS1	41.20	18.04	100%	96%	94%	117065.93	0.00
R5-T0-E	YCS2	45.13	10.36	50%	14%	39%	35930.20	304.94
R5-T25-E	YCS2	44.67	11.03	58%	19%	45%	43047.20	299.95
R5-T50-E	YCS2	44.09	12.06	63%	27%	50%	49772.87	288.63
R5-T75-E	YCS2	43.52	13.20	73%	42%	61%	62142.10	275.98
R5-T100-E	YCS2	43.31	13.74	81%	54%	69%	72584.37	0.00
R20-T0-E	YCS2	38.28	24.52	56%	20%	47%	36226.77	699.39
R20-T25-E	YCS2	36.95	27.66	66%	28%	56%	43329.60	736.80
R20-T50-E	YCS2	34.99	32.98	74%	41%	65%	50169.33	758.37
R20-T75-E	YCS2	33.40	37.93	87%	64%	79%	63348.40	789.04
R20-T100-E	YCS2	32.15	42.11	97%	84%	91%	75203.03	0.00
R5-T0-H	YCS2	43.42	13.55	69%	33%	57%	55165.37	434.60
R5-T25-H	YCS2	42.88	14.47	75%	46%	64%	64831.93	410.43
R5-T50-H	YCS2	42.41	15.35	83%	59%	72%	75922.87	377.75
R5-T75-H	YCS2	42.04	16.16	95%	78%	85%	93069.70	358.04
R5-T100-H	YCS2	41.08	18.34	100%	96%	94%	117039.9	0.00

Table B.6.: Results concerning HMT performance measures for the RTG-based layout with transfer lanes

Scenarios	Algorithms	HMT-Dist	AVG-HMT-Dist	HMT-Occ	HMT-Occ2
R5-T0-E	YCS1	1040907.72	346.63	40%	79%
R5-T25-E	YCS1	1243168.09	345.81	46%	78%
R5-T50-E	YCS1	1436327.04	346.02	51%	80%
R5-T75-E	YCS1	1790627.87	345.47	61%	83%
R5-T100-E	YCS1	2089238.85	345.37	69%	86%
R20-T0-E	YCS1	1114371.50	363.82	57%	88%
R20-T25-E	YCS1	1325087.25	362.58	65%	88%
R20-T50-E	YCS1	1530525.75	362.23	71%	89%
R20-T75-E	YCS1	1919886.83	361.44	83%	92%
R20-T100-E	YCS1	2260907.25	361.84	90%	94%
R5-T0-H	YCS1	1609302.05	348.44	62%	85%
R5-T25-H	YCS1	1892427.06	347.83	68%	86%
R5-T50-H	YCS1	2208758.71	347.34	75%	88%
R5-T75-H	YCS1	2704426.34	347.38	86%	90%
R5-T100-H	YCS1	3400803.47	348.62	94%	94%
R5-T0-E	YCS2	1038218.32	346.77	39%	78%
R5-T25-E	YCS2	1240664.70	345.88	45%	77%
R5-T50-E	YCS2	1435182.51	346.09	50%	80%
R5-T75-E	YCS2	1788241.06	345.34	61%	83%
R5-T100-E	YCS2	2090708.29	345.68	69%	86%
R20-T0-E	YCS2	1099684.25	364.26	47%	85%
R20-T25-E	YCS2	1310385.44	362.92	56%	85%
R20-T50-E	YCS2	1514804.68	362.35	65%	87%
R20-T75-E	YCS2	1910034.84	361.79	79%	91%
R20-T100-E	YCS2	2267100.88	361.75	91%	94%
R5-T0-H	YCS2	1600159.74	348.11	57%	83%
R5-T25-H	YCS2	1878427.47	347.70	64%	85%
R5-T50-H	YCS2	2195058.07	346.96	72%	87%
R5-T75-H	YCS2	2693932.48	347.35	85%	90%
R5-T100-H	YCS2	3396525.46	348.26	94%	94%

Table B.7.: Results concerning stack and yard performance measures for the RTG-based layout with transfer lanes

Scenarios	Algorithms	StaMov	StaOcc	StaOcc2	AVG-GanT	GanT	AVG-TroT	TroT	YCIdleT	NumRetr	NumSto	NumOver	RatioTotalStaMov
R5-T0-E	YCS1	31.59	37%	72%	30.31	109913.17	7.09	57040.38	709023.21	36336.17	36235.03	0.00	97.27%
R5-T25-E	YCS1	31.54	38%	63%	30.28	111393.04	7.19	58161.94	701055.11	36465.67	37162.67	0.00	98.69%
R5-T50-E	YCS1	31.37	37%	58%	30.27	108261.70	7.33	56826.76	708953.10	35197.23	36393.80	0.00	95.96%
R5-T75-E	YCS1	31.32	39%	53%	30.30	112944.79	7.41	59410.74	688216.15	37414.60	37190.03	0.00	100.00%
R5-T100-E	YCS1	31.33	38%	47%	30.28	109838.65	7.73	58694.51	692950.03	35806.60	36793.53	0.00	97.31%
R20-T0-E	YCS1	31.50	37%	56%	30.25	110820.98	7.09	57567.02	713085.09	36604.23	36715.10	4254.93	96.27%
R20-T25-E	YCS1	31.50	37%	50%	30.29	112520.58	7.16	58706.68	706759.22	36723.20	37644.53	3993.07	97.65%
R20-T50-E	YCS1	31.33	36%	46%	30.27	109669.04	7.28	57641.76	717093.19	35584.00	36910.67	3189.60	95.19%
R20-T75-E	YCS1	31.37	38%	42%	30.28	115178.12	7.34	60865.16	701775.38	38014.83	38142.97	3545.50	100.00%
R20-T100-E	YCS1	31.39	37%	39%	30.29	113495.34	7.67	60924.58	731862.62	36903.60	38090.87	4504.73	98.47%
R5-T0-H	YCS1	32.63	54%	74%	30.25	165432.50	7.01	85057.36	523361.18	54251.77	55177.67	21.83	93.47%
R5-T25-H	YCS1	32.61	55%	69%	30.24	168386.96	7.03	86815.26	510345.13	55676.60	55726.30	47.70	95.16%
R5-T50-H	YCS1	32.31	54%	63%	30.23	165555.12	7.10	85894.74	522974.38	54652.23	54904.77	0.00	93.58%
R5-T75-H	YCS1	31.89	55%	58%	30.19	168964.44	7.17	87838.80	517091.99	56287.00	55591.40	91.90	95.57%
R5-T100-H	YCS1	31.86	51%	51%	29.86	175367.80	7.60	94013.19	632813.19	58398.93	58670.90	2681.03	100.00%
R5-T0-E	YCS2	31.85	37%	73%	28.86	104903.95	7.08	56865.37	712654.89	36255.80	36207.83	0.00	97.20%
R5-T25-E	YCS2	31.76	37%	64%	29.08	107432.53	7.18	58106.17	704036.51	36397.53	37134.57	0.00	98.64%
R5-T50-E	YCS2	31.49	37%	58%	29.37	105747.57	7.33	56800.97	710178.48	35176.27	36368.87	0.00	95.97%
R5-T75-E	YCS2	31.41	39%	53%	29.66	111412.79	7.37	59328.26	689286.25	37375.80	37171.73	0.00	100.00%
R5-T100-E	YCS2	31.37	38%	47%	29.70	108777.66	7.73	58651.17	692501.97	35806.20	36779.13	0.00	97.37%
R20-T0-E	YCS2	31.95	36%	64%	28.58	101404.69	7.10	57279.01	720518.93	36455.00	36397.80	3981.33	96.11%
R20-T25-E	YCS2	31.81	37%	55%	28.85	103720.76	7.20	58434.88	712348.29	36554.00	37330.83	3797.40	97.47%
R20-T50-E	YCS2	31.59	36%	49%	29.20	102575.61	7.32	57394.69	720848.12	35390.87	36590.57	3093.60	94.96%
R20-T75-E	YCS2	31.45	38%	44%	29.55	109642.39	7.38	60754.88	701199.09	37924.50	37878.23	3464.80	100.00%
R20-T100-E	YCS2	31.37	37%	38%	29.76	110011.01	7.63	61084.36	736480.75	36991.30	38224.17	4524.73	99.23%
R5-T0-H	YCS2	33.15	53%	77%	28.06	153535.79	7.01	84673.16	530982.88	54099.87	55086.40	17.27	93.29%
R5-T25-H	YCS2	33.04	54%	72%	28.39	158201.04	7.04	86300.25	517953.70	55455.53	55521.47	42.63	94.82%
R5-T50-H	YCS2	32.59	54%	64%	28.96	159095.90	7.10	85521.22	525561.50	54436.93	54742.93	0.00	93.28%
R5-T75-H	YCS2	31.99	55%	58%	29.39	165137.74	7.17	87599.73	519009.02	56119.80	55411.33	127.43	95.29%
R5-T100-H	YCS2	31.89	51%	51%	29.25	172824.95	7.57	93936.62	637077.22	58390.73	58653.57	2756.57	100.00%

List of Abbreviations

A-RMG	Automated rail-mounted gantry (crane).
AGV	Automated guided vehicle.
ALV	Automated lifting vehicle.
AS/RS	Automated storage and retrieval systems.
BDP	Block design problem.
FBM	Fix block model.
FLP	Facility layout problem.
HMT	Horizontal means of transport.
ILP	Integer linear program.
LMTT	Linear motor-based transfer technology.
m	meter.
NYLM	Network formulation of the yard layout model.
OHBC	Overhead bridge cranes.
OR	Operations research.
QC	Quay crane.
QCR	Quay crane rate.
RCSP	Resource constrained shortest path problem.
RMG	Rail-mounted gantry (crane).
RTG	Rubber-tired gantry (crane).
SC	Straddle carrier.
sec	second.
TEU	Twenty-foot equivalent unit.
TGS	Twenty-foot ground slot.
TSA	Truck service area.

UML	Unified modeling language.
VND	Variable neighborhood descent.
YC	Yard crane.
YLM	Yard layout model.
YLP	Yard layout problem.
YT	Yard truck.

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