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Inland waterway terminal yard configuration contributing to sustainability
Modeling yard operations

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Abstract

In order to encourage a substantial shift from highly polluting freight transport by road to more sustainable Inland WaterWay (IWW) transport, one of the possible options is to optimize handling activities at Inland Waterway Terminals (IWTs). Therefore, this research focused on efficiencies of IWTs and possible improvements by analyzing the optimal configuration and operation of Reach Stackers (RSs) and terminal Yard Cranes (YCs) given certain throughput levels at IWTs. Our paper contributes to current scientific knowledge through the development of a tailor-made new model based on the maritime container terminal literature combined with the specificities of IWTs. The model results show that a growing throughput results in scale economies for IWTs. For small terminals, an unbalanced import/export-ratio (80-20 or vice versa) is often more efficient (and thus sustainable) than a balanced ratio (50-50), while this changes for larger terminals. Furthermore, by applying the model and analyzing the sensitivities, the paper contributes to managerial decisions to be taken by IWW terminal operators and also gives insight into the consequences of certain sustainability policies of local authorities on terminal operations. If these environmental rules and regulations are implemented, results indicate that this leads to a lower terminal capacity and thus higher costs.

1. Introduction

Due to the dominant role of road freight transport, a large variety of problems arises in this sector (Verdonk, et al., 2014). These problems include for instance congestion and different types of emissions (carbon dioxide, noise, fine dust), see e.g. Bergqvist et al. (2015). Intermodal freight transportation such as Inland WaterWay (IWW) transport and the use of IWW-terminals (IWTs) can be considered as a partial solution for these sustainability issues. This is because intermodal freight transport is often considered as more sustainable (less congested and depending on the exact characteristics also emitting less pollution) compared to freight transport by road. Furthermore, IWW transport is often seen as offering sufficient additional capacity for further growth of intermodal freight transport (Konings, et al. 2013). The more precise growth potential of IWW transport depends on the IWW network which in certain parts of Europe is well developed (Belgium, France, Germany, the Netherlands) and in other parts of Europe is less well developed limiting the growth potential there (or maybe even blocking further growth). Overall, in Europe, IWW transport represents around 5% of the container transport, but this share is growing (Smid et al., 2016). While in the Netherlands, the market share is considerably higher; approximately 35% of all container transport is executed by barge (Bureau Voorlichting Binnenvaart, 2016). IWW transportation through scale economies could therefore meet the need for efficient, environmentally friendly and less congested transportation in certain parts of Europe as compared to road transport. However, the (environmental) advantages of IWW transportation can be disputable because a delicate interplay is needed between pre- and end-haulage, terminals, and the barge transport. Especially the barge transport part contains a wide range of variables such as the area concerned, the kind of barge (type and size), the competitive transport alternative, the need for the river maintenance, the route (upstream or downstream), the type of operations (maximum 14 hours per day), semi-continuous (max. 18 hours/day) or continuous operations (24 hours/day)), fuel consumption, loading degree, delays in port areas, and the

possibilities for a roundtrip that influence the resulting environmental advantages (see e.g. Wiegmans and Konings, 2015).
In order to compete with road transport, it is of importance to further increase the quality and sustainability of IWW transport and especially also the IWTs. In Dotoli et al. (2017), the authors analyze the combined operation of terminal handlings and transport mean (train) composition to arrive at optimized combinations. Sun and Schonfeld (2016) analyze the effect of severe disruptions at intermodal rail freight transfer terminals. Both papers focus on the importance of planning rail transport with rail terminal operations, while IWTs are much more flexible with respect to transport mean (barges) schedules and schedule disruptions pose less of a challenge to IWTs. Still, these hinterland terminals are often regarded as crucial points in transport chains, where costs increase and chances exist for quality decreases (Bowersox et al. 1986). One of the ways to increase the performance, sustainability and quality of IWW transportation is to focus on the configuration of the IWT. In this respect, it is essential to ensure that the terminals work as efficient and effective as possible (Verdonk et al., 2014). One of the most important aspects of these inland container terminals is the interplay between quay, the terminal internal transport means and the container yard operations (Carlo et al., 2014a). This interplay can also be seen in more detail in Figure 1 below. In this paper, the container terminal infrastructure and operations that are concerned with the container handling are being examined, especially the use and interplay of the two main yard handling systems: Reach Stackers (RSs) and terminal Yard Cranes (YCs) operating in the container yard.
The most important decisions to be made concerning the operations in the terminal yard area are: selecting the type and number of handling systems to perform the handling and terminal internal transport. Selecting the appropriate equipment combination is important because it determines the fixed and variable terminal costs, as well as the terminal performance. If the IWT performance is good, it is able to contribute to a better performance of intermodal freight transport and to improve the sustainability of the overall freight transport system at the same time. This problem differs from more common problems at maritime terminals where for example, the scheduling of yard cranes with minimum energy consumption takes center stage (Sha et al. 2017). Given the number of Quay Cranes (QCs) in operation at IWTs, the most important decision is to implement an YC (or increase the number of YCs), in combination with the number of RSs. The moment for implementing an YC (or add a second or third one) at the IWT, to increase efficiency, performance and thereby the sustainability of the transport system is being evaluated given the IWT size. This leads to the following research question: How could the efficiency and sustainability of an IWW container terminal be improved by an optimal configuration and operation of RSs and terminal YCs? Our paper contributes to current knowledge through the development of a new model that focusses purely on the specificities of IWTs. In that respect is our model unique. Furthermore, by applying the model and analyzing sensitivities, the paper contributes to managerial decisions to be taken by IWW terminal operators. In section 2, the system that is analyzed will be described, followed by the literature review on the sustainability of intermodal freight transport and the most important decision variables for an IWT. In section 3, the required data for modeling the yard operations is presented. The container terminal operations model, consisting of the model objectives and the model specifications, is introduced in section 4. In section 5, this is followed by model simulations, including the results and analysis. Finally, section 6 will consist of the conclusions, discussions, and recommendations for further research.

2. Research context and methods

Sustainability in freight transportation receives more and more scientific attention. More traditional freight transport modes such as maritime transport and trucking largely depend on fossil fuels such as diesel. This propulsion of ships and trucks with fossil fuels leads to sustainability issues such as exhaust and emissions leading to degradation of our society. Especially also in intermodal freight transport, efforts are made to make solutions offered more competitive and also to increase the environmental advantages as compared to road transport. For example, the implementation of electric or hybrid trucks is analyzed in order to improve the sustainability of the pre- and end-haulage phase of IWW transport. The implementation of this type of trucks would indeed lead to less harmful emissions being emitted (Macharis et al. 2007). Iannone (2012) analyzed the social and private cost efficiency of port hinterland container distribution through a regional system. An important conclusion from the research was that the performance of the hinterland system depends on the quality of the interactions between the actors and the optimal functioning of all its elements. Reis (2014) proved that on short distance intermodal freight transport, especially price is a very important decision-making variable. Given the search for more sustainability in intermodal freight transport, combined with the need for cooperation between actors and the high importance of price, resulted in our focus on the efficient terminal operations. If terminal operations are efficient this might enable a lower price, making intermodal freight transport more attractive compared to road transport and thus leading to a more sustainable freight transport system with less road transport and more IWW transport (and rail).

2.1 Research context: inland waterway container terminal operations

The IWT consists of five direct handling-related components: 1. Berth, 2. Quay, 3. Terminal internal transport, 4. Storage yard, 5. Terminal gate (see Figure 1).

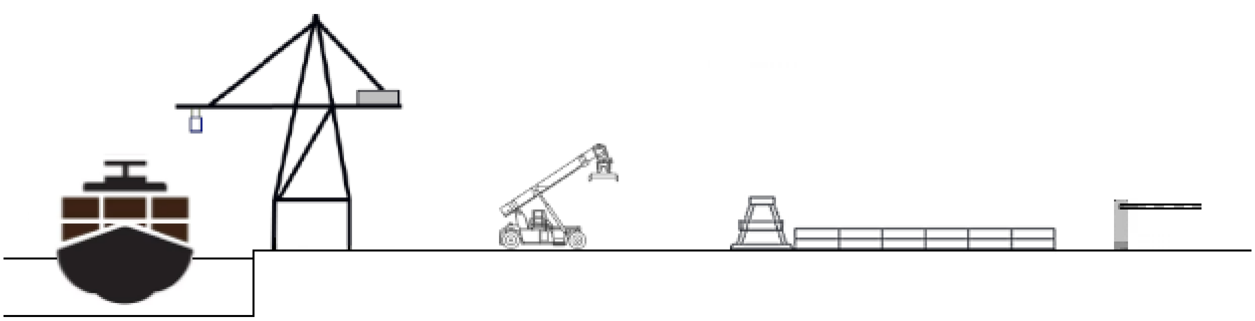

Figure 1 - Five main stages in an IWW container terminal
Source: based on Carlo et al., 2014a.

The berth (1) refers to the available space for a barge to maneuver and dock. The quay (2) is one of the costlier aspects of the IWT. The length of the quay, the water depth, and the carrying capacity for the cranes all influence the total cost of the quay. The terminal internal transport (3) could be executed with RSs or terminal tractors combined with chassis. The storage yard (4) can be operated by RSs, but usually when larger volumes are handled at the IWT, an YC is implemented. Finally, the terminal gate (5) handles the access to the terminal. In this paper, the focus will especially be put on the operation of the terminal yard because this has been indicated as being one of the most crucial areas of the IWT (Steenken et al., 2004, Carlo et al., 2014a, Carlo et al., 2014b, Hilhorst, 2017). In theory, the handling of containers at IWTs can be performed with 4 different types of handling/transport equipment: 1. Tractor with chassis for terminal internal transport from quay crane (QC) to storage yard, 2. RSs, 3. Straddle Carriers (SC), 4. YCs: Rubber-Tired Gantry (RTG) cranes and Rail-Mounted Gantry (RMG) cranes (see e.g. Carlo et al., 2014a). In the paper, two handling systems are considered: RSs and terminal YCs (RTG and RMG). Tractors with chassis are not considered, because they are not often found on IWTs and the straddle carrier is not included in the research because they are more the equipment type for maritime container terminals.

2.2 Literature review: IWT yard operation methods

Much scientific research has been done into the terminal configurations and operations in maritime container ports. For good reviews about container terminal operations and storage yard operations we refer to Steenken et al., 2004, Carlo et al., 2014a, and Carlo et al., 2014b. These reviews contain very good and detailed analyses of different individual container terminal operational aspects discussed in scientific papers. From these reviews, all important decision problems for maritime terminals treated in the scientific literature have been derived and these are displayed in the below Table 1.

Table 1. Main decision problems for maritime container terminals

	1 Berth	2 Quay	3 Transport	4 Yard	5 Gate
Decision problems	Berth allocation Stowage planning	Crane split Crane travel time Crane assignment Load sequence Unload sequence	Automated guided vehicles (AGVs) Dispatching AGV routing SCs routing Trailer (chassis) routing RS routing Truck scheduling Assign containers to RS AGV Waiting locations	Stack strategy Gantry crane transport optimization YC scheduling Crane travel time Reshuffling Export stack strategy Import stack strategy Yard allocation Scheduling multiple YCs AGV waiting location	n.a.

Underlined: these decision problems are important for IWTs

Sources: based on review papers: Steenken et al., 2004, Carlo et al., 2014a, Carlo et al., 2014b and based on Hilhorst, 2017.

Table 1 depicts that for maritime container terminals most decision problems are located in the terminal internal transport and in the terminal yard (fourth and fifth column). For example, Lee et al. (2006) analyze a yard storage allocation problem in a transshipment hub. On the one hand this is an interesting problem, but for IWTs there is not such a thing as a transshipment hub as most IWTs are located inland and function as begin or end terminals. However, also at IWTs the yard is an important area which takes center stage in analyses. Another research by Zhang et al. (2018) focusses on the optimization of truck appointments at container terminals. Although interesting, for IWTs this is not really a problem as their operations are much smaller and spread more evenly over the days. However, on the other hand a better truck appointment system at IWTs might enable a more efficient handling through more direct handlings from barge to truck and vice versa (bypassing the yard). Based on the scientific literature in IWT and IWW transport, for the IWTs it holds that the terminal internal transport and especially the yard, are the terminal areas where the most important decision problems are located (see underlined in Table 1). In addition, the yard is of crucial importance as this is the area where the terminal result is determined (Hilhorst, 2017). This altogether forms the most important reason in this paper to focus on the terminal yard. We also assume that if the yard operations improve, this also results in a better terminal performance, leading to a better intermodal barge transport service. This results in a better competitive position versus single-mode road transport contributing to a better environmental performance of the freight transport system.

2.2.1 Stack strategy

At most IWTs, the yard consists of all available space, besides the space used for the quay, gate and office. The terminal yard capacity can be used under the conditions that all the containers are reachable and that there is enough room to accommodate horizontal transport. When the quayside is also used for stacking, this can be considered as a dedicated part to stack containers as well. With equipment selection, a choice between two types of stacking equipment can be made: 1. RSs, and 2. YCs. An IWT usually starts operations with RSs as main handling system, because they are cheaper and more versatile. An estimate of a terminal manager of an export-oriented terminal is that it is feasible to implement an YC if the yearly throughput of import containers is approximately 20,000 (Hilhorst, 2017). In general, more expensive cranes for a given area result in shorter response times for a pickup call but in higher crane investment cost. In summary, there is an economic trade-off among storage density, accessibility, investment cost, and level of service (Kim & Kim, 2002). This economic trade-off in the IWT yard takes center stage in our yard operations model.

General requirements and empties: There can be different stack strategies for import, export and empty containers. The stacking of empty containers is the easiest. According to Steenken et al., 2004, empty containers are often stored separately from loaded containers due to the possibility of using different equipment to store them higher than loaded containers. While methods for storage and stacking of empty containers do not differ for import and export stacking strategies, the distribution of empty containers to ports has been considered as a separate problem deserving specialized approaches (see e.g. Hjortnaes et al. 2017). For the import and export containers, often the exact container must be reached. When using YCs, the containers in maritime terminals can be stacked in blocks with a width of 6-8 and a length of 40 (Ng & Mak, 2005). This is not the case when using RSs at IWTs, here blocks with a width of 2-3 can be made, and the length does not matter. Furthermore, the way of stacking containers in the yard is limited by several layout requirements and external factors (Petering et al., 2009). Guo and Huang (2012) proposed a new dynamic YC workload partitioning scheme. They proved that this works well for maritime terminals, however, for IWTs such an approach is too advanced as operations usually are much simpler and do not justify such an approach. Jin et al. (2016) studied the daily storage yard management problem arising in maritime terminals. Their objective is to minimize the yard crane operating cost and the yard crane interblock moving cost. Although the IWT carries certain similarities, where the planning horizon differs (more on a weekly basis) and the planning can be overrun by the employees working in the yard which calls for an own dedicated IWT model. Specific operations layout requirements can be linked to the limited availability of space at the terminal, which is quite common for IWTs in the Netherlands. In terms of external factors, IWTs must respect (local) legislation concerning environmental and societal issues, which can limit their storage space (height) or operations as well. An environmental requirement for an IWT in the Netherlands can, for example, be to install a 4 or 5 high wall of containers around the terminal to limit the noise nuisance. A social requirement can, for example, be to vary the color of this container wall on a periodic basis (Hilhorst, 2017).

Import containers: After arrival, the barge is unloaded and most containers (99%) are stacked at the yard (average container stay is 5 days) and a small number of containers (1%) are immediately picked up by trucks. These numbers are based on judgements of 10 managers of randomly selected Dutch IWTs. For an import-oriented or unbalanced terminal (more import than export containers), it is more efficient to stack the import containers at the quay, to minimize the number of handlings. Kim (1997) investigates various stack configurations and their influence on the expected number of reshuffles in a scenario of loading maritime import containers onto outside trucks with a single transfer crane. For easy estimation regression equations were proposed. They found that the expected number of reshuffles for various configurations is different from each other. Therefore, in designing the container stack and the container handling equipment, the throughput performance of the equipment is an important factor to consider. Because of that, the throughput is an important input variable in our yard operations model, which is maximized to minimize the costs per container. Kim and Kim (1998, 2002) discuss the determination of the optimal storage space and the optimal number of transfer cranes for import containers. The decision is based on a cost model including fixed investment costs and variable operational costs. A solution procedure is illustrated with a numerical example including a sensitivity analysis. Two different objectives are considered: cost minimization of the terminal operator only and terminal cost minimization combined with the customers' costs. First, they conclude that the optimal space decreases as the space cost increase, but the optimal number of transfer cranes is insensitive to the change of the space cost. Secondly, both the optimal number of transfer cranes and the optimal space area increase as the cost of outside trucks increase. For both, the cost and the operations, our model is focused on the IWT yard where the space pressure is often less than on maritime terminals. Carlo et al. (2014b) mentioned that the yard operations of maritime import containers are decoupled from the transfer operations. This results in other objectives for the storage yard operations: instead of minimizing the vessel operational time, the objective of the storage yard operations could be to maximize throughput or minimize the maximum completion time.

Export containers at IWTs arrive at the gate by truck. The containers are either taken to the yard or directly to the quay, where they are stacked (Hilhorst, 2017). For an export-oriented terminal, it is more efficient to stack the export containers at the quay, to minimize the number of handlings. When containers are stacked at the quay, the 'best-practice' strategy is to stack the heaviest containers on top (Dragović et al. 2017). In this way, the number of reshuffles is reduced, because the heaviest containers should be loaded onto the bottom of the barge. In this respect, Kim and Bae (1998) propose a methodology to convert a current order of export containers in the yard into a bay layout which is best from the point of view of operations for loading a maritime vessel. The goal is to find the fewest possible number of containers and/or shortest possible travel distance to minimize the total turn-around time of a vessel in a port. The problem is decomposed, mathematical models (dynamic programming, transportation problem) for the three sub problems are suggested, and a numerical example is given. Their main conclusions are that since all the sub-problems are solved by mathematical programming techniques, it took a considerable computational time to solve each sub-problem, especially for the task sequencing problem. Because of this insight, just one all-including model will be developed for our research. Ng et al. (2010) present an Integer programming (IP) formulation and an iterative constructive heuristic for the problem with export containers in ports with cyclical calling patterns. A SA-based heuristic for this problem is proposed by Huang and Ren (2011) that requires enumerating all possible assignment permutations for three export container groups. The performance of the heuristic is not compared to existing storage policies. Their main conclusions are that it is very time consuming to optimally solve realistic problem sizes and that under certain conditions, the yard template found by the heuristic is indeed the optimal yard template. A computational experiment has been conducted to evaluate the performance of the heuristic and the results show that the heuristic can find the optimal yard template for 99% of the tested problems. Based on the simulation result, the addressing algorithm can obtain smaller re-stowing rates compared to the traditional decision. When the bay capacity increases, the advantage is more apparent. We use predefined parameters for the yard area to describe the yard template in our model, because the proposed optimal yard templates only hold under certain specific conditions.

2.2.2 Reshuffling strategy

In terminal yards, in general, reshuffles are caused by land-scarcity and information uncertainty. The second reason for generating reshuffles took center stage in the research of Zhao and Goodchild (2010). They studied the effect of considering container departure time information to minimize the number of reshuffles and intra-bay gantry crane travel distances for import containers for three different heuristics by means of simulation. They conclude that a complete arrival sequence is not required to reduce the number of reshuffles. Already little information is enough for significant benefits. Secondly, information requirements are significantly lowered when the information is updated real time. In our model, annual throughputs are considered, so information is not modeled in great detail and not really real time. However, their conclusions are useful for the determination of the average number of reshuffles relative to the productive moves at the terminal. Hirashima et al. (2006) focus on the pre-marshaling process for export containers. In the arrangement problem, the number of container-arrangements increases exponentially with increasing container volume. A Q-Learning algorithm, assuming that each container has several preferred final positions, is presented. It is concluded that the number of reshuffles by the proposed heuristic is smaller than those generated by the human operator in a real-scale problem. In our model, we use the exponential growing number of container arrangements for a growing throughput in the reshuffle rate formula which results in larger rates for larger IWTs. Important reshuffling strategies and their corresponding objectives for IWTs can be QC/ handling system (YC or RS) reshuffling, preventing unnecessary stacking height, and departure information uncertainty. From these reshuffling strategies, the following important model variables result: separate reshuffle rates for the yard handling systems and for import and export containers, reshuffle rates dependent of the stacking height and the throughput.

2.3 Research objectives

In order to reduce the number of polluting lorries at the road and achieve more sustainable freight transport, a growing share of IWW transport offers opportunities. This requires a growth of IWTs and an optimization of the yard activities can be part of this improved performance of IWW transport. Based on this, three research objectives for the IWT yard are distinguished: 1. focusing on the current situation, 2. focusing on the future situation considering a growth in throughput, and 3. focusing in more detail on what happens in between the first two situations in order to seek the best moments to invest in additional RSs and YCs. These three situations 'translate' into the following three objectives:

Obj. 1. Minimizing total costs (for the yard and entire terminal) for the current throughput.

Obj. 2. Minimizing total costs (for the yard and entire terminal) for variable throughput, by increasing the throughput until the bottleneck capacity is reached.

Obj. 3. Determining switching moments (in terms of throughput) based on the minimization of total costs (for the yard and entire terminal) for variable throughputs.

For these three objectives the assumption is that once the IWT performance improves this contributes to a better IWW transport, making road transport less attractive and leading to a better environmental performance of the total freight transport system.

3. Data: terminal inputs and cost inputs

A gross dataset has been collected (via https://www.inlandlinks.eu/nl/terminals/filter in combination with an extensive search including terminal company websites) containing data of 127 container terminals in Europe. Countries with relatively large contributions to the dataset are Germany, Belgium, and the Netherlands (Wiegmans and Witte, 2017). In the analysis, three different terminal types have been included: a small IWT with a capacity of 20,000 containers, a medium IWT with a capacity of 50,000 containers, and a large IWT with a capacity of 125,000 containers (Smid et al. 2016). The selection of these three different terminal sizes is based on average terminals that are 'representative in size' according to a large IWT database. A detailed explanation on the three alternative terminal layouts, references on terminals and data on other terminal characteristics are given, and an explanation on why those three alternatives are considered representative is provided in Appendix A (taken from Smid et al. 2016). The core model input parameters are given in Table 2 below. Based on the differences in terminal lay-out, the values for the handling equipment, operations and crew variables are determined in more detail. This determination is based on Smid et al. (2016) supplemented by findings from the literature review and by practical information obtained from an extended interview with an IWT operator of a relatively large IWT at Alphen aan de Rijn, in the Netherlands. This practically based data has been validated by data obtained from interviews with ten additional IWT managers in the Netherlands.

Table 2. Input parameters for three concept terminal layouts

Variable	Unit	Terminal S (small)	Terminal M (medium)	Terminal L(large)
Terminal layout				
Total terminal area	Ha	1.5	3	4
- quay yard	Ha	0.4	0.4	0.47

- yard	Ha	1	2.4	3
- office	Ha	0.03	0.03	0.03
- other	Ha	0.07	0.17	0.5
Quay length	m	200	200	240
Handling equipment				
QCs	Nr.	1	1	2
RSs	Nr.	1	3	3
YCs	Nr	0	0	1
Operations				
Throughput	TEU	20 000	50 000	125 000
Import/export balance	-	50-50	50-50	50-50
Operating hours/day	Hours	11	13	15
Operating days/week	Days	5	5	5
Crew				
Employees	Nr.	4	8	12
Manager	Nr.	1	1.5*	3
Guards	Nr.	2	2	2

Source: based on and extended from Smid et al., 2016. *part-time employee

Especially in densely populated areas, some not very efficient terminal layouts can be found, leading to inefficiently designed and operating terminals. The terminal layout is also influenced by the available possibilities for expansion at current terminals and by available locations for new IWTs. For simplification, the terminal layouts in this paper have been assumed to have general shapes. On the one hand this enables generalization of conclusions and on the other hand each terminal is different making it a challenge work with specific terminal layouts. In the model, the containers will be stacked in the terminal according to combined strategies based on the literature about handling equipment and interviews with IWT managers. Therefore, in the model, an import-oriented, an export-oriented and an import/export terminal are considered, with import/export-ratios of respectively 80%-20%, 20%-80% (unbalanced) and 50-50% (balanced).

Besides the yard operations model, a cost model is made for the calculation of the annual terminal costs. The cost model that has been used was originally obtained from Smid et al. 2016. Here, fixed costs based on the investment costs and variable costs are distinguished. The original cost model has been split into total terminal costs and yard costs. The values for different cost components are based on the fixed, predefined values from Smid et al. (2016) or are adapted based on the throughput, handling configuration, number of employees, terminal operating hours and the terminal layout linked to the yard operations model. Given a certain annual throughput the cost model will calculate the costs per container: specific for the yard and for the entire terminal for the different terminal types (see also Appendix A).

4. Inland waterway terminal yard operations model specification

In this section, the model specifications are provided. The indices, decision variables, input variables and operation parameters are included in Appendix B. These are implemented in the equations, shown in the cost functions, constraints and formulas concerning stacking strategy and reshuffling.

4.1 Cost functions

The model uses a cost function that calculates the cost/TEU for the entire terminal and specific for the yard, for four different variable handling configurations per terminal size. It calculates the minimum cost/TEU for that given handling configuration as well. This is done by increasing the throughput to the maximum design throughput. It then gives the share of the stacking cost that can be attributed to the yard. The formulas used to describe the cost functions are given in Appendix C.

4.2 Constraints

Two types of constraints are explained here: an equality constraint and a capacity constraint.

Equality constraint: the terminal handling configuration switching point

The switching moment between two handling configurations, i.e. when an extra RS can be added, can be calculated by dividing the yard costs by the minimal yard cost/TEU of the previous handling configuration. This point, expressed in TEU, is called the switching point. The same calculation is used for the total terminal costs.

$$SP_{yard,1\rightarrow 2} = \frac{C_{2,yard}}{C_{cmin1,yard}}$$

$$SP_{total,1\rightarrow 2} = \frac{C_{2,total}}{C_{cmin1,total}}$$

Capacity constraints:

The capacity constraints which are implemented in the model are related to the handling and the stacking capacity. The constraint that has the lowest value is leading and will determine the terminal throughput capacity. The handling equipment cannot operate at 100% of its' capacity, due to maintenance needed, breaks for the crew, etc., therefore 80% of the maximum handling capacity is considered (Hilhorst, 2017). For the determination of the capacity constraints, a distinction is made between six different groups of containers in the model. First, a separation in containers stacked by RS and YC is made. Then, for both groups the empty, import and export containers are distinguished. The number of containers per category depends on the share of the throughput per category for each part of the yard (YC and RS). For simplification, only the distinction in containers stacked by RS and by YC is shown in the formulas.

$$T_{max} = \min(S_{cap,rs}\ ;\ 0.8 * H_{cap,,rs}) + \min(S_{cap,yc}\ ;\ 0.8 * H_{cap,yc})$$

$$S_{cap,rs} = A_{y,rs} * SS_{rs} * h_{rs} * \frac{365}{t_{y,q,e}}$$

$$S_{cap,yc} = A_{y,yc} * SS_{yc} * h_{yc} * \frac{365}{t_{y,q,e}}$$

$$H_{cap,rs} = t * RS * Y_{rs} * HC_{,rs}/(1 + RF_{rs})$$

$$H_{cap,yc} = t * YC * HC_{yc}/\left(1 + RF_{yc}\right)$$

4.3 Stacking strategy and reshuffle factors

The current IWW stacking strategy is a 'best-practice' strategy. In the model, the largest category of loaded containers, import or export, is stacked at the quay. The containers from the other category, together with all empty containers and the surplus of containers from the quay, are stacked in the yard. Those are all stacked by RSs if only RSs are available in the configuration. If there is/are also (a) YC(s) available, the largest category of loaded containers going to the yard, is stacked by the YC(s). The smallest category and the empty containers are stacked by RSs. This best-practice strategy is based on practical Dutch IWT operations and optimal use of available handling equipment.

The reshuffle factors used in the calculation of the handling capacity (H_cap) are based on the average annual stacking height for both handling systems. Four different groups of containers are distinguished here: RS import, RS export, YC import and YC export. The reshuffle factor will be equal to zero when the stacking height is one and will be exponentially growing if the stacking height grows. The reshuffle factor for empty containers is always equal to zero. The average annual stacking height is slightly underestimated by taking 80% of the yard stacking capacity into account, to reckon with the unequally spread of stacking heights over the terminal. The reshuffle factors based on the initial throughput are also used for the determination of the maximum throughput. Also, this underestimated reshuffle factor for the future situation is partly compensated by considering just 80% of the yard stacking capacity.

$$h = T_y \; / \; (0.8 * \frac{S_{cap}}{h_{max}})$$

$$RF = k * \min(h \, ; \, h_{max})^2 - k$$

5. Simulation, results and analysis

In this chapter, the results of three simulated cases are shown (see also Table 3). Trial and error is used for obtaining the represented configurations for each terminal.

5.1 Handling configurations for Small, Medium, and Large terminals

Small terminal: Given a 'fixed' throughput of 20,000 TEU, the 2RS handling configuration results in the lowest costs per container. For further growth of the throughput towards the maximum design throughput, the 1RS and 1YC configuration becomes the cheapest. The maximum throughput could increase to more than 60,000 TEU. Concerning the bottlenecks of the different configurations, the handling capacity is the bottleneck for the 1RS and 2RS configurations. Whereas for the 3RS configuration, the handling capacity is sufficient and the yard stacking capacity becomes the bottleneck. This is the same for the 1RS and 1YC configuration, where the RS is left with a smaller area to operate, due to the area that the YC is occupying, which is relatively large for a small terminal. When the yard stacking capacity becomes the bottleneck, a solution could be to increase the size of the yard. This can however be difficult given the already limited expansion possibilities that IWTs are confronted with. The switching moments indicate when a terminal configuration needs an upgrade given the handled volume.

Medium: Given the current throughput of 50,000 TEU, a handling configuration with 1RS and 1YC is most optimal, when the total terminal costs per container are considered. For further growth of the throughput, the 1RS and 2YC configuration becomes most optimal. The handling capacity is leading for the RSs in the first two configurations. For the other configurations is the yard stacking capacity the bottleneck, which means that it makes no sense to add more RSs. For the YC in terminal M the handling capacity is always leading. However, the handling capacity is approaching the yard stacking capacity in the 1RS and 2YC configuration, so a configuration with more than two YCs leads to higher costs per TEU.

Table 3. Overview of basic configurations for small, medium, and large terminals

Terminal S (small)	**1RS**	**2RS**	**3RS**	**1RS and 1YC**
Max design throughput (TEU)	14635 total, 10142 yard	29270 total, 20284 yard	40699 total, 28205 yard	65495 total, 45388 yard
Bottleneck	Handling capacity RS	Handling capacity RS	Yard stacking capacity RS	- Yard stacking capacity RS - Yard stacking capacity YC
Cost/TEU 20 000 throughput	€99,56 terminal €60,55 yard only	€84,20 terminal €53,02 yard only	€95,55 terminal €61,73 yard only	€86,69 terminal €65,59 yard only
Cost/TEU, max design throughput	€99,56 terminal €60,55 yard only	€57,53 terminal €36,23 yard only	€46,95 terminal €30,34 yard only	€26,47 terminal €20,03 yard only
Switching moments (TEU)	-	1RS to 2RS 16914 terminal, 12137 yard	1RS to 3 RS 19194 terminal, 14132 yard 2RS to 3 RS 33214 terminal, 23618 yard	1RS to 1RS+1YC 17415 terminal, 15014 yard 2RS to 1RS+1YC 30136 terminal, 25092 yard 3RS to 1RS+1YC 36927 terminal, 29965 yard
Terminal M (medium)	**3RS**	**1RS and 1YC**	**2RS and 1YC**	**1RS and 2YC**
Max design throughput (TEU)	50353 total, 34744 yard	101890 total, 70304 yard	120093 total, 83280 yard	153834 total, 116686 yard
Bottleneck	Handling capacity RS	- Handling capacity RS - Handling capacity YC	- Yard stacking capacity RS - Handling capacity YC	- Yard stacking capacity RS - Handling capacity YC
Cost/TEU 50 000 throughput	€48,04 terminal €34,67 yard only	€43,32 terminal €35,33 yard only	€47,57 terminal €38,61 yard only	€49,54 terminal €44,21 yard only
Cost/TEU, max design throughput	€47,70 terminal €34,67 yard only	€21,26 terminal €17,59 yard only	€19,80 terminal €16,23 yard only	€16,10 terminal €13,26 yard only
Switching moments (TEU)	-	3RS to 1RS+1YC 45412 terminal, 35671 yard	3RS to 2RS+1YC 49861 terminal 38985 yard 1RS+1YC to 2RS+1YC 111871 terminal 76836 yard	3RS to 1RS+2YC 51926 terminal, 44633 yard 1RS+1YC to 1RS+2YC 116504 terminal 87968 yard 1RS+1YC to 1RS+2YC 125066 terminal 95346 yard
Terminal L (large)	**3 RS and 1 YC**	**1 RS and 2 YC**	**1 RS and 3 YC**	**1 RS and 5 YC**
Max design throughput (TEU)	66709 total, 46029 yard	99762 total, 68836 yard	155628 total, 111338 yard	212096 total, 167248 yard
Bottleneck	- Yard stacking capacity RS - Handling capacity YC	- Yard stacking capacity RS - Handling capacity YC	- Yard stacking capacity RS - Handling capacity YC	- Yard stacking capacity RS - Yard stacking capacity YC
Cost/TEU 125 000 throughput	€52,33 terminal €39,57 yard only	€33,57 terminal €27,51 yard only	€29,31 terminal €25,23 yard only	€34,34 terminal €32,41 yard only
Cost/TEU, max design throughput	€52,33 terminal €39,57 yard only	€33,57 terminal €27,51 yard only	€23,54 terminal €19,83 yard only	€20,24 terminal €16,96 yard only
Switching moments (TEU)	-	3RS+1YC to 1RS+2YC 64008 terminal, 47849 yard	3RS+1YC to 1RS+3YC 70014 terminal, 55791 yard 1RS+2YC to 1RS+3YC 109122 terminal, 80260 yard	3RS+1YC to 1RS+5YC 82026 terminal, 71674 yard 1RS+2YC to 1RS+5YC 127844 terminal, 103110 yard 1RS+3YC to 1RS+5YC 182327 terminal, 143035 yard

Large: Given a throughput of 125,000 TEU, a handling configuration with 1RS and 3YCs is most optimal. A configuration with only 1 or 2 YCs is insufficient for this throughput. If the throughput could increase, the costs/TEU could even become lower. Then, the 1 RS and 5 YCs configuration would be most optimal. For that configuration, the maximum throughput could become more than 200,000 TEU. When looking at the bottlenecks of the different configurations, the bottleneck for RSs is always due to the yard stacking capacity. That is the reason why only 1 RS is used in most of the configurations. The handling capacity becomes the bottleneck for the YCs, excepted for the last configuration. In case of multiple YCs in the yard, it is more efficient to change the stacking strategy. Now, just a small part of the smallest category and a small part of the empty containers can be stacked by RSs. It would be more efficient to use one YC to stack import containers, another to stack export containers and RSs can still be used to stack (a part of) the empties.

Overall, it is important that IWTs function as efficient as possible as this contributes to the attractiveness of intermodal freight transport. It improves the competitive position versus single-mode road transport and in this respect makes the freight transport system more sustainable. It is also important to use public finances in a socially acceptable way and therefore detailed insights in terminal size operations are important in order to be able to decide upon public involvement in terminal subsidies.

5.2 Stacking strategies for Small, Medium, and Large terminals

The literature review showed that different stacking strategies can be applied to the terminal yard. For IWTs the most important one is 'best-practice' combined with a division of containers in import, export, and empties. Below, the configurations for the S, M, and L terminals with the lowest cost are analyzed on their stacking strategy, combined with unbalanced throughput (80-20 or 20-80) and balanced throughput (50-50) (see also Table 4).

Small 2RS: An unbalanced terminal does have a considerable higher design throughput than a balanced terminal leading to lower cost/TEU when the design throughput is realized. In the case of the balanced terminal, the relatively high number of containers going to the yard and reshuffles are the main aspects that limit the potential growth. In the 'fixed' throughput case (20,000 TEU), a balanced terminal has lower yard costs/TEU than an unbalanced terminal. This is caused by the fact that more containers are going to the yard in the case of the balanced terminal (69% instead of 51%). On the other hand, more containers to the yard of the balanced terminal results in higher reshuffle ratio's (35% instead of 13%), so the terminal costs per container are even a little bit higher. The higher ratio of containers going to the yard, results in an earlier purchase of an YC in case of a balanced ratio. The results for an 80-20 or a 20-80 ratio (unbalanced) are the same, because there are no main differences between import and export containers.

Medium 1RS+1YC: In the case of the unbalanced terminal, the maximum design throughput could be a bit higher, because of the more efficient utilization of the quay capacity. This results in lower cost/TEU for the maximum design throughput. The maximum yard throughput is the same for both cases, because the potential growth is always bottlenecked by the handling capacity of the yard equipment. The terminal cost/TEU are approximately the same, because in both cases is it possible to prevent reshuffles. For this terminal size, the influence of different import/export-ratios is of less importance compared to terminal S, however, the ratio of containers to the yard is growing for the case with the balanced ratio, just like for

Terminal S (69% instead of 51%). The maximum design throughput of the (un)balanced terminal do not differ much, leading to not too much difference in the switching moments.

Large 1RS+3YC: The design throughput of the (unbalanced) terminal does not differ much. For the balanced terminal, the cost/TEU is slightly lower, given the initial throughput. There is not enough space to stack 80% of the loaded containers at the quay (the quay stack is sufficient to stack 50% of the loaded containers). For the balanced terminal 69% of the containers is stacked in the yard (instead of 65%). In this balanced terminal case, only two different container categories go to the yard instead of three. For a further growing throughput, the cost/TEU for the case of an unbalanced ratio becomes slightly lower due to the higher maximum throughput. This is caused by the reshuffle factor for the YC (62%). For the unbalanced terminal, this reshuffle factor is higher (73%). In case of an unbalanced terminal, the yard stacking capacity has already been reached in a configuration with 4 YCs. Therefore, it would not be efficient to add a fifth one.

Table 4. Terminal configurations and impact of import-export flows on stacking strategies

	Terminal S (small) (2RS)		Terminal M (medium (1RS+1YC)		Terminal L (large)(1RS+3YC)	
	50-50 import-export	**80-20 import-export 20-80 import-export**	**50-50 import-export**	**80-20 import-export 20-80 import-export**	**50-50 import-export**	**80-20 import-export 20-80 import-export**
Max throughput (TEU)	29270 TEU total 20284 TEU yard	44699 TEU total 23011 TEU yard	101890 TEU total 70304 TEU yard	106987 TEU total 70304 TEU yard	155628 TEU total 111338 TEU yard	162427 TEU total 118070 TEU yard
Bottleneck	Handling capacity RS	Yard capacity RS	Handling capacity RS Handling capacity YC	Handling capacity RS Handling capacity YC	Yard capacity RS Handling capacity YC	Yard capacity RS Handling capacity YC
Cost/TEU 20 000 throughput	€84,20 terminal €53,02 yard only	€82,28 terminal €75,78 yard only	€43,32 terminal €35,33 yard only	€43,32 terminal €49,92 yard only	€29,31 terminal €25,23 yard	€29,88 terminal €27,54 yard
Cost/TEU, max design throughput	€57,53 terminal €36,23 yard only	€36,81 terminal €33,91 yard only	€21,26 terminal €17,59 yard only	€20,25 terminal €18,46 yard only	€23,54 terminal €19,83 yard	€23,00 terminal €19,19 yard
Switching moments (TEU)	2RS to 3RS 33214 TEU terminal 23618 TEU yard 2RS to 1RS+1YC 30136 TEU terminal 25092 TEU yard	2RS to 3RS - - 2RS to 1RS+1YC 47097 TEU terminal 28601 TEU yard	1RS+1YC to 2RS+1YC 111871 TEU terminal 76836 TEU yard 1RS+1YC to 1RS+2YC 116504 TEU terminal 87968 TEU yard	1RS+1YC to 2RS+1YC 117468 TEU terminal 76526 TEU yard 1RS+1YC to 1RS+2YC 122332 TEU terminal 87132 TEU yard	1RS+3YC to 1RS+4YC 168978 TEU terminal 127187 TEU yard 1RS+3YC to 1RS+5YC 182327 TEU terminal 143035 TEU yard	1RS+3YC to 1RS+4YC 176093 TEU terminal 134449 TEU yard 1RS+3YC to 1RS+5YC - -

5.3 Sensitivity Analysis

When varying the decision variables to test the sensitivity, different outcomes arise, shown in Table 5. This is done to show that when the generalized decision variables are changed for different local contexts, the results are also affected. This is important to note because decision variables for individual terminals can deviate from the ones used in this paper.

Table 5. Sensitivity analysis Terminal S, M and L

Terminal S (small)(2RS)	**Original decision variables**	**Allowed stacking height (3-high)**	**Average staying time container in yard 6 days**	**Average staying time container at quay 5 days**	**Average staying time empty container 15 days**	**Share (of direct transport 5%)**
Costs per TEU	€57,53 terminal €36,23 yard	€57,53 terminal €36,23 yard	€59,27 terminal €37,31 yard	€57,53 terminal €36,23 yard	€77,39 terminal €48,57 yard	€53,59 terminal €35,18 yard
Maximum design throughput (TEU)	29270 terminal 20284 yard	29270 terminal 20284 yard	28516 terminal 19762 yard	29270 terminal 20284 yard	22639 terminal 15689 yard	31312 terminal 20822 yard
Terminal M (medium) (1RS + 1YC)	**Original decision variables**	**Allowed stacking height (3-high)**	**Average staying time container in yard 6 days**	**Average staying time container at quay 5 days**	**Average staying time empty container 15 days**	**Share (of direct transport) 5%**
Costs per TEU	€21,26 terminal €17,59 yard	€24,90 terminal €20,60 yard	€23,03 terminal €19,06 yard	€21,71 terminal €17,59 yard	€23,17 terminal €19,17 yard	€20,03 terminal €17,59 yard
Maximum design throughput (TEU)	101890 terminal 70304 yard	86991 terminal 60024 yard	94044 terminal 64891 yard	99791 terminal 70304 yard	93484 terminal 64504 yard	108160 terminal 70304 yard
Terminal L (large) (1RS + 3YC)	**Original decision variables**	**Allowed stacking height (3-high)**	**Average staying time container in yard to 6 days**	**Average staying time container at quay to 5 days**	**Average staying time empty container to 15 days**	**Share (of direct transport) 5%**
Costs per TEU	€23,54 terminal €19,83 yard	€26,06 terminal €20,25 yard	€26,91 terminal €23,50 yard	€25,75 terminal €20,47 yard	€24,07 terminal €20,45 yard	€22,64 terminal €19,83 yard
Maximum design throughput (TEU)	155628 terminal 111338 yard	141475 terminal 108013 yard	136168 terminal 93956 yard	142866 terminal 107253 yard	152190 terminal 107935 yard	161791 terminal 111338 yard

Important decision variables for terminals are the allowed stacking height, the average staying time in the yard, at the quay and of empties and the share of direct transport. When the allowed stacking height would be restricted to 3-high, due to environmental reasons for instance, the costs will increase for all terminal sizes. An exception is terminal S, where only RSs are operating and RSs already have a maximum stacking height of three containers. When the average staying time of a container in the yard is increased from 5 to 6 days, the cost/TEU increases slightly due to a drop-in throughput as a result of the longer staying time. When the average staying time of a container at the quay is increased from 4 to 5 days, no changes in cost arise for terminal S, meaning that the quay stack does not bottleneck the maximum design throughput, even when the staying time of containers increases by a day. For terminal M and L, the costs/TEU increases a little, because the factor of containers going to the yard increases slightly. When the average staying time of empty containers increases from 10 to 15 days, the costs for the entire terminal and the yard increase, especially for terminal S. This is caused by an increasing reshuffle factor for the RSs from 35% towards 75%. When the share of direct transport increases from 1 to 5% the costs/TEU for the entire terminal decrease. Fewer containers need to be stacked in this scenario, meaning that the design throughput can be higher, resulting in lower average terminal costs. Especially the terminal yard has been indicated a crucial element for the inland terminal performance by the terminal managers. Therefore, terminal yard performance is important for two reasons: 1. If the handlings in the yard are minimized, this minimizes energy usage and also noise, CO_2 and particulate emissions. 2. If the handlings in the yard are minimized this contributes to a healthy financial performance of the terminal and in that way it also contributes to a better performance of intermodal freight transport.

6. Conclusion, discussion and further research

In order to encourage a substantial shift from highly polluting freight transport by road to more sustainable IWW transport, one of the possible options is to optimize handling activities at IWTs. Therefore, this research focused on efficiencies of IWTs and possible improvements by analyzing the optimal configuration and operation of RSs and terminal YCs given certain throughput levels. If the efficiencies of IWTs improve, this contributes to more sustainable terminals and better IWW transport. The novelty of the paper is the optimization of IWT yard operations, by selecting the right handling equipment. Therefore, a new dedicated model that analyzes yard operations for IWTs in detail is developed. Furthermore, the application of this model gives policymakers and terminal operators insight in efficient operations and implications of environmental policies on operations can be determined. In the literature review, a wide range of decision problems are identified for maritime terminals. For IWTs only a small number of these problems concentrated in terminal internal transport and the yard are important. This paper mainly focused on these yard activities and determined how the efficiency and sustainability of an IWT could be improved by an optimal configuration and operation of RSs and terminal YCs.

The literature review revealed that most of the decision issues from IWTs are located in the terminal internal transport and in the terminal yard. In the terminal yard, different stacking strategies such as import- and export stacking and reshuffling minimization can be found. In general, the stacking activities of IWTs are more basic and in practice, more flexible than those of maritime terminals. The terminal and cost inputs led to different concept terminal layouts which were further specified according to handling equipment used. For the terminal yard operations model, the objectives have been identified as cost minimization and determining the handling equipment switching moment. The model is developed to calculate the costs/TEU for an initial design throughput and a further growing throughput, bottlenecked by the yard stacking capacity or the handling capacity. If efficiency improves at IWTs at lower costs can be realized, at the same the sustainability of the IWT will improve because resources are used more efficiently leading to lower emissions. The model results indicate the optimal configuration (the initial design throughput) and the maximum throughput. For the period in between are the optimal moments determined, in terms of throughput, to switch from one configuration to another. In Table 6, an overview of the most important results obtained from the model simulation are presented.

Table 6 Overview of the main important simulation results

		Terminal S (small)	**Terminal M (medium)**	**Terminal L (large)**
Initial throughput	Optimal configuration	2RS	1RS and 1YC	1RS and 3YC
	Throughput	20000	50000	125000
	Cost/TEU	€84,20 terminal €53,02 yard	€43,32 terminal €35,33 yard	€29,31 terminal €25,23 yard
	Optimal import/ export-ratio	Unbalanced	Does not matter	Balanced
Maximum throughput	Optimal configuration	1RS and 1YC	1RS and 2YC	1RS and 5YC
	Throughput (TEU)	65495 total, 45388 yard	153834 total, 116686 yard	212096 total, 167248 yard
	Cost/TEU	€26,47 terminal €20,03 yard	€16,10 terminal €13,26 yard	€20,24 terminal €16,96 yard
	Bottleneck	Yard stacking capacity RS Yard stacking capacity YC	Yard stacking capacity RS Handling capacity YC	Yard stacking capacity RS Yard stacking capacity YC
	Switching moments (TEU)	1RS to 1RS+1YC 17415 terminal, 15014 yard 2RS to 1RS+1YC 30136 terminal, 25092 yard 3RS to 1RS+1YC 36927 terminal, 29965 yard	3RS to 1RS+2YC 51926 terminal, 44633 yard 1RS+1YC to 1RS+2YC 116504 terminal 87968 yard 1RS+1YC to 1RS+2YC 125066 terminal 95346 yard	3RS+1YC to 1RS+5YC 82026 terminal, 71674 yard 1RS+2YC to 1RS+5YC 127844 terminal, 103110 yard 1RS+3YC to 1RS+5YC 182327 terminal, 143035 yard
	Optimal import/ export-ratio	Unbalanced	Unbalanced	Unbalanced

In the model, the largest category of containers, import or export, is stacked at the quay, while the containers from the other category, together with the empty containers, are stacked in the yard. For small terminals, an unbalanced ratio between import and export containers results in lower cost/TEU, because the quay stack is used efficiently. For larger terminals, where the quay stack becomes too small to stack all containers from the largest category, a more efficient use of the quay stack can be realized by a balanced terminal. In general, an efficient use of the quay stack results in more postponement of purchasing an (additional) YC. The maximum design throughput can be higher for an unbalanced terminal, so an unbalanced ratio is always more favorable for all terminal sizes when the throughput is as large as the bottleneck capacity. Reshuffle ratios from both the RSs and the YCs are also important factors here. Larger throughputs going to the yard result in higher reshuffle factors. These high reshuffle factors are the result of more additional moves needed in the yard leading to more emissions and therefore, more efficiency in the yard (less reshuffles) results in a better sustainability. An efficient distribution of the different categories over the handling systems (QCs, YCs and RSs) can reduce these reshuffle factors. For larger terminals, this becomes often more difficult, so in general they deal with higher reshuffle factors and use a YC-focused stacking strategy. In general, upgrading the handling capacity is often easier for IWTs than upgrading the yard stacking capacity, because the limited space for IWTs is, especially in a dense country like the Netherlands, an important problem.

Yard operations are sometimes restricted by local legislation concerning environmental and societal aspects. Therefore, locally determined IWT dependent decision variables, for instance stacking height, staying time of containers and/or direct transshipment ratio, are varied in order to analyze variations in local contexts, regulations and policies as well as the model sensitivity. This results in changes in the cost/TEU and possible throughputs. Overall, these results indicate that if environmental rules and regulations are implemented, this leads to a lower terminal capacity and thus higher costs. Furthermore, it seems that smaller terminals are more sensitive for those changes than larger terminals.

Overall, the efficiency of IWTs could be improved realizing a growing throughput in order to realize scale economies. This could increase the modal shift from road to barge, leading to the use of a more sustainable mode of transport as compared to single-mode road transport. The efficient use of the valuable space at the quay can be encouraged by using the QC as a stacking crane and if the quay stack is used efficiently, the purchase of an (extra) YC can be postponed. This would lead to higher efficiency without having to grow in throughput, making this a relatively more sustainable solution. In addition, an unbalanced terminal (mainly export or mainly import) is more efficient for small terminals, because the quay stack can be used more efficient than in case of a balanced terminal. For all terminals operating on their maximum capacity, an unbalanced ratio is more efficient, because of the higher possible maximum design throughputs. Also, direct transshipment between the barge and the pre- and end-haulage encourages the efficiency of the terminal as the capacity of the terminal increases while at the same time the terminal resource use increases less. Finally, for the terminal operator, it is important to switch from or add a handling system at the right moment in order to prevent large differences between capacity and volume.

Our paper contributes to current scientific knowledge through the development of a tailor-made new model based on the maritime container terminal literature combined with the specificities of IWTs. In that respect, our IWT model is unique and new to the scientific literature. Furthermore, by applying the model and analyzing the sensitivities, the paper contributes to managerial decisions to be taken by IWT operators and also gives insight into the consequences of certain sustainability policies on terminal operations. The conclusions are generalizable because the terminal sizes have been built out of a larger database and in that sense are representative. On the other hand, the exact outcomes for a particular IWT depends on the precise terminal layout of that terminal. The outcomes can be influenced by local contexts, environmental regulations or other factors.

Further research could concentrate on varying the QC types for the three terminal sizes. Especially for a small terminal, it is more affordable to invest in a smaller crane. The possibilities for direct transshipment can also be elaborated further. It is important to note that through optimizing the efficiency at IWTs, the IWW transportation has a better chance to compete with road transport. This mode of transport is less polluting, so more environmentally friendly and sustainable. However, it should always be carefully monitored that the problems are not shifted to densely populated areas, making this also a topic that could be researched in future studies. In addition to our new developed model, alternative modelling approaches are agent-based modelling and also simulation of IWTs and their respective operations could contribute to bottom-up analysis strategies instead of top-down strategies (see e.g. Nelson et al. 2017).

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Appendices

Appendix A: Explanation about the terminal types 100% originating from Smid et al. (2016):

"From the joint perspective of volume and capacity, we identify the following five characteristic types of IWTs: XXL-terminals, XL-terminals, L-terminals, M-terminals, and S-terminals (See Table 1 for an overview). In this paper, terminal classes 3, 4, and 5 are used.

Name	TEU Volume	Terminal area	*Quay length*	Cranes	Reach stackers
1. XXL-Terminal	500,000	20 hectares	400 meters	4	4
2. XL-Terminal	200,000	7 hectares	300 meters	3	4
3. L-Terminal	125,000	4 hectares	240 meters	2	3
4. M-Terminal	50,000	3 hectares	200 meters	1	3
5. S-Terminal	20,000	1.5 hectares	200 meters	1	1

Table 1. Intermodal IWW terminal types distinguished according to volume.
Source: based on a database of approximately 50 IWW terminals

The main advantage of this classification system is that it is 'neutral' in the way the different terminal types are distinguished. Therefore, we use this classification to distinguish between the different terminal types in our research. More specifically, we combine distinct volume classes of the respective terminals with operating characteristics in more detail for the classes3, 4, and 5.

In principle, the average cost of an IWW terminal handling service should reflect all costs that are needed to produce this service. The average cost may include a wide range of cost drivers because offering a handling service may involve many activities. Criteria are needed to split costs into different categories. Important categories include (Cooper and Kaplan, 1999): 1) direct versus indirect costs, 2) fixed costs versus variable costs, 3) completely individualized and restrained individualized costs, and 4) activity-based costing. In this analysis, we utilized a widely used and accepted system of fixed and variable cost. Fixed costs can be defined as expenses that are not dependent on the level of services produced by a business, or, in other words, they do not change as a function of the business activity within the relevant (considered) period. Important fixed cost components for IWW container terminals are terminal area, quay, crane, reach stackers, fence, IT systems, office, lighting poles, interest, licenses, insurance, administration costs, and taxes. Variable cost components depending on the level of services produced by the business are employees, manager, electricity, fuel, guards, and maintenance (see Table 2 and 3 for an overview). Also, in practice, many of these variable components are 'fixed' or semi-variable (except fuel and electricity) because the terminal needs to be open and ready for use by (potential) customers.

Table 2 Overview of the most important cost categories

	S	M	L	XL	XXL
Fixed costs					
Area	9%	13%	8%	12%	17%
Quay(s)	5%	4%	3%	2%	1%
Crane	19%	13%	20%	14%	10%
Reach stackers	3%	2%	2%	2%	1%
Office	1%	0%	0%	0%	0%
IT Systems	5%	5%	3%	2%	1%
Fence	0%	0%	0%	0%	0%
Lighting poles	0%	0%	0%	0%	0%
Interest	21%	20%	18%	18%	19%
Insurance	2%	2%	2%	1%	0%
Terminal taxes (licenses)	3%	2%	2%	1%	0%
Other	3%	3%	3%	3%	3%
Semi variable costs					
Employees	14%	19%	18%	23%	23%
Management fee	7%	7%	9%	9%	10%
Guards	0%	0%	0%	0%	0%
Variable costs					
Fuel/electricity	7%	7%	9%	11%	12%
Repair & Maintenance	2%	2%	2%	2%	2%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Own calculations

Table 3 Intermodal IWW terminal assets

Cost drivers – Assets IWW terminal	**Newly Built/installed**		**Unit**
	Supply Lump sum		Unit
Quay	7.500 - 12.500		m
Handling area	€ 176		m2
Storage area	€ 176		m2
Handling equipment (Quay-side Gantry Crane)	€ 3 mln		Unit
Handling/storing equipment: straddle carrier	€ 0,5 mln		Unit
Handling/storing equipment: RTG crane	€ 0,8 mln		Unit
Handling and storing equipment: rail-mounted GC	€ 1 mln		Unit
Handling and storing equipment: terminal tractor with trailer	€ 0,75 mln		Unit
Handling and storing equipment: reach stacker	€ 0,4 mln		Unit
Office	€ 50k		Unit
ICT-systems	€ 200-300k		Unit
Fence	€ 85		m
Lighting poles	€ 780		Unit

* Global prices, excl. VAT, index 2012 = 100

Smid et al. 2016. ”

Appendix B

Terminal yard operations indices

Indices	Description	Value
Ts	Terminal size, this determines the terminal characteristics	(S, M or L)
RS	The number of RSs present on the terminal	$RS \in rs\ \{0, \dots, X\}$
YC	The number of YCs present on the terminal	$YC \in yc\{0, \dots, X\}$
QC	The number of QCs present on the terminal	$QC \in qc\{0, \dots, X\}$

Terminal yard operations decision variables

Decision variables	Description	(Original) value
Im/Ex/Ep	Import/export/empty container ratio	$Im \in \{0, \dots, 1\}, Ex \in \{0, \dots, 1\}, Ep = 0{,}4\ and\ \mathrm{Im} + \mathrm{Ex} + \mathrm{Ep} = 1$
$h_{max,rs}$ $h_{max,yc}$	Allowed stacking height of the containers	3 (RS), 4 (YC)
t_y	Average container terminal yard staying time	5 days
t_q	Average container quay staying time	4 days
t_e	Average empty container staying time	10 days
H	Handlings per container	Depending on reshuffling rate
$S_{y/dt}$	Ratio yard/direct transshipment	$S_{y/dt}$ = 0,99/0,01
h_{rs} h_{yc}	Average annual container stacking height	Calculated
k_{rs} k_{yc}	Fixed value (constant) for the determination of reshuffle factors	k = 1/4 (RS), 1/6 (YC)
RF_x	Reshuffling factor, dependent on stacking height and throughput	Calculated

Terminal yard operations input variables

Input variables	Description	Value
t	Opening hours (per year)	Terminal specific, table 2
l_q	Quay length	Terminal specific, table 2
A_t	Terminal area	Terminal specific, table 2
A_y	Yard area	Terminal specific, table 2
A_{yc}	Stacking surface YC	8 * min (40;$\sqrt{A_y}$) TEU
A_q	Quay area	Terminal specific, table 2
A_{qc}	Stacking surface QC	Quay length [TEU] * 8 TEU
A_o	Office area	Terminal specific, table 2
T_t	Total throughput	Terminal specific, table 2
T_y	Yard Throughput	Terminal specific, calculated
E	Employees	Terminal specific, table 2
M	Managers	Terminal specific, table 2
l_f	Fence Length	Terminal specific, calculated
lp	Light posts	Terminal specific, calculated
Costs		
C_l	Used land Investment costs	176 euro/m2
C_q	Quay Investment costs	7500 euro/m
C_{qc}	QC Investment costs	3.700.000 euro
C_{yc}	YC Investment costs	2.760.000 euro
C_{rs}	RS Investment costs	400.000 euro
C_o	Office Investment costs	500 euro/m2
C_{ICT}	ICT-systems Investment costs	200.000 euro
C_f	Fence Investment costs	85 euro/m
C_{lp}	Lightning poles Investment costs	780 euro/n
t_l	Land depreciation	20 years
t_q	Quay depreciation	20 years
t_{qc}	QC deprecation	10 years
t_{yc}	YC deprecation	10 years
t_{rs}	RS depreciation	10 years
t_o	Office depreciation	5 years
t_{ICT}	ICT systems depreciation	3 years
t_f	Fence deprecation	10 years
t_{lp}	Lightning poles deprecation	5 years
I	Interest rate	4% of the total assets
In	Insurance	50.000 euro
Tt	Terminal taxes (licenses)	50.000 euro
O	Other	5% of all fixed costs
C_{la}	Labor costs	50.000 euro per employee
C_m	Management fee	100.000 euro per manager
C_g	Guards costs	10.000 euro
C_{fu}	Fuel costs	1 liter/ TEU
C_e	Electricity costs	30 kWh/operating hour
C_{rm}	Repair and maintenance costs	5% of all variable costs

Terminal yard operations parameters

Parameters	Description	Value
HC_{RS}	Handling capacity of RSs in terms of container handlings per hour	15 TEU/h
SS_{RS}	Stacking space of RSs in terms of containers per hectare	500 TEU/ha
Y_{RS}	Share of RS use contributing to yard activities	Yrs= 0,4
HC_{YC}	Handling capacity of YCs in terms of container handlings per hour	20 TEU/h
SS_{YC}	Stacking space of YCs in terms of containers per hectare	1000 TEU/ha

$H_{cap, total}$	*Handling capacity*
S_{cap}	*Stacking capacity*
T_{max}	*Maximum throughput*
SP_{total}	*Switching point for the entire terminal, in TEU*
SP_{yard}	*Switching point for the yard, in TEU*
$C_{c,total}$	*Container Costs entire terminal*
$C_{c,yard}$	*Container Costs yard*
$C_{cmin,total}$	*Minimum container costs entire terminal, in euro*
$C_{cmin,yard}$	*Minimum container costs yard, in euro*

Sources: Kalmar (2016), Hilhorst (2017), Smid et al. (2016).

Appendix C

$$C_{fixed,total} = (\frac{A_t * C_l}{t_l} + \frac{l_q * C_q}{t_q} + \frac{QC * C_{qc}}{t_{qc}} + \frac{YC * C_{yc}}{t_{yc}} + \frac{RS * C_{rs}}{t_{rs}} + \frac{A_o * C_o}{t_o} + \frac{C_{ICT}}{t_{ICT}} + \frac{l_f * C_f}{t_f} + \frac{lp * C_{lp}}{t_{lp}}$$

$$+I * \left(A_t * C_l + l_q * C_q + QC * C_{qc} + YC * C_{yc} + RS * C_{rs} + A_o * C_o + C_{ICT} + l_f * C_f + lp * C_{lp}\right) + In + Tt) * (1 + O)$$

$$C_{variable,total} = E * C_{la} + M * C_m + C_g + C_{fu} + C_e + C_{rm} * \left(\frac{A_t * C_l}{t_l} + \frac{l_q * C_q}{t_q} + \frac{QC * C_{qc}}{t_{qc}} + \frac{YC * C_{yc}}{t_{yc}} + \frac{RS * C_{rs}}{t_{rs}} + \frac{A_o * C_o}{t_o} + \frac{C_{ICT}}{t_{ICT}} + \frac{l_f * C_f}{t_f} + \frac{lp * C_{lp}}{t_{lp}}\right)$$

$$C_{c,total} = \frac{C_{fixed} + C_{variable}}{\min(T, T_{max})}$$

$$C_{cmin,total} = \frac{C_{fixed} + C_{variable}}{T_{\max}}$$