Optimising quay crane operations based on data-driven cycle time prediction

A case study at APM Terminals MVII

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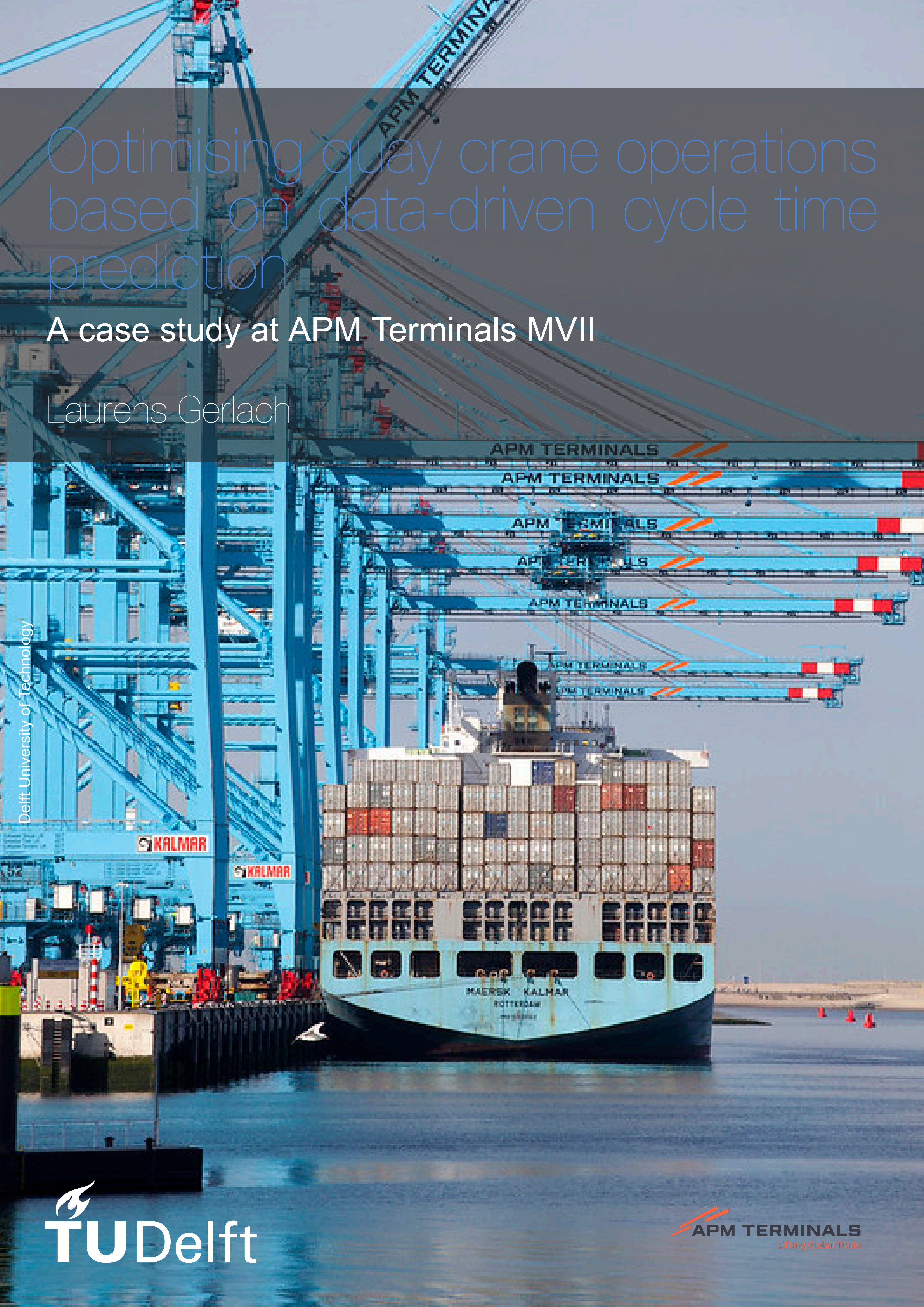

TU Delft

APM TERMINALS
Lifting Global Trade

Optimising quay crane operations based on data-driven cycle time prediction

A case study at APM Terminals MVII

by

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Preface

Before you lies the master thesis 'Optimising quay crane operations based on data-driven cycle time prediction'. It has been written to fulfil the graduation requirements of the MSc programme Transport, Infrastructure and Logistics at Delft University of Technology. I have conducted the research and writing this thesis from February to October 2022.

The topic of optimising quay cranes at a container terminal comes from my interest in container terminals and the equipment used there. In addition, the methods used to answer the research question match my background and interest in computer science.

This research would not have been possible without the help and support of my daily internal supervisors, Bilge and Jaap. Whenever I sent my report and asked for feedback, I received highly valuable feedback in a very short period of time for which I am very thankful. Also, I am thankful for the attendance and critical feedback of Rudy during the formal meetings which helped me to keep the research in the right direction.

Furthermore, I am grateful for the opportunities APM terminals offered me and leaving me very free in choosing a topic. It was not easy at the start to come up with a suitable topic but in the end I am very satisfied with it. I would also like to show my appreciation for my external supervisor Fabian from whom I learned a lot about container terminal operations and other essential skills. Also thanks to him and other colleagues at the terminal I felt really welcome and appreciated at the company.

Last but not least, I would like to thank my family and friends for supporting and helping me in various different ways, not only during my thesis but during my entire student life.

Laurens Gerlach
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Abstract

Quay cranes on modern container terminals have the possibility to lift two 40ft. containers side by side. In order to be able to perform this type of lift, the crane must be equipped with a tandem spreader. As this type of spreader cannot be used for performing certain lifts, such as the handling of hatch covers, switches between single spreader and tandem spreader are inevitable. However, there is no method in current literature nor in practice to determine when the spreader changes should be performed. Therefore, the aim of this research is to develop a model that calculates the optimal moments to switch spreaders. As the performance of tandem lifting depends on the cycle times, a cycle time prediction model is developed first. This Artificial Neural Network model predicts the cycle time based on the type of lift, the actual position of the container(s) on the ship, the weight of the load and the current wind speed. The predictions yield a Mean Absolute Percentage Error of less than 11%. Afterwards, the cycle time prediction model is used to develop an optimal spreader switching strategy model in the form a of Mixed Integer Linear Programming model. A case study, in which several different bay layouts of a container ship need to be handled, shows a decrease in handling time of up to 22% compared to the traditional spreader switching strategy.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AGV	Automated Guided Vehicle
ANN	Artificial Neural Network
ARMG	Automated Rail Mounted Gantry
CMPH	Crane Moves Per Hour
LR	Linear Regression
MAPE	Median Absolute Percentage Error
MILP	Mixed-Integer Linear Programming
MSE	Mean Squared Error
MT	Main Trolley
PT	Portal Trolley
RCO	Remote Crane Operator
SQC	Super Quay Crane
TEU	Twenty foot Equivalent Unit

1 Introduction

1.1. General Introduction

In 2019, 825 million TEUs of containers were handled in ports worldwide according to on Trade and Development (2022). In order to minimize the handling time and maximize the profit, container terminals are constantly looking to improve the efficiency of container handling. One of the ways to improve the efficiency is by increasing the moves per hour of a quay crane. This can be done by loading or unloading two 40ft. containers at the same time which is called a tandem move. As a tandem move requires a spreader change which takes time, it is not always beneficial to handle two 40ft. containers with a tandem move. In this report, the handling process of a bay is analysed and the optimal moments to change between single and tandem spreader are determined in order to minimize the handling time of the bay.

1.2. Practical Problem

As can be read in section 2.1, an SQC needs to change its spreader when switching between single operations and tandem operations. This spreader change takes time so when changing a single spreader to a tandem spreader, there needs to be a certain amount of cycles that can be performed afterwards in order to make up for this lost time caused by changing spreaders. In current practice, a spreader change from single to tandem is considered profitable if there are 100 containers that can be tandem loaded or unloaded. The actual amount of time that is saved by performing tandem operations instead of single operations, however, is dependent on the cycle times which the following example will show. Suppose 100 containers need to be loaded at the quay side of the ship as indicated in black in Figure 1.1 and the weather conditions are optimal, so mild temperatures, low wind speed and no precipitation. A realistic cycle time for loading under those conditions would be 90 seconds. In case of single loading, 100 cycles need to be performed which will take $90 * 100 = 9000$ seconds. In case of tandem loading, only 50 cycles are needed so this will take $90 * 50 = 4500$ seconds. This means that in this case, 4500 seconds are saved by performing tandem operations. Assume that the same number of containers must be loaded on the opposite side of the ship as shown in blue in Figure 1.1 and that there is now a strong wind. Due to the combination of both the extra distance the crane needs to travel, which can be more than 50 metres with the current size of container ships, and the more challenging weather conditions, a realistic cycle time of 150 seconds is taken. In case of single operations, the unloading time will take $150*100 = 15000$ seconds while the unloading time when using tandem operations will be $150 * 50 = 7500$ seconds. This means that 7500 seconds are saved by performing tandem operations instead of single operations. Compared to the first example, there is a difference of 3000 seconds or 50 minutes that is saved dependent on the cycle times. The example shows that there are less cycles needed to save a certain amount of time when the crane cycles are longer, so taking a fixed amount of 100 containers, which is currently done in practice, is likely not optimal.

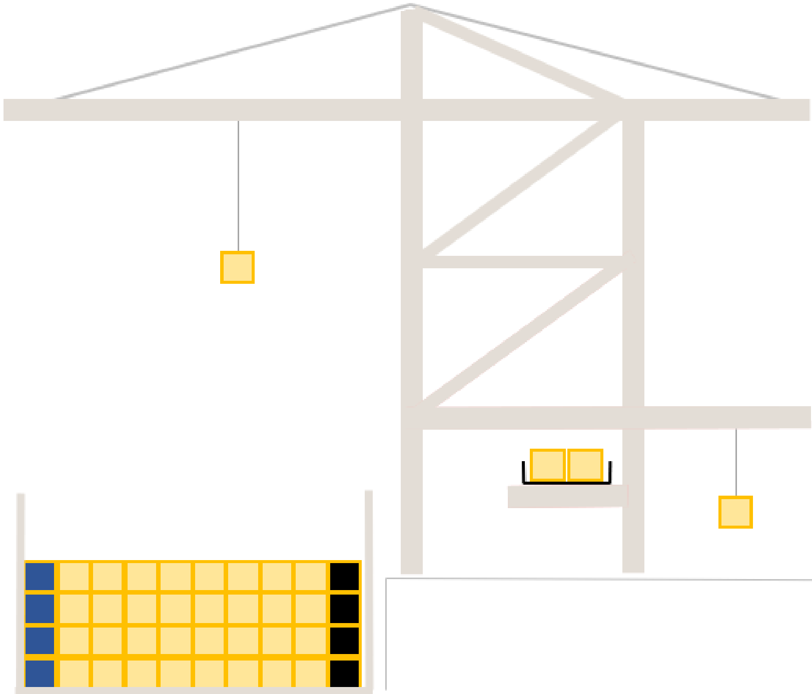


Figure 1.1: Quay crane and container ship.

1.3. Scientific Problem

Many processes at container terminals such as the handling time of container ships or the performance of tandem operations rely on the cycle time of the quay cranes. Therefore, a quay crane's cycle time is often used as an input to models in the literature. However when a cycle time is used as an input, it is always a fixed value or a value sampled from a distribution. Due to the large variety in cycle times based on several factors such as the location of the containers on the ship, weather conditions and type of containers, the models using a fixed value for those cycle times may yield very different results from reality. Literature search shows that there are currently no models available that accurately predict the cycle time of a quay crane.
Besides, literature about models assessing the performance of tandem operations compared to single operations can be found as well. When comparing the two different types of operations, often a fixed cycle time value is taken which is the same for both operation types. As this does not match reality in which tandem cycles take significantly more time than single cycles, the performance of tandem operations might be overestimated. Furthermore, as the models use fixed values or values sampled from a distribution as cycle times, factors such as wind speed, location of the containers on the ship, etc. that change the cycle times are not taken into account. It can be the case that some of those factors have a larger impact on tandem moves than on single moves or the other way around. By taking this into consideration, the performance increase of tandem operations compared to single operations can differ strongly for different scenarios. However as said before, the models used in literature do not take this into account leading to unrealistic performance estimations of tandem operations.

1.4. Research Question

The main goal of the research is to improve the performance of a quay crane. This is done by developing a model which accurately predicts the quay crane's cycle times based on the location where the containers need to be unloaded from or loaded on the ship. Then those cycle time estimates are used to find the optimal spreader switching moments. This is achieved by answering the following main research question:

How can a quay crane's cycle time prediction model be developed and used to calculate the optimal spreader switching strategy?

The main research question can be jointly answered by the following sub-questions:

- What are the factors that influence the quay crane's cycle time?
- How can a model be developed to accurately predict the cycle time of a quay crane?
- How can this model be used to calculate the optimal spreader switching strategy?
- How can the model be evaluated?

1.5. Methodology

This section provides an overview of the methods that will be used to answer the research questions formulated in section 1.4. In Table 1.1 an overview of the sub-questions with their corresponding methods is given. A more detailed explanation of the used methods is given in the according subsections in the remainder of the methodology section.

How can a quay crane's cycle time prediction model be developed and used to calculate the optimal spreader switching strategy?	
Sub-question	**Method**
1. What are the factors that influence the quay crane's cycle time?	Literature Review and Data Analysis
2. How can a model be developed to accurately predict the cycle time of a quay crane	Literature Review and Modelling
3. How can this model be used to calculate the optimal spreader switching strategy?	Modelling/Optimization
4. How can the model be evaluated?	Case Study

Table 1.1: The methods used to answer each sub-question.

In Figure 1.2, the goal hierarchy of the research is presented. The main goal at the top is to calculate the optimal moment to change between single spreader and tandem spreader. This is done by identifying the factors that influence the quay crane's cycle time and selecting an appropriate model to predict the cycle times. Those goals can be obtained by a data analysis and a literature review.

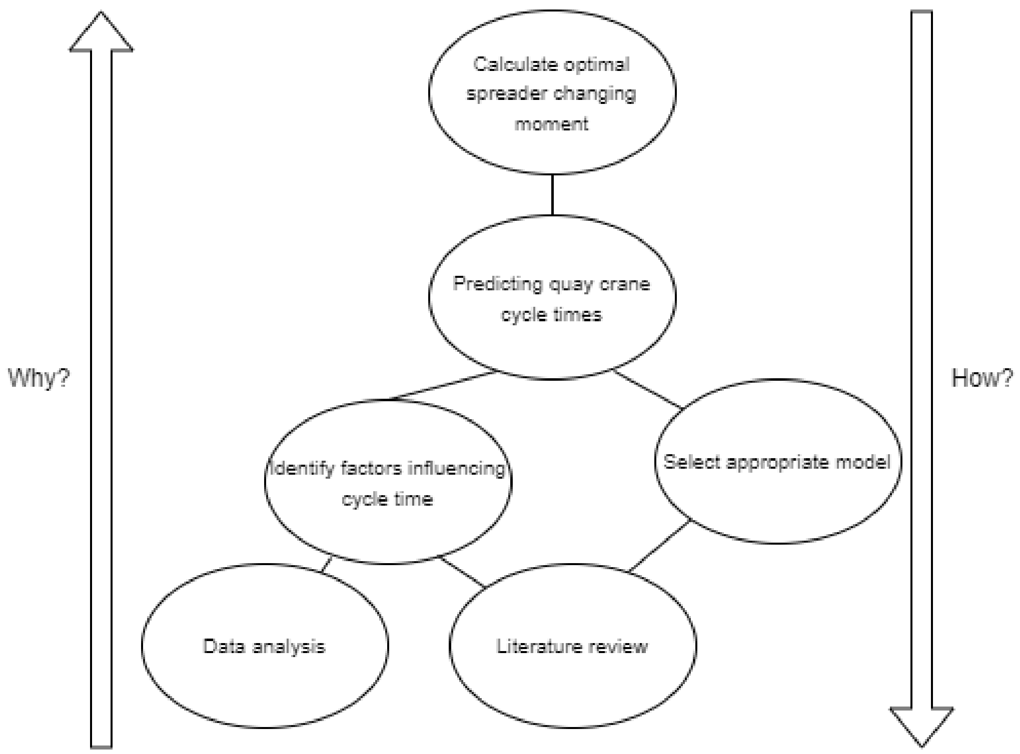


Figure 1.2: Goal hierarchy.

1.5.1. Sub-question 1

By answering this sub-question, the factors that influence the quay crane's cycle time will be known which will be needed for the next sub-question. First of all, a literature review is performed to identify those factors. As most of the literature is about external factors such as the configuration of the yard or the availability of AGVs, literature about direct factors influencing the SQC's cycle is scarce. Therefore a data analysis is conducted to identify those direct factors such as the type of lift, the weight of the load etc. The total set of factors analysed is based on the availability of the data which can be found in subsection 3.1.1.

1.5.2. Sub-question 2

The goal of this sub-question is to build a model that accurately predicts the cycle time of a quay crane. First of all a literature review is performed to find a suitable model. As literature about prediction models for an SQC's cycle is too specific and nonexistent, prediction models in other fields are studied such as prediction models in high speed machining, food delivery, wafer lots and garment manufacturing. Based on those findings, a choice is made to develop an Artificial Neural Network to predict the cycle times of an SQC. The variables used as input to the model are based on the results of the literature review and data analysis in subsection 1.5.1.

1.5.3. Sub-question 3

After an accurate prediction model for a quay crane's cycle time is developed in subsection 1.5.2, the aim of this question is to show how this model can be used to improve the quay crane's performance by finding the optimal spreader switching strategy. One possibility to find those optimal moments is to formulate this as a Mixed-Integer Linear Programming (MILP) optimization problem. The goal of the the optimization is to minimize the loading or unloading time for a whole bay. This consists of the sum of predicted cycle times and the time taken by the spreader changes. A decision variable indicates which containers should be handled by single moves and which by tandem moves. Several constraints are needed to make the optimization as realistic as possible. For instance a constraint that two containers can only be handled by a tandem move if they are located next to each other.

1.5.4. Sub-question 4

A case study will be applied to evaluate the model and its performance. In this case study, several scenarios are created in which a bay needs to be loaded or unloaded. The scenarios differ from each other on several variables such as the amount of containers, the type of containers, the location of the containers, the wind speed, the weight of the containers etc. Then for each scenario the handling time is computed by the model defined in subsection 1.5.3 while taking the optimal spreader changing moments into account. Then the handling time is calculated if the spreader changes were done as it is done in current practice, which is when a fixed amount of tandem cycles can be performed. By comparing those calculated handling times, the increase in performance achieved by using the optimal spreader changing model can be calculated.

1.6. Structure of the Report

In the next chapter, chapter 2, background information is given about container terminals and related matters. Also a literature review is performed in order to gain knowledge about tandem operations, turnaround time prediction models, factors that influence the quay crane's performance and lastly about cycle time prediction models in order to find out how cycle times are predicted in different fields. Then in chapter 3, a data analysis is performed to find direct factors that influence the quay crane's cycle time and the actual cycle time prediction model is implemented. Then this cycle time prediction model is used to develop a model which determines the ideal moments to change between single and tandem spreader. This is done in chapter 4 as well as the execution of a requirements analysis. In chapter 5 the model is used to calculate the optimal handling strategy for different bay layouts under different circumstances. Lastly, the report is wrapped up in chapter 6 with conclusions and recommendations.

2

Background and Literature Review

This chapter is split into two parts. The first part, section 2.1, provides some background information about terminal processes and related matters that is needed to understand the remainder of the report. The second part, section 2.2, is devoted to the literature review.

2.1. Background

This section contains some general information about the terminal process and the equipment. This knowledge is assumed to be known in the remainder of the report.

2.1.1. Terminal Process

SQCs are used to move containers from ships to the quay which is explained in subsection 2.1.2. The containers are put directly on AGVs which provide the movement of the containers from the quay to the stack, also called horizontal movement. Those vehicles are completely automated and are able to carry one or two 20’ containers or one 40’ container. When the AGVs arrive at the stack, they can lift the container(s) on a rack and hand off the handling to the ARMGs. Each stack has two ARMGs; a water-side one and a land-side one. The former is responsible for the movement of containers between the stack and the AGVs or racks and the latter’s main task is to provide the transportation of containers between the stack and the trucks. An overview of this process is visualized in Figure 2.1.

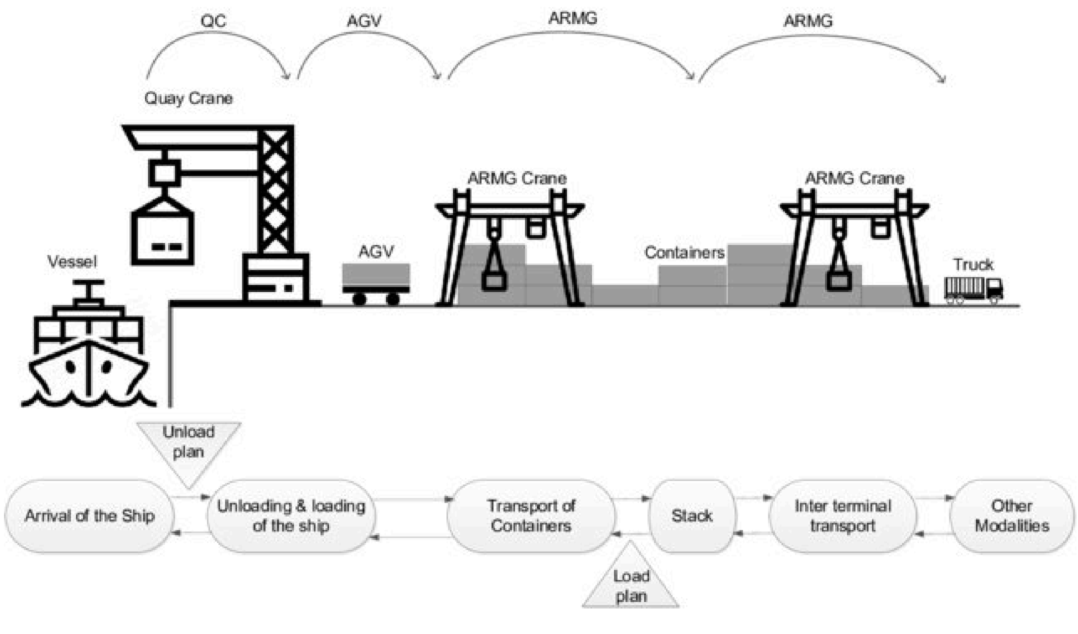


Figure 2.1: Graphical representation of an automated terminal process, adopted from Huynh et al. (2019).

2.1.2. Super Quay Crane Process

SQCs are responsible for the movement of containers between the quay and the container ships. The main parts of an SQC are the Main Trolley (MT), Portal Trolley (PT) and the platform. The MT is semi-automated and partly controlled by a crane operator at the office. The primary function of the MT is moving containers between the ship and the platform which is located on the crane and provides place for 2 40ft containers or 4 20ft containers. This is also the place where normally two people remove or place the twistlocks. The transfer of the containers between the platform and the AGVs is then carried out by the PT. At the back of the crane, there is a platform on which the tandem spreader lies and ready to be picked up by the MT when needed. Also the gondola or lashing cage is available at the back of the crane which used to unlock the twistlocks of the containers on board and above deck in case of unloading. This is done by the crane moving the gondola between two bays such that the persons in the gondola are able to unlock the twistlocks of the containers in three different tiers simultaneously. An image of a SQC with the parts pointed out above can be seen in Figure 2.2.

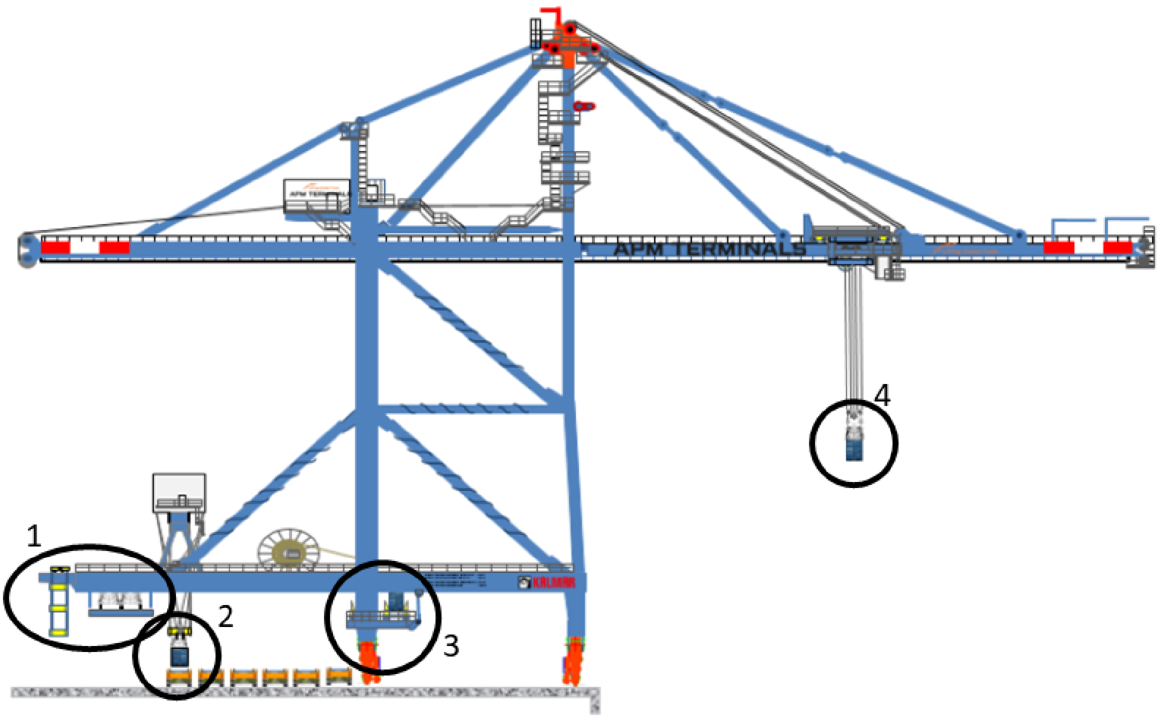


Figure 2.2: Graphical representation of an SQC. 1=gondola and tandem spreader platform, 2=PT, 3=platform and 4=MT.

In Figure 2.3, a swimlane diagram represents the unloading process of a container from a ship to the quay. It starts with the automated movement of the main trolley to the container on the ship while adjusting its spreader based on the type of container that needs to be unloaded. When the MT is within a certain distance, the crane operator at the office needs to take over the autopilot and land the spreader on the container. When the container is lifted to a certain height, the autopilot can be activated again and transfers the container to the platform. The actual landing of the container on the platform needs to be performed again by the crane operator. When the container was unloaded from above deck, it has twist locks attached to it which need to be removed at the platform by the pin men. The remainder of the process is fully automated and consists of the portal trolley transferring the container from the platform to the AGV.

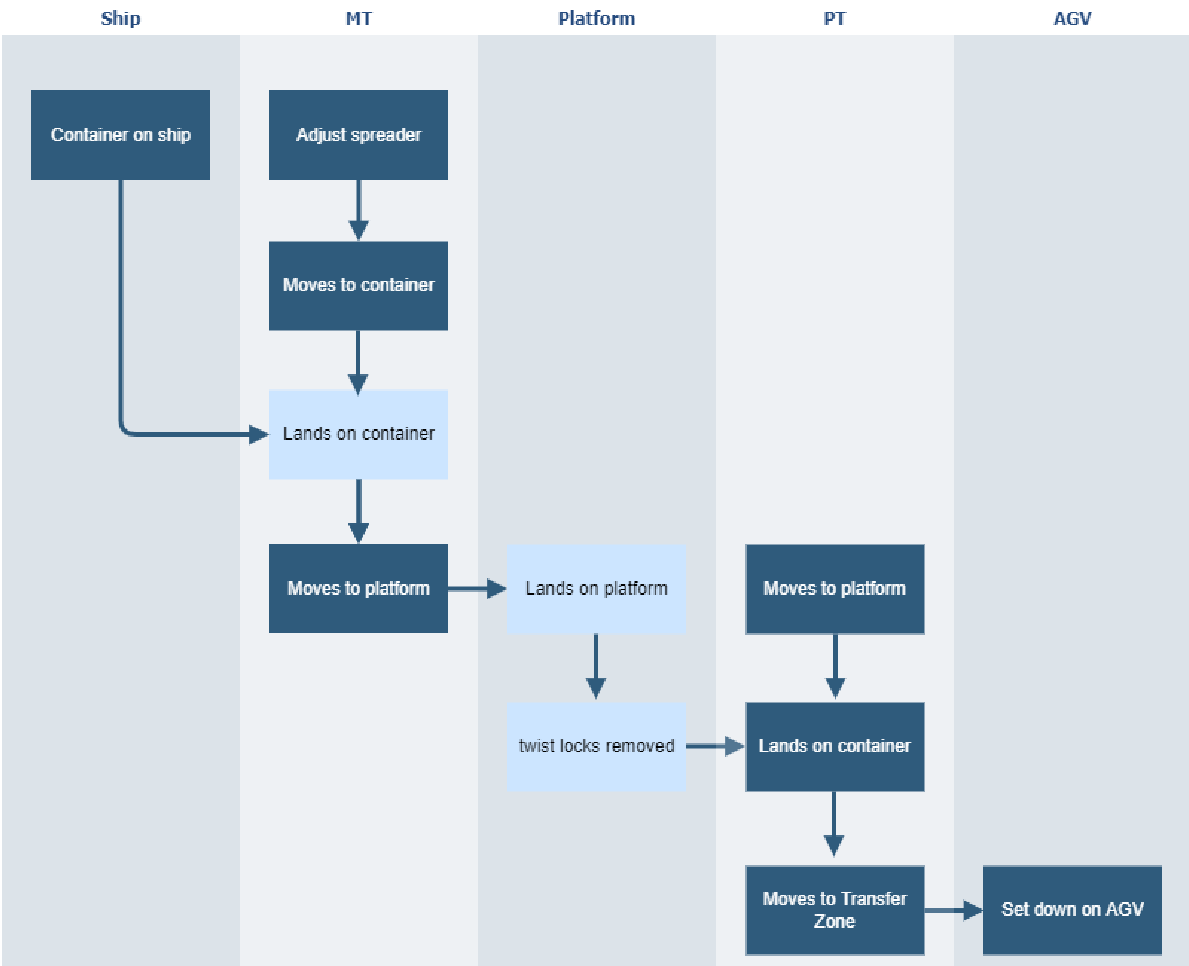
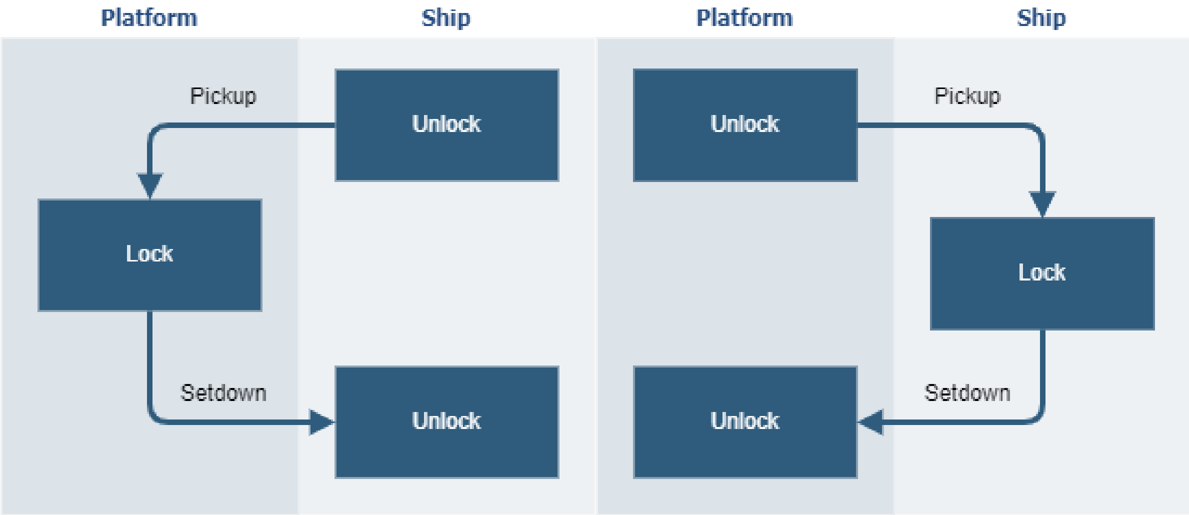


Figure 2.3: Unloading process of a container from ship to quay. Dark blue indicates automated processes and light blue indicates human actions.

2.1.3. Super Quay Crane Cycle

A cycle of an SQC is defined from a spreader unlock until the next spreader unlock, both performed at the platform for discharge cycles and both performed on the boat for load cycles. In case of a load cycle, this means that the cycle starts with a spreader unlock on the ship in order to load the previous container. Then the spreader moves to the platform and performs a spreader lock to pickup the next container. Subsequently the spreader moves back to the ship and performs a spreader unlock to load the container. This is defined as one cycle. In case of a discharge cycle, it works the other way around. So then the cycle starts with a spreader unlock on the platform, then a spreader lock is performed on the ship and at the end again a spreader unlock on the platform.

Furthermore, each cycle can be divided into two parts, namely a pickup part and a setdown part. The pickup part is the first part of the cycle starting from the cycle start until the spreader has landed on a container and locked the twistlocks. Then the setdown part starts and end when the the spreader has unlocked the twistlocks. A visualization of the different cycle parts is visualized in Figure 2.4.



(a) Load cycle.

(b) Discharge cycle.

Figure 2.4: Set up and outcome for this scenario.

Concerning the horizontal movement of the trolley, from platform to quay is 30 meters. Then from quay to the location on the vessel depends on the vessel size but can be up to 60 meters. The vertical range of the crane is about 60 metres as well and the location of the platform is about 16 metres above ground level.

2.1.4. Lift Types

The MT of a SQC is able to perform two type of lifts, namely single lifts and tandem lifts. The former can be seen as the movement of one or two TEU and the latter means the movement of 4 TEU. When two 20ft. containers are handled with a single lift, this is called a twin lift. In the remainder of the report, tandem lifts are assumed to be two 40 ft. containers and the other two types of tandem lifts are taken out of consideration. An overview of the configurations of those lifts is visualized in Figure 2.5.

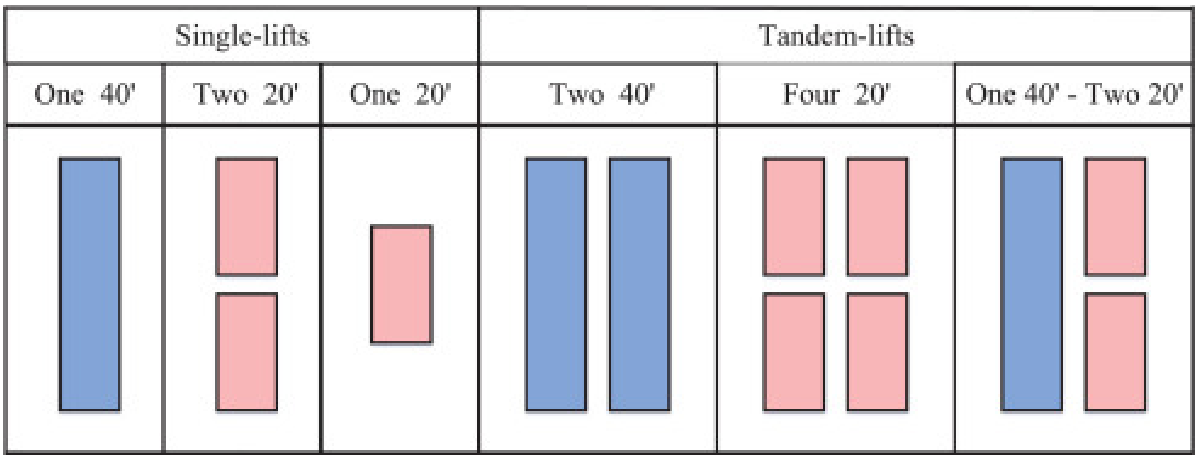
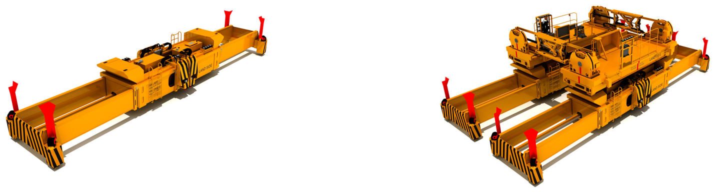


Figure 2.5: Different lift types, adopted from Kong et al. (2021)

When changing between single lifts and tandem lifts, the SQC needs to change spreaders. A spreader is the equipment used by a SQC to be able to lift containers. At the back of the crane, there is a special platform where the crane can put down its spreader and attach the other spreader as explained in subsection 2.1.2. Examples of the two type of spreader can be seen in Figure 2.6. The red objects in the image are called flippers which help the crane operator to guide the spreader on a container.

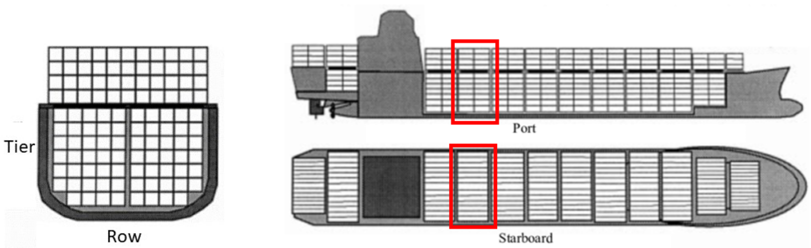


(a) Single Spreader **(b)** Tandem Spreader

Figure 2.6: An example of a single spreader (a) and a tandem spreader (b).

2.1.5. Container Ship Structure

When looking at the side view or top view of a container ship, the ship consists of several bays as can be seen in Figure 2.7b. The widths of the bays are based on the standardized shipping containers. Most bays are as wide such that it can fit exactly one 40ft. container or two 20ft. containers. There are also so-called 20ft. bays which are logically as wide as one 20ft. container. Those bays are often located at the front of the ship. Each bay is numbered with an even number indicating the location of 40ft. containers and two odd numbers indicating the location of 20ft. containers. For instance bay 2 covers bays 1 and 3. When a 40ft. container is located in this bay, its bay number is 2. When a 20ft container is loaded in this bay, its location can either be bay 1 or bay 3.
Within a bay, each container is located at a specific tier and row as can be seen in Figure 2.7a. Tiers are counted in even numbers, beginning with number 2, the lowest tier beneath deck. The first tier above deck used to be tier 82. However since container ships are getting bigger and bigger with having more than ten tiers above deck, some tiers would have a tier number higher than 100 which would be a problem with the numbering which is explained later. Therefore, the first tier above deck is numbered as 72 nowadays for large ships. The row numbers of a bay start from the center of the ship and are even numbered on the port side and odd numbered on the starboard side.
The location of a container on a ship is expressed with a 6-digit code in which the first 2 digits indicates the bay, the middle two the row and the last two the tier. For instance a container with a location of 14 84 03 means the container is located in bay 14, tier 84 and row 03. Since the bay is even, the container must be a 40ft. container. The tier and row number also give the information that the container is located above deck and on the starboard side, not too far away from the center of the ship.



(a) Cross section of a bay. **(b)** Side and top view of container ship with one bay indicated with the red box.

Figure 2.7: Cellular structure of a container ship, adopted from Wilson et al. (2000).

The handling of a vessel can be done by multiple cranes simultaneously where each crane is working on a different bay. However, the structure of the cranes prevents them from standing close enough to each other in order to work on two adjacent bays at the same time. Therefore there is always at least one bay between two cranes. When multiple cranes are working at the same time on a ship, the weight distribution of the ship can change quickly. For instance when all cranes are unloading containers vertically, so row by row, starting at the same side of the ship, the ship will start leaning to that side causing negative consequences. In order to solve this problem, the loading process of a bay must always be done horizontally, tier by tier. This way the cranes can work independently on their own bay without worrying about the weight distribution of the ship.

2.2. Literature Review

This literature review is divided into five parts. First of all, literature about tandem operations is analyzed in subsection 2.2.1. Then literature is found in subsection 2.2.2 about models predicting the turnaround time of a vessel. This is followed by subsection 2.2.3 in which research is done about the factors that have an impact on the performance of a quay crane. In subsection 2.2.4 prediction models used in different fields are studied. Lastly, the literature review is concluded with a summary in subsection 2.2.5.

2.2.1. Tandem Operations

Tandem operations consists of lifting two 40 ft. containers, four 20 ft. containers or one 40 ft. container and two 20 ft. containers according to Bartosek and Marek (2013). By using tandem operations, containers are placed side by side as opposed to twin operations where containers are placed end-to-end as is explained in subsection 2.1.4. Theoretically, tandem operations can double the quay crane's performance since double the number of containers are loaded or unloaded simultaneously compared to the traditional way. However, there are many more factors involved in real operations preventing the crane from doubling its performance when performing tandem lifts. Models can be found in literature that simulate the actual increase in performance of tandem lifts compared to single lifts. First of all, the paper by Kong et al. (2021) uses mixed integer linear programming to optimize tandem operations. Since quay cranes without a platform are used in this research, the cooperation between yard trucks and crane is very important because two yard trucks at the same time are required in order to perform a tandem lift. When one of the yard trucks is delayed, a decision has to be made whether the crane will perform a single lift or wait for the delayed yard truck to perform a tandem lift. This is one part of the optimization. The other part of the optimization is the container slot planning. An optimal stowage plan is made such that the number of possible tandem operations is maximized.

In the research conducted by Huang and Li (2017), a method is proposed to group containers into tandem lifts in order to minimize the spreader changes and intra-bay movements of the crane. A reduction of 40 to 50% in vessel completion time can be obtained by applying this method. However, cycle times are set to two minutes for both single lifts and tandem lifts which does not match reality.

The paper by Lashkari et al. (2017) proposes a new mathematical model to optimize the unloading sequence of a bay. One of the possible pitfalls of this research is its theoretical point of view. First of all, the removal of hatch covers is not taken into consideration while it has a big influence on the unloading strategy as removing of a hatch cover can only be done by a single spreader. Furthermore, the unloading process does not follow a tier-by-tier order which is done in practice due to several reasons such as the weight distribution on the ship and the unlocking process of the twist locks using a gondola. Another drawback of the research are the fixed values for cycle times of 1.5 minutes for single lifts and 1.8 minutes for tandem lifts.

Very similar to the research just mentioned is the work done by Ding et al. (2017). The main difference is that this paper also includes the possibility of performing a dual cycle which means loading and unloading at the same time. The cycle times are fixed values again varying based on the type of lift and cycle and taking spreader changes into account.

Table 2.1 presents an overview of the literature analysed above.

Citation	Spreader change	yard trucks	hatch covers	Cycle time	Loading/ unloading	SQC with platform	Change stowage plan
Kong et al. (2021)	No	Yes	No	1.5 minutes for both single and tandem cycle	Both	No	Yes
Huang and Li (2017)	Yes	No	Yes	2 minutes for both single and tandem cycle	Both	Yes	No
Lashkari et al. (2017)	Yes	No	No	1.5 for single and 1.8 for tandem	Unloading	No	No
Ding et al. (2017)	Yes	No	No	Fixed values	Both	No	No
This thesis	Yes	No	Yes	Cycle time prediction model	Both	Yes	No

Table 2.1: Literature review table for tandem operations.

2.2.2. Turnaround Time Prediction Models

Predicting the berthing time of a ship is something which is widely researched. The paper by Stepec et al. (2020) uses a machine learning based system to predict the turnaround time for vessels in the port of Bordeaux. There are several features considered of which the cargo type and tonnage appeared to be the most important. For certain cargo types, the model can estimate the turnaround time of a vessel with an error rate below 10%. Therefore this model offers a good prediction for a specific vessel type.
A similar approach is taken in the paper by Li et al. (2013) which designs three different neural networks to predict the berthing time of a ship. The three networks are; Back Propagation (BP), Radial Basis Function (RBF) and Linear (L). Those networks are then applied in a case study for the Port of Valencia and the RBF showed the highest accuracy. However, the output of the model is a berthing time number from 1 to 4 which indicates a large time time span of eight hours. So 1 means a berthing time of 0-8 hours, 2 means a berthing time of 8-16 hours etc. While this gives a broad indication of a vessel's berthing time, an accurate prediction is not made. Also the data used to train the neural networks only consist of four factors; the line of the ship, the type of the ship, the berth at which the ship is handled and the month of berthing. In reality, the berthing time of a ship is affected by more factors but those were not available for the authors of the paper. However, by including more factors, more realistic predictions might be made.
Smaller time spans and more factors are taken into account in the paper by Li and He (2020). Deep learning is applied to predict the Liner Berthing Time (LBT) in time ranges of half an hour. As this is way harder than predicting the LBT in time range of eight hours as done in the previous paper, the results are much worse. Only one third of the results are predicted correctly with an error range of two hours.
In the paper by Lee et al. (2021), the quay crane's working time is predicted using a multi-layer perceptron model. The factors that are taken into account are type of the container, bay cluster movement, work type change, employee shift, single or twin lift and whether the container is full or empty. The results are then compared to the conventional cycle time estimates of 1.5 minutes of unloading and 2.5 minutes for loading. Compared to those, the method is capable of reducing error rate up to 54%.
Not only machine learning techniques but also stochastic models are used in order to estimate vessel handling time. Dhingra et al. (2017) proposes a two-level stochastic model of which the higher level represents the quay crane assignment and scheduling and the lower level models the dynamic interactions amongst the terminal equipment such as the quayside, stackside and vehicle transport processes. While this model is useful to examine the effect of the factors on the handling time of a vessel, accurate predictions are lacking. This partly caused by two assumptions that are made: (1) only 20 ft. standard containers with identical shape and size are used in the simulation and (2) the time it takes to load or unload all the containers in a zone is exponentially distributed.
Table 2.2 presents an overview of the literature analysed above. Although this thesis does not make a direct turnaround time prediction model, the turnaround time of a container ship can be predicted by using the cycle time prediction model.

Citation	ship type	Method	Case study	Crane cycle time	Factors
Stepec et al. (2020)	All	Machine learning	Yes	No	Cargo type, cargo tonnage, day/hour of entry and berth
Li et al. (2013)	All	BP, RBF and Linear	Yes	No	Line of ship, type of ship, berth and month
Li and He (2020)	Container	Deep learning	Yes	2 minutes	Fundamental points and quantity configurations
Lee et al. (2021)	Container	Multi-layer perceptron model	No	1.5 minutes for unloading and 2.5 minutes for loading	type of the container, bay cluster movement, work type change, employee shift, single/twin lift and container full/empty
Dhingra et al. (2017)	Container	two-level stochastic model	No	Exponentially distributed	Crane assignment and scheduling and interaction amongst terminal equipment
This thesis	Container	Machine learning	Yes	Cycle time prediction model	Location of containers on the ship, type of lift, wind speed and container weight

Table 2.2: Literature table for turnaround time prediction models.

2.2.3. Factors SQC's Performance

this part of the literature review provides research on factors that influence the performance of a SQC. Because performance of an SQC is quite specific and the behaviour of an it is similar to the behaviour of a normal quay crane, this type of crane is also included in the literature search.

Container location dispersion

The first factor identified in literature that affects the quay crane's performance is the location dispersion of the containers in the yard. The paper by yu et al. (2017) investigates this relationship using a discrete-event-based simulation model for export containers. There are six dispersion levels in the simulation. Level 1-2 means a low level of dispersion indicating a concentrated allocation of containers in the yard and level 5-6 means a high level of dispersion indicating that containers are spread over different blocks in the yard. These dispersion levels are evaluated based on the gross crane rate (GCR) which is the total number of quay crane lifts divided by the total number of quay crane hours beside a busy berth. The results show that lower levels of dispersion improves the GCR.

Double cycling

Double cycling is a technique were loading and unloading of a ship are done simultaneously which minimizes crane moves with an empty spreader. The paper by Goodchild and Daganzo (2006) formulates this double cycling technique as a scheduling problem and then solved optimally and also with a greedy algorithm. The results reveal a reduction of 20% in the number of cycles and 10% in the operational time for double cycling below deck. There are however some requirements for applying the double cycling technique. First of all, and obviously, containers (of the same type) have to be loaded and unloaded in the same bay of the ship. When a ship only needs to be loaded or unloaded, double cycling cannot be applied. The same holds when different bays are used for loading and unloading. Furthermore, double cycling requires adaptations in almost every part of the container terminal. As stated in Zhang et al. (2019), modifications to the TOS (Terminal Operating System) and storage yard utilization are needed as well as additional container handling equipment.

Yard configurations

The layout of the yard affects indirectly the gross crane rate (GCR) of the quay cranes through the YTs (Yard Trucks) and the YCs (Yard Cranes). In the paper by Petering and Murty (2009), a fully dynamic, discrete event simulation is applied in order to simulate the relationship between the length of the storage blocks in the yard and the quay cranes' performance. When the block size is larger, there will be fewer blocks and thus also less space for road ways which makes the travel time of the yard trucks longer. On the other hand, larger block sizes also mean that the stacks in each zone are closer together which makes the average distance covered by a YC between two containers handling operations shorter. According to the simulation performed in the research, a block size between 56 and 72 (20 ft.) slots shows the best results for the quay cranes work rate.

Yard trucks/AGVs
When there is a delay in supply or discharge of containers to or from the quay, the quay crane has to wait which will cause a decrease in crane moves per hour (CMPH). This is the responsibility of the yard trucks or the AGVs (Automated Guided Vehicles) on an automated container terminal. The paper by Saanen (2013) shows the relationship between available AGVs for a quay crane and its CMPH. When there are more AGVs available for a crane, it is less likely that the crane has to wait for one. The paper shows that in case of three AGVs for a crane, the CMPH is only 18.0. Assigning five extra AGVs to that crane, so a total of eight, raises the CMPH to 30.4.
Besides the number of available AGVs for a quay crane, the routing and scheduling of the AGVs is also important for the supply and discharge of containers in order to minimize the waiting time of the quay cranes.

Weather conditions
Also weather conditions contribute to the performance of the quay cranes on a container terminal. The paper by Chhetri et al. (2016) designs a Container Terminal Operation Simulation (CTOS) for a terminal at the Port of Sydneu in order to simulate the impact of extreme weather conditions on several KPIs including the Crane Rate (CR). Five different scenarios are simulated for a period of 24 hours. The first one is the baseline scenario which is a day without extreme weather. The second scenario represents a day with high temperature which is defined as more than 38 degrees for a period of minimum six hours. The third scenario is a day with heavy rainfall of more than 100mm. The fourth scenario consists of high speed wind between 70 and 90 km/h for six hours. The last scenario represents a flooding of the port area affecting straddle operations for five hours. Results show that the CR for both the third (heavy rain) and fourth (high speed wind) scenario drops with 13% while the other scenarios have no impact on the CR.

The article by van den Bos (2006) also focuses on weather impacts and more specifically on the influence of wind. Two of the undesirable movements caused by wind are called sway and skew. Those disturbances can be dealt with taking several measures. First of all, sway can be corrected for by the crane operator. Also the type of trolley used influences the sway and skew. A rope trolley with a V-shape cable configuration is more stiff than a machine trolley having vertical inner ropes and therefore can reduce sway by 40%. Lastly, rectangular hoisting can be applied which avoids combining horizontal and vertical moves. Although the process becomes slower, skew and sway are reduced significantly.

2.2.4. Cycle Time Prediction Models
In this subsection, research on cycle time prediction models used in other fields is conducted in order to gain knowledge about the used models.
The paper by Gelmereanu et al. (2014) proposes a method to predict the cycle time for High Speed Machining. This is done based on three parameters which are the spindle speed, the feed rate and the depth of cut. Those parameters are used as the input for an Artificial Neural Network (ANN) which is trained automatically by the Levenberg-Marquardt algorithm. After five seconds, the algorithm achieves a result with an acceptable error rate.
Also in the research done by Wang et al. (2018), machine learning is used to predict cycle times but in a different field, namely the cycles of wafer lots. As there is a total of 774 candidates identified that influence the cycle time of wafer lots, Linear Regression (LR) is used to determine the most important ones. The results of the LR model leads to a total of 108 factors which are included in a Deep Neural Network (DNN) model and an Adaptive Fuzzy C-Means (AFCM) model. This approach leads to more accurate results than other methods used for cycle time predictions of wafer lots.
Food delivery from the moment the order is placed until the food is delivered can also be seen as a cycle and accurate predictions are needed to make the customers satisfied. In the paper by Zhu et al. (2020), a deep neural network is used to estimate those cycles for one of the largest on-demand food delivery platform in the world. As an input to the model, eight different feature classes are identified; order information, demand-and-supply, ETA-based drop-off time, cooking time, courier, meteorological,

aggregation and dish. Then feature encoding is applied to normalize the features and to categorize non-categorical features. At the end, the model shows a reduction of 9.8% in average predicting error compared to the current models used in on-demand food delivery industry.
Also in the garment manufacturing industry, models are used to predict the production cycle time. In the paper by Cao and Ji (2021), an artificial neural network is used which takes the product quantity and the initial cycle time as input. Ten test groups were created of which six have an overall error rate below 5% and three have an overall error rate between five and ten %. Only one group has an overall error rate higher than 10% (11.9).
The cycle time prediction models identified in literature and elaborated on above can be found in Table 2.3.

Reference	Model				Field	Remarks
	AFCM	DNN	LR	ANN		
Gelmereanu et al. (2014)				✓	High Speed Machining	Model is easy to use and trained automatically, but only used with limited number of parameters (3).
Zhu et al. (2020)		✓			Food delivery	Feature classes used instead of parameters and feature encoding is applied.
Wang et al. (2018)	✓	✓	✓		Wafer lots	LR model makes it possible to have a very large initial set of parameters (774).
Cao and Ji (2021)				✓	Garment manufacturing	Works well in case of few input parameters (2).
This thesis				✓	Quay cranes	Accurate predictions (MAPE value below 11%) and limited number of input parameters (6).

Table 2.3: Overview of the literature about cycle time prediction models. AFCM: Adaptive Fuzzy C-Means, DNN: Deep Neural Network, LR: Linear Regression, ANN: Artificial Neural Network.

2.2.5. Summary

In the first part of the literature review, literature about tandem operations is found and analysed. Each paper proposes its own method to simulate the performance of tandem lifts compared to single lifts having different input parameters. All models do take the cycle time of the quay cranes into account although as a fixed number and often the same for both tandem and single lifts. This is also remarked as a limitation of the models in some of the papers as there is a large variety in the actual cycle times. The cycle time of actual cycles can be as short as one minute to as long as 4 minutes based on a wide range of factors. Logically when more precise approximations for the cycle times are used as an input to the tandem performance models, their representation of the real world will improve. A literature search reveals however that there are no prediction models available for the cycle times of a quay crane.

The knowledge gap identified above does not only affect the tandem performance models, but also the turnaround time prediction models which are studied in the second part of the literature review. Also here the cycle time of a quay crane is used as an input in the majority of the models but only a fixed cycle time again due to the lack of accurate cycle time prediction models. This is possibly the reason for the inaccurate turnaround time predictions for container ships specifically as also stated as limitation in some of the research.

Literature about factors influencing the SQC's performance and therefore also its cycle time is studied in the literature review. First of all, the location of the containers in the yard affects the performance as the simulation shows that higher levels of dispersion generally lead to less crane moves per hour. Then double cycling is introduced where the loading and unloading processes of containers take place simultaneously. In cases where there needs to be unloading and loading done in the same bay of a ship, the number of cycles can be reduced by 20%. Concerning the configuration of the yard, a relation between the length of the storage blocks and the quay crane's performance is observed in a simulation. In short a trade-off needs to be made between an optimal configuration for the yard cranes, which means larger block sizes, and an optimal configuration for the yard trucks, which means shorter block sizes. Quite obvious is also the impact of the yard trucks or AGVs themselves on the performance of a SQC. When a yard truck or AGV is not at the crane on time, the crane has to wait having a decrease in performance as a consequence. Lastly the correlation between weather conditions and crane's performance is studied. The outcomes show that high speed wind and heavy rainfall have a significant negative impact on the performance.

The last part of the literature review is used to study prediction models in other fields, such as high speed machining, food delivery, wafer lots and garment manufacturing. The Artificial Neural Network used for the high speed machining prediction is relatively easy to use and can also be trained automatically but can only be used in cases of a limited number of parameters. The same holds for the Back-Propagation Neural Network used for garment manufacturing prediction which also works well for a limited number of input parameters. On the other hand, Linear Regression can be used in cases of many input parameters as was shown in the wafer lots prediction paper. The food delivery prediction method gave insight on how feature classes and feature encoding can be used.

3

Cycle Time Predictions

The aim of this chapter is to develop a model to predict the cycle time duration of an SQC's main trolley. First of all, the factors that will be needed as input to the model are identified in section 3.1. Then the next step consists of the actual model implementation itself which is done in section 3.2.

3.1. Data Analysis

In subsection 2.2.3 factors influencing the performance of a quay crane and thus also its cycle time duration are identified. The majority of those factors, namely container location dispersion, yard configurations and the yard trucks or AGVs themselves, can be considered as indirect factors. The only direct factors on cycle time found in the literature are weather conditions such as wind, temperature, and precipitation. Since the focus of this research is on SQC's, also known as dual Double Trolley Quay Cranes rather than traditional quay cranes, the importance of the indirect factors becomes less significant. For instance when looking at the indirect factor of a late arrival of an AGV at the crane. In case of a traditional quay crane, the crane has to wait since the container is moved from the AGV directly to the ship or the other way around, which decreases the performance of the crane. However, in the case of an SQC, the platform acts as a buffer, so if an AGV arrives too late at the crane, only the portal trolley needs to wait, but the main trolley can continue because there are already two other containers ready to be loaded on the platform, or the main trolley has two places on the platform to put down containers in case of unloading. Therefore data analysis needs to be performed in order to identify more direct factors on the cycle time duration of an SQC.
The data used for this analysis is from November 2021 as this is considered to be a representative month. The number of cycles performed for each type is given in Table 3.1. As tandem loading was still in the testing phase at that moment, the number of tandem loading cycles performed is relatively low which leads to less accurate analyses for this type of move in the subsections below. The other numbers of cycles performed per move type are inline with the expectations and observations in other months.

Cycle type	Number
Single discharge	16.466
Single load	31.525
Tandem discharge	7.329
Tandem load	116
Twin discharge	5.103
Twin load	4.133

Table 3.1: The number of cycles performed for each lift type.

3.1.1. Available Data

The first dataset that can be used is the so called LSOPC data which is measured by sensors on the SQCs. Each second, the speed of the main trolley and the hoist is measured as well as their positions.

There is also an entry in the dataset when a change is noticed on whether a spreader has landed on a container. This also holds for the locking and unlocking of the twistlocks and the SPS system. This system scans the containers and obstacles on board in order to determine the safe height for the autopilot. By combining the twistlock (un-)lock observations and the trolley and hoist position, the location on the ship where the container is loaded or unloaded can be derived. An overview of the data can be found in Table 3.2.

Next to the LSOPC data, data about the cycles can be used as well. Each cycle performed by the main trolley of an SQC has an entry in the dataset with information about the cycle. This information includes the following:

- Cycle time
- Weight of container
- Type of ship
- Type of lift (tandem, single, twin, load or unload, ...)
- Location of the container (row, bay, tier, above/below deck)
- Wind conditions (speed, direction, ...)

Aspect	**Description**	**Value**	**Frequency**
Main trolley speed	This is the percentage of the maximum speed the main trolley is currently moving at. The sign indicates the direction of the movement.	Percentage	1 second
Main hoist speed	This is the percentage of the maximum speed of the current hoisting. The sign indicates the direction of the movement.	Percentage	1 second
Main trolley position	This is the current position of the main trolley.	Position	1 second
Main hoist position	This is the current hoisting position.	Position	1 second
Landed all pins	Indicates if the spreader has landed on a container	Boolean	On change
Twistlock lock	Indicates if the twistlocks are locked	Boolean	On change
Twistlock unlock	Indicates if the twistlocks are unlocked	Boolean	On change
SPS system on	SPS system scans the containers on board to determine the safe height for the autopilot. Otherwise the safe height is determined by the lowest location so far of the spreader.	Boolean	On change

Table 3.2: The format of the LSOPC data.

3.1.2. Type of Lift

As explained in subsection 2.1.4, a crane can handle 1, 2 or 4 TEU at per move. The handling of 1 TEU must corresponds to the move of one 20ft. container which is called a single move. A move is also called a single move when 2 TEU is handled in the form of a 40ft. container. However, if 2 TEU consists of two 20ft. containers, then it is called a twin lift. The last option, the handling of 4 TEU, means that two 40ft. containers are handled at the same time which is called a tandem move. Figure 3.1 shows several descriptive statistics about the cycle time duration for each type of move. As could be expected, the single moves take the least amount of time, followed by the twin moves and lastly the tandem moves take the longest amount of time.

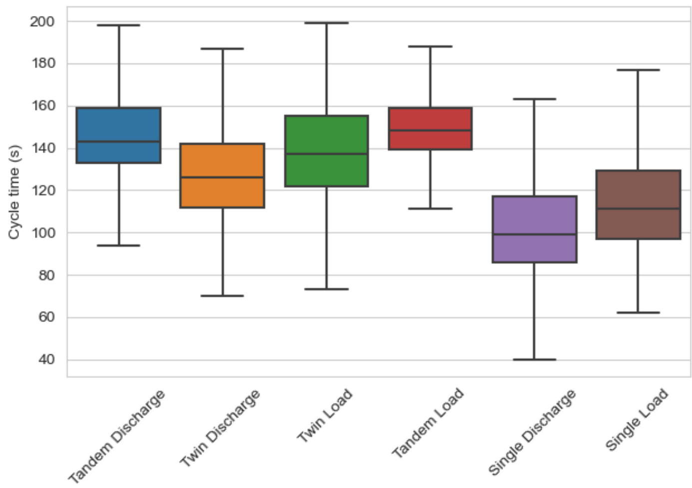


Figure 3.1: The median cycle times of the different types of lifts

The cycles are split into a pickup part and a setdown part as explained in subsection 2.1.3. As can be seen in Figure 3.2 the setdown part of a load cycle takes more time than its pickup part. The other way around is also true as the pickup part of a discharge cycle takes more time than the setdown part. As the pickup part and the setdown part for discharge and load respectively mean that the spreader moves towards the ship and it needs to land on the ship, it is expected that this takes more time. This is the case because landing on the ship is harder than landing on the platform as the platform provides more guidance to the spreader. Furthermore, the conditions of the platform, such as the location are always the same which is not the case for the ship.

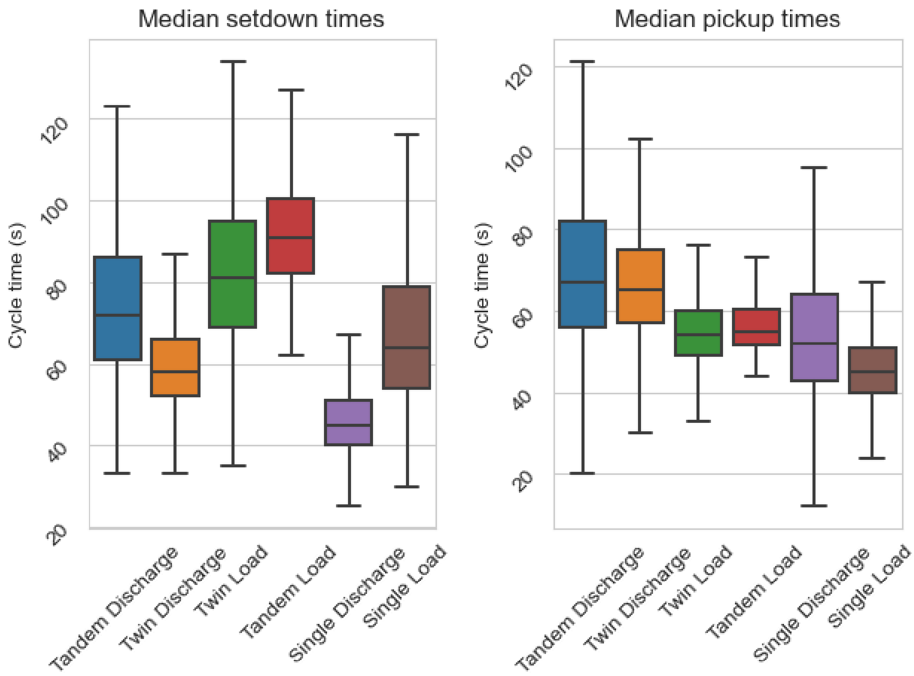


Figure 3.2: The median pickup and setdown times for the different types of lift.

3.1.3. Weight of Load

The weight of the containers has an influence on the hoist and movement speed of the trolley. This leads to longer cycle times for certain types of lifts as can be seen in Figure 3.3. For tandem operations the most time consuming part is the actual setdown and pickup part of the containers so the trolley's speed does not influence the total cycle time significantly.

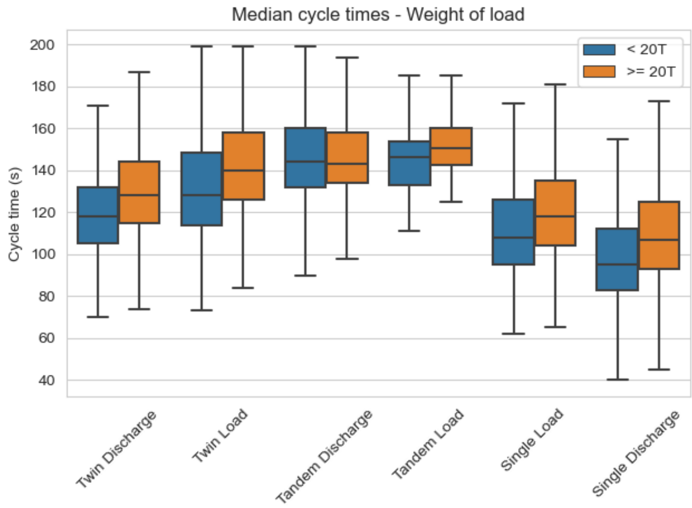


Figure 3.3: The influence of the weight of the load on the median cycle times for each lift type.

3.1.4. Location on Ship

The position of the container on the ship has an influence on the cycle time. The horizontal distance is visualized in the top graphs in Figure 3.4 where 'close' means from the middle of the ship to the quay and 'far' means the other side. As can be seen from those graphs, the difference between the two categories is less for tandem lifts compared to single and twin lifts. This is the case because the actual travel time from platform to ship is roughly the same for tandem lifts and single lifts but the pickup and setdown for tandem lifts require more time. Therefore the overall horizontal difference is less significant for tandem lifts. The bottom graph indicates the difference between cycle times of containers located above deck and below deck.

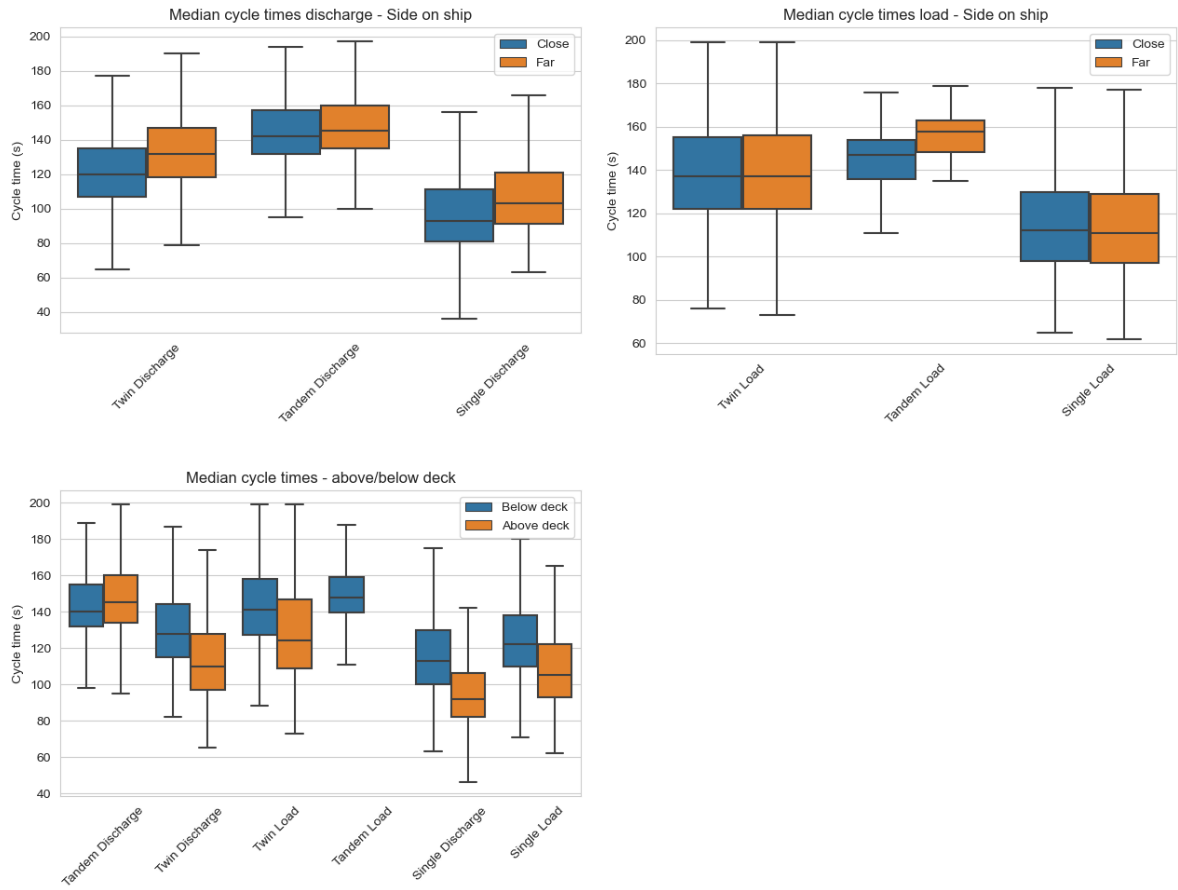


Figure 3.4: The influence of the container's location on the ship on the cycle time.

3.1.5. Wind

The influence of the wind speed on the cycle time duration was already revealed in the literature review in subsection 2.2.3, but can be seen in the data as well. Figure 3.5a and Figure 3.5b show descriptive statistics of the cycle time duration for the different move types under different wind conditions varying in wind speed and wind gust. As can be seen from those images, cycles performed with a wind speed higher than 10m/s or a wind gust of more than 10m/s take longer than cycles performed under calm wind conditions. Furthermore it is assumable that the direction of the wind also has an influence on the cycle time duration. Figure 3.5c shows the cycle time duration for cycles performed with a wind direction along the quay, indicated in blue and cycles performed with a wind direction perpendicular to the quay, indicated in orange. From this image, the wind direction does not appear to have a significant impact on the cycle time duration.

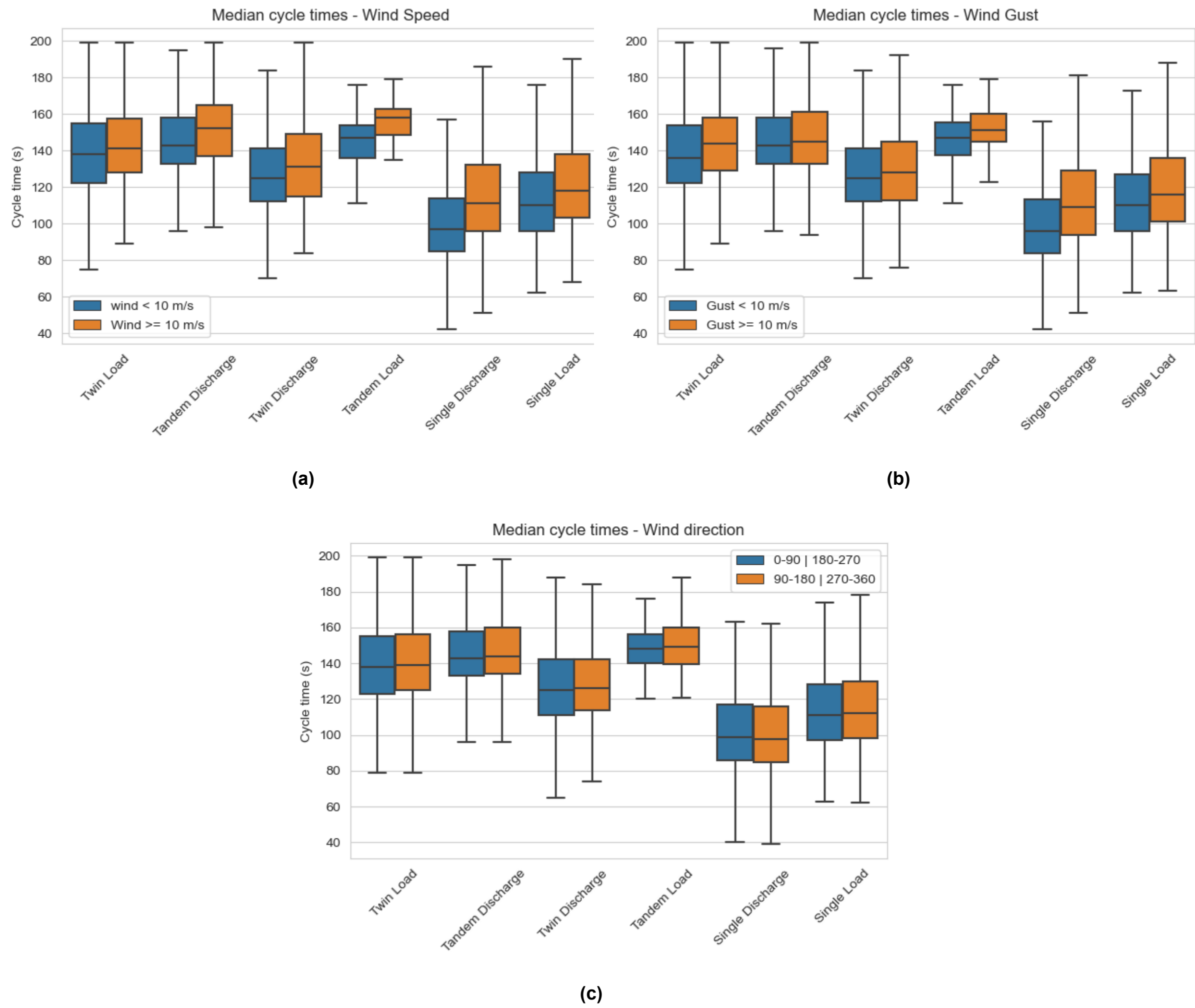


Figure 3.5: The influence of wind speed, gust and direction on the cycle time.

Concerning the wind gusts, there is also a technical maximum after which the cranes become unable to operate. Any wind gusts below 17.7 m/s are fine which means that the crane is able to operate without any restrictions. When wind gusts between 17.8 and 25 m/s are observed, the crane will switch automatically to a lower operational speed. In case of wind gusts of over 25.1 m/s, the crane is unable to operate and switches off automatically. More details about the bad weather procedure can be found in Appendix B.

3.2. Model Development

The goal of this part of the report is to obtain accurate predictions for the duration of an SQCs cycle (as defined in subsection 2.1.3). Those predictions can then be used later to determine the optimal spreader changing moments in order to obtain a minimal loading or discharging time for a whole bay.
Based on the literature study about prediction models in other fields performed in subsection 2.2.4, an Artificial Neural Network (ANN) is chosen to make the cycle time predictions. Historical data of cycles containing the cycle time duration and values for the factors influencing this duration, as discussed in section 3.1, is used as an input to the model.
Historical data of roughly two months of cycles is available which corresponds to a total of just over 100.000 cycles. Sometimes it can happen that a crane has to wait for several reasons, such as meal breaks, technical malfunctions, waiting for an AGV etc. As those cycles are also included in the dataset, a correction needs to be made as they have a longer cycle duration than usually observed for those kinds of cycles. When a crane has to wait three seconds or more during a cycle, the cycle is omitted from the dataset which brings the final number of cycles that can be used as input to the model to 86.125.
The next phase consists of preprocessing the data such that it can be given as an input to the model. First of all the target variable is extracted from the data which is the cycle time measured in seconds. Then there are two categorical variables, namely the type of lift and whether the container is located above or below deck. An encoding strategy is used to transform those variables to a numerical format as this is the only input machine learning models accept. Each different type of lift, six in total, gets its own column which only takes two values, 1 and 0. This means that a single discharge for example has a '1' in the column for single discharge and a '0' in all other columns. This type of encoding is called 'one hot encoding'. When five of the six columns are zero, it has to have a one in the last column. This means that one column can be dropped which changes the one hot encoding to dummy encoding. Label encoding whereby a number is assigned to each lift, for instance 1 for single discharge, 2 for single load etc. is not possible as the model will consider lift types assigned to a higher value as more important. The same dummy encoding method as described above is applied for the variable whether the container was loaded or unloaded above or below deck.
The next step is the normalization of the numerical data. Normalization is necessary to have all the values in the same range such that the model will not give more importance to higher values. For instance the weight of the container is measured in kilograms so it can go up to a high value while the wind speed is measured in metres per second so these values will be lower. In order to make the model assign equal importance to both variables, normalization is needed.
A visualization of this data preprocessing phase is presented in Table 3.3.

Cycle Duration	Wind Speed	Weight	Trolley Position	Hoist Position	Move Type	Above/Below deck
108	5.9	19232	47.844	23.592	Tandem Discharge	Below
80	6.5	46280	21.876	0.754	Twin Discharge	Above
91	6.7	4000	5.558	29.999	Single Load	Below
138	3.9	5926	41.246	-2.121	Single Discharge	Above
119	4.2	33478	31.208	2.092	Single Discharge	Above
116	11.7	54000	56.026	-2.585	Twin Discharge	Above
102	7	14200	23.915	14.572	Single Discharge	Below
107	2.2	29600	27.482	-7.602	Single Discharge	Above
141	5	4000	18.635	-4.477	Single Discharge	Above
146	3.9	11723	26.13	34.4	Single Discharge	Below

(a) First ten rows of the original dataset.

Cycle Duration	Wind Speed	Weight	Trolley Position	Hoist Position	Single Load	Tandem Discharge	Tandem Load	Twin Discharge	Twin Load	Above Deck
108	0.32	0.289	0.71	0.586	0	1	0	0	0	0
80	0.354	0.696	0.279	0.25	0	0	0	1	0	1
91	0.365	0.06	0.008	0.68	1	0	0	0	0	0
138	0.21	0.089	0.6	0.208	0	0	0	0	0	1
119	0.227	0.503	0.434	0.27	0	0	0	0	0	1
116	0.641	0.812	0.846	0.201	0	0	0	1	0	1
102	0.381	0.213	0.313	0.453	0	0	0	0	0	0
107	0.116	0.445	0.372	0.127	0	0	0	0	0	1
141	0.271	0.06	0.225	0.173	0	0	0	0	0	1
146	0.21	0.176	0.35	0.745	0	0	1	0	0	0

(b) First ten rows of the dataset after normalization and dummy encoding.

Table 3.3: Preprocessing of the input data.

As the data is now ready to be given as input to an ANN, it first needs to be split into three different datasets. The first dataset is called the training dataset which is used to fit the model and tune the parameters. Then a validation dataset is needed to evaluate the model fit during the parameter tuning phase. This means that the validation set is used to determine the hyper-parameter values. Lastly a test dataset is given as an unseen dataset to the model in order to obtain an unbiased evaluation of the final model fit. A frequently used split of 80:10:10 for training, validation and testing data respectively is applied to the dataset.

When training the model, accuracy metrics need to be chosen to evaluate the performance of the model. An often used metric for prediction models with continuous values is the Mean Absolute Percentage Error (MAPE) which expresses the mean percentage that the predictions deviate from the actual values. Another well known accuracy metric is the Mean Squared Error (MSE) which is the averaged squared difference between the predicted values and the actual values. Due to the squaring of the difference, the MSE is more sensitive to outliers. The mathematical implementations of both functions can be seen in Equation 3.1 and Equation 3.2, with A_i denoting the actual value, F_i denoting the predicted value and n the total number of observations.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|A_i - F_i|}{A_i} \tag{3.1}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(A_i - F_i)^2 \tag{3.2}$$

Because the MAPE metric is a percentage and thus does not depend on the range of the target variable, general rules can be used to interpret the goodness of a MAPE value. According to Lewis (1982), a MAPE value below 10% is highly accurate and a value larger than 50% is inaccurate. A total overview of the categories can be seen in Table 3.4. Concerning the MSE, such categories cannot be used as it is dependent on the range of target variables. For instance when something is predicted which takes on average 5 hours, an MSE of 1 minute is extremely good but when something is predicted which takes on average 2 minutes, an MSE of 1 minute is not that good anymore. In general, taking the square root of MSE provides the most intuitive interpretation as this is the mean time the predicted value deviates from the actual value.

Mape	**Interpretation**
<10	Highly accurate forecasting
10-20	Good forecasting
20-50	Reasonable forecasting
>50	Inaccurate forecasting

Table 3.4: Interpretation of the MAPE values, according to Lewis (1982).

3.2.1. Linear Regression Model

First of all a neural network without any hidden layers is constructed where the input variables are directly connected to the output layer. This means that a weight is assigned to each input variable which transforms the model to a linear regression model, as stated in Hastie et al. (2001). The training phase of the model runs for as long as there is no improvement made for fifteen epochs. For this model, it occurs at around 2500 epochs with a MAPE value of 11.2% as can be seen in Figure 3.6. Similar MAPE values are also observed for the validation and test datasets, respectively 11.15% and 11.09%. When comparing those values to the categories in Table 3.4, the results can be considered as good forecasting. Concerning the MSE, a value of 311.49 is obtained. By taking the square root of this value (17.65), it indicates how many seconds the prediction deviates from the actual cycle time. Figure 3.5 shows the weights of the variables which correspond to the findings presented in section 3.1. Tandem discharge and tandem load were identified as the longest cycle types in that section and therefore also have assigned the highest weight by the linear model. The trolley and hoist position are of equal importance but the hoist position is a negative value as the higher the hoist position, the less hoist distance is required.

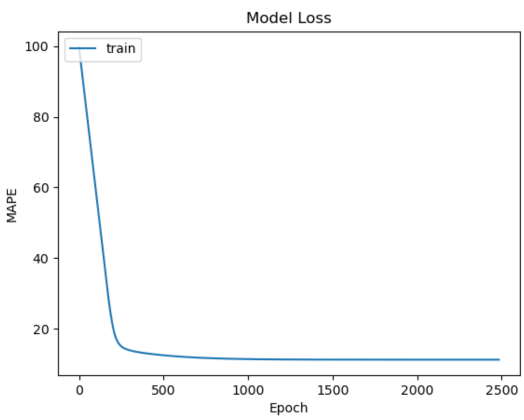


Figure 3.6: The MAPE value of the regression model related to the number of epochs.

Variable	**Weight**
Wind speed	6.89
Weight	4.08
Trolley Position	25.89
Hoist Position	-26.77
Single Load	7.63
Tandem Discharge	38.76
Tandem Load	33.27
Twin Discharge	12.99
Twin Load	21.11
Above deck	7.70

Table 3.5: Weights for the input variables.

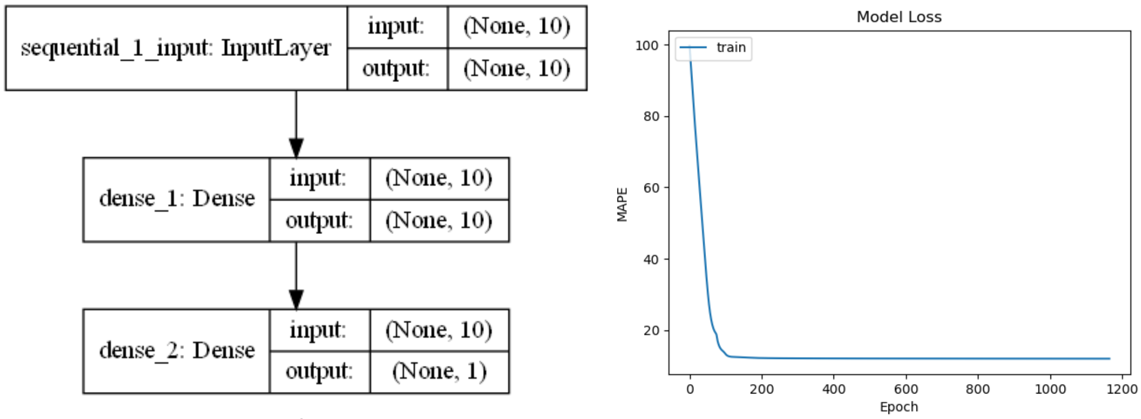
3.2.2. Artificial Neural Network

Due to the uncertainty in linearity of the input variables (Appendix C), an extra layer is added to the model such that it is no longer a linear regression model. This layer is a so-called 'dense' layer which is the most commonly used layer in ANN. Dense layers are deeply connected to its previous layer as all neurons of the layer are connected to every neuron of the previous layer. For this layer, the best number of neurons and the activation function need to be determined. A general accepted rule of thumb is that the optimal number of neurons is usually between the size of the input and the size of the output layer, according to Heaton (2008). In this case, the size of the input layer is 10 and the size of the output layer is 1. Concerning the activation function, the used library Keras provides 9 different functions, namely relu, sigmoid, softmax, softplus, softsign, tanh, selu, elu and exponential. This means that there are 90 different combinations possible as activation function and number of neurons. In order to find the best combination, several possibilities are tried and compared on MAPE and MSE value. Then the combination that provides the lowest MAPE and MSE values is chosen. The results of the grid search performed to find the best combination of activation layer and number of neurons in the hidden layer can be found in Table 3.6. As can be seen from this table, the activation function sigmoid with 10 neurons provides both the lowest MSE and the lowest MAPE values, 287.93 and 10.64 respectively, and thus used as the hidden layer. As the differences between some other activation functions are quite small, the grid search is applied to different datasets as well yielding similar results. Comparing the MAPE value to the categories in Table 3.4, it lies between highly accurate forecasting and good forecasting. The square root of the MSE, which is 16.97, tells the average time the prediction deviates from the actual cycle time.

		relu	sigmoid	softmax	softplus	softsign	tanh	selu	elu	exponential
MAPE	2	11.2	10.77	17.29	11.2	10.87	10.83	10.84	10.85	10.82
MSE	2	310.94	293.84	619.53	311.34	297.47	295.54	295.7	296.11	294.59
MAPE	6	11.2	10.65	17.29	11.2	10.78	10.73	10.74	10.78	10.69
MSE	6	311.06	288.71	619.53	311	293.28	291.88	291.44	293.23	290.37
MAPE	10	11.2	10.64	17.29	11.2	10.73	10.68	10.75	10.77	10.7
MSE	10	310.99	287.93	619.53	311.18	290.7	289.78	291.71	292.32	290.42

Table 3.6: MAPE and MSE values for different activation functions and number of neurons.

As the input consists of 10 variables as can be seen in Table 3.3b, both the input and output of the input layer is 10. Since two consecutive layers are fully connected to each other, the input size of the hidden layer must be 10 as well. The output size of this layer is based on the chosen number of neurons, which was based on the grid search explained above and also set to 10. As the hidden layer is connected to the output layer, the input size of the output layer is also 10. Since there is only one output variable, namely the cycle time duration, the number of neurons is set to one for this layer which is also the output size. A visualization of the layout of the network explained above can be seen in Figure 3.7a. Concerning the training phase of the model, the MAPE decreases drastically for the first 150 epochs after which it continues to decrease slowly until the moment there is no improvement noticed for 15 epochs, which is around 1200. A graphical representation of this training phase is showed in Figure 3.7.



(a) Layout of the model.

(b) MAPE valued related to the number of epochs.

Figure 3.7: Layout and training of the model.

3.2.3. Comparison and Verification of the Models

When comparing the ANN model to the regression model, a slight improvement in both MAPE and MSE value can be observed. This holds for all three datasets, test train and validate, as can be seen in Table 3.7.

	Regression		ANN		Percentage difference	
	MAPE	MSE	MAPE	MSE	MAPE	MSE
Train	11.2	311.49	10.64	287.93	5.0%	7.6%
Validate	11.15	305.22	10.58	280.13	5.1%	8.2%
Test	11.09	303.94	10.67	288.36	3.8%	5.1%

Table 3.7: MAPE and MSE difference for the Linear Regression model and the Artificial Neural Network Model.

The slight improvement of the ANN over the LR model is also visible in Figure 3.8. Besides the MAPE and MSE values, the models can be verified by this graph as well. The percentage difference between the actual cycle time and the predicted cycle time is plotted on the x-axis. The y-axis indicates the percentage of the test data. For instance when looking at an error rate of 10% on the x-axis, it can be seen that around 52% of the predicted cycles by the Linear Regression model have an error rate below 10%. For the Artificial Neural Network model, the number of cycles predicted with an error rate below 10% is slightly higher, approximately 56% of the data as can be seen in the graph.

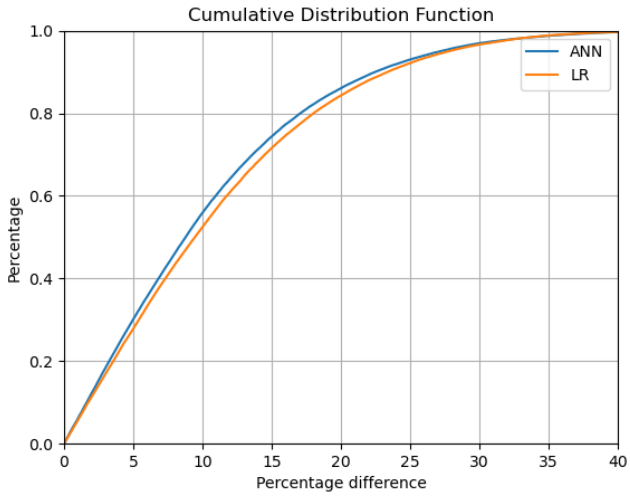


Figure 3.8: Comparison of the LR model and ANN model based on the percentage error.

4 Spreader Switching Strategy

The goal of this chapter is to develop a model which calculates the optimal moment to change between single spreader and tandem spreader in order to minimize the handling time for a bay of a container ship. First of all, the traditional way the spreader changes are done in current practice is explained in section 4.1. Then a requirements analysis is performed in section 4.2 in order to specify the needs and expectations of the model as well as the assumptions. After those are defined, the implementation of the model is done in section 4.3. Last but not least, the model is used in several different scenarios in chapter 5.

4.1. Traditional Spreader Switching Strategy

In current practice, the switch to the tandem spreader is made when at least 50 tandem cycles can be performed afterwards. This means that there should be at least 100 40ft. containers that can be handled in succession with the tandem spreader without a move or action that requires the single spreader. Those moves or actions are the handling of hatch covers, lashing cage operations (see subsection 2.1.2) or the handling of 20ft. containers.

Table 4.1 shows the number of 40ft. containers that had to be unloaded for three different Maersk Triple-E ships and the location of the containers on the ship. The division above and below deck is made because a hatch cover needs to be removed when going from unloading above deck to unloading below deck which requires the single spreader. When assuming the containers are located in a way possible for tandem moves and there are no operations or moves needed requiring the single spreader in between, the number of 40ft. containers gives an indication of the number of tandem cycles that could be performed. As can be seen in the table, it happens frequently that this number is below the threshold value of 100 containers as explained above which means that the whole bay is handled with the single spreader.

Bay	Deck position	Ship 1	Ship 2	Ship 3
2	Above	93	117	114
2	Below	25	15	28
6	Above	81	101	20
10	Above	91	3	116
10	below	0	0	13
14	Above	94	109	74
14	Below	63	96	44
18	Above	92	110	98
18	Below	16	51	62
22	Above	119	124	65
22	below	0	75	0
26	Above	111	152	148
26	below	0	84	51
30	Above	26	135	141
30	below	0	34	70
34	Above	61	155	155
34	below	0	89	22
38	Above	22	19	50
42	Above	66	181	141
42	below	0	90	79
46	Above	101	95	77
46	Below	44	0	39
50	Above	156	151	156
50	Below	34	50	34
54	Above	76	78	111
54	below	0	31	17
58	Above	18	15	16
62	Above	184	174	206
62	Below	151	79	116
66	Above	22	16	26
70	Above	96	118	136
70	Below	46	31	60
74	Above	120	192	7
78	Above	45	6	63
82	Above	52	197	136
82	below	0	88	29
86	Above	28	0	30
90	Above	133	163	42
90	Below	34	31	0
94	Above	135	87	71

Table 4.1: The amount and deck positions of 40ft. containers over the bays for three different ships.

4.2. Requirements Analysis

In this section, a requirement analysis for the model is performed. The overall goal is to reduce the current loading and unloading time of a bay.

4.2.1. Hard Constraints

The hard constraints of the model state the necessities of the model in order to consider it as successful. Those constraints must be satisfied at all times. A distinction is made between functional and technical constraints. Functional constraints are introduced to match reality of the handling sequence while technical constraints make sure that the solution is technically possible.

Technical

- **Hatch cover handling requires single spreader**
  Often one or more hatch covers need to be removed during the loading or unloading process of a bay. In order to be able to lift a hatch cover, the crane must be equipped with the single spreader.
- **Two 40ft. containers require tandem spreader**
  A tandem lift consisting of two 40ft. containers can only be performed if the crane is equipped with the tandem spreader as explained in subsection 2.1.4.
- **One 40ft. container requires single or tandem spreader**
  Normally a single lift consisting of one 40ft. container is performed with the single spreader. However, it is also possible to lift a single 40ft. container with a tandem spreader but increases the cycle time duration. When looking at the data, an increase of 50% can be observed when a 40ft. container is handled with the tandem spreader compared to when it is handled with the single spreader.
- **One or two 20ft. containers require single spreader**
  The handling of either one 20ft. container or two 20ft. containers (called twin lifts) must always be done with the single spreader.

Functional

- **Tier by tier**
  The handling sequence of a bay is always done tier by tier. This means that a whole tier should be finished before a container on the next tier can be handled. In very rare occasions, for instance when a container located on a lower tier is needed urgently, an exception can be made. Overall the tier by tier constraint must be followed as much as possible in order to avoid problems with the ship's balance.
- **Possibility of tandem moves**
  Two 40ft. containers can only be handled with a tandem move if certain technical constraints are met. First of all the containers must be located in the same tier. Furthermore, the rows in which the containers are located must be next to each other.

4.2.2. Soft Constraints

The soft constraints are things that are not essential in order to consider the model as successful but are desirable.

Functional

- **Row by row**
  Generally speaking, the loading process of a tier starts with the container the furthest away from the quay and then the next container one row closer towards the quay. For discharge, it is the other way around as the first container of a tier is the container closest to the quay and the discharge process continues towards the waterside. This handling sequence is used to simplify the process as the previous handled container or the flippers on the spreader (see subsection 2.1.4) can be used as guidance optimally. However, this handling order is not something that must be satisfied and also does not change the optimal spreader switching strategy significantly. Therefore it is taken as a soft constraint.

4.2.3. Assumptions

Assumptions are made about the circumstances under which the bay is handled.

- **Continuous crane process**
  During the handling process of a bay, it can happen that the crane cannot continue its process due to several different reasons, for instance a technical failure or a meal break. As this can happen as likely in the current situation as in the optimal spreader switching situation, it is assumed that the crane can work without interruptions during the handling process of a whole bay.
- **No change of twistlock boxes**
  At the platform of an SQC (see subsection 2.1.2), boxes are located to store the twistlocks. When the boxes are full in case of unloading or empty in case of loading, the main trolley of the crane is used to change the boxes. For this process, the crane must be equipped with the single spreader. As this does not happen too often and is also as likely for both the traditional situation as the optimal spreader switching situation, it is assumed that the boxes do not become full or empty during the handling process of a bay.
- **Duration spreader changes and hatch cover handlings**
  Based on the data of spreader changes and hatch cover handlings in the last couple of months, an acceptable value of 5 minutes is taken for both a spreader change and hatch cover handling.
- **Single container handled with tandem spreader**
  A single container can be handled with a tandem spreader. However, this is harder for the crane operator and takes more time. Based on the available data of single containers handled with a tandem spreader, a time increase of 50% of the cycle time is assumed.

4.3. Model Implementation

After the requirements of the model are determined, the implementation of the model itself is done in this section. First of all, the sets, constants and variables needed for the model are defined.
There are two sets needed; the set of all containers and hatch covers in the bay that need to be handled, indicated with the letter I and the set of all cycles, including both single cycles and possible tandem cycles, indicated with the letter J. Then there are two constants, the predicted cycle time of each cycle denoted as P_j and a binary constant C_{ij} which is 1 if container i belongs to cycle j.
Concerning the variables, the model uses six binary variables and one continuous variable. The binary variables are X_j which is 1 if cycle j is used, CS_{jk} which is one if cycle j is followed by cycle k, TS_j and SS_j are 1 if cycle j is performed with a tandem spreader or a single spreader respectively, SC_j is 1 if the crane has changed spreaders before cycle j and lastly STS_j is 1 if a single container is handled with a tandem spreader. The continuous variable is CT_j which stands for the elapsed time so far after cycle j is performed. An overview of all the sets, constants and variables described above can be found in Table 4.2.

Constants and sets	
I	Containers and hatch covers index set
J	Cycles index set
$H \subset J$	Set of hatch cover cycles
P_j	Predicted time of cycle j
C_{ij}	is 1 if container i belongs to cycle j
Variables	
$X_j \in \{0,1\}$	Cycle j is used
$CS_{jk} \in \{0,1\}$	Cycle j is followed by cycle k
$TS_j \in \{0,1\}$	Cycle j is performed with tandem spreader
$SS_j \in \{0,1\}$	Cycle j is performed with single spreader
$SC_j \in \{0,1\}$	Spreader is changed before cycle j
$STS_j \in \{0,1\}$	Single container is handled with tandem spreader
CT_j	Elapsed time so far after cycle j is performed

Table 4.2: Sets, constants and variables of the MILP model.

The goal of the model is to minimize the handling time of a whole bay as described above and is expressed in the objective function in Equation 4.1. The first part of this objective function consists of the sum of the predicted cycle times of the performed cycles while taking a 50% time penalty into account when a single container is handled with the tandem spreader. The second part of the objective function adds 5 minutes for each spreader change. As a container can belong to multiple cycles, for instance a single cycle and two tandem cycles, constraint Equation 4.2 ensures that each container only belongs to one performed cycle. Constraint Equation 4.3 states that when two containers belong to a performed cycle, the tandem spreader must have been used. Then constraint Equation 4.4 is used to make sure that each cycle is either performed with a single spreader or a tandem spreader. Each cycle has one previous cycle except for the first one which has no previous cycles. This is constrained in Equation 4.5 and Equation 4.6. Similar to those constraints are constraints Equation 4.7 and Equation 4.8 which state that each cycle is followed by one other cycle except the last cycle which has no next cycle. Constraint Equation 4.9 defines the elapsed time so far after a cycle is performed which is the elapsed time at the previous cycle plus the predicted cycle time duration of the current cycle. Either constraint Equation 4.10a or Equation 4.10b for load or discharge respectively is included to make sure that the handling of the bay is done tier by tier. Constraint Equation 4.11 is used to set STS to one when a cycle with one container is performed with the tandem spreader. When a cycle is performed with a tandem spreader and the previous cycle with a single spreader, the variable SC must be one which is ensured with constraint Equation 4.12a and constraint Equation 4.12b for the other way around. As hatch covers need to be handled with a single spreader, constraint Equation 4.12c is used to make sure that cycles handling a hatch cover are performed with a single spreader.

$$min \sum_{j \in J} (X_j * P_j + P_j * 0.5 * STS_j + 300 * SC_j) \tag{4.1}$$

s.t.

$$\sum_{j \in J} C_{ij} * X_j = 1 \quad \forall i \in I \tag{4.2}$$

$$\sum_{i \in I} C_{ij} * X_j \leq 1 + TS_j \quad \forall j \in J \tag{4.3}$$

$$SS_j + TS_j = X_j \quad \forall j \in J \tag{4.4}$$

$$\sum_{k \in J} CS_{kj} = X_j \quad \forall j \in J \setminus \{0\} \tag{4.5}$$

$$\sum_{j \in J} CS_{j0} = 0 \tag{4.6}$$

$$\sum_{j \in J} CS_{kj} = X_k \quad \forall k \in J \setminus \{|J|-1\} \tag{4.7}$$

$$\sum_{j \in J} CS_{(|J-1|)k} = 0 \tag{4.8}$$

$$CT_k \geq CT_j + P_k - M * (1 - CS_{jk}) \quad \forall j, k \in J \tag{4.9}$$

$$CT_j \geq CT_k \quad \forall j, k \in J \quad \text{and} \quad Tier_j > Tier_k \tag{4.10a}$$

$$CT_j \geq CT_k \quad \forall j, k \in J \quad \text{and} \quad Tier_j < Tier_k \tag{4.10b}$$

$$\sum_{i \in I} C_{ij} - M * (1 - TS_j) \leq STS_j + M * (\sum_{i \in I} C_{ij} - 1) \quad \forall j \in J \tag{4.11}$$

$$SS_j + TS_k - M * (1 - CS_{jk}) \leq SC_j + 1 \quad \forall j, k \in J \tag{4.12a}$$

$$TS_j + SS_k - M * (1 - CS_{jk}) \leq SC_j + 1 \quad \forall j, k \in J \tag{4.12b}$$

$$SS_j = 1 \quad \forall j \in H \tag{4.12c}$$

4.4. Verification and Validation

The validation process of the model consists of checking that the results provided by the model are valid solutions in real operation. In order to be a possible handling sequence in real life, all the hard constraints defined in section 4.2 must be satisfied. As the models are used for several different scenarios in the case study in chapter 5, the satisfaction of all constraints in all scenarios can be seen as the validation process. Table 4.3 shows for each scenario that all constraints are met if they are applicable and thus that the solutions provided by the model to the scenarios are possible in real operation.

	A.1	A.2	B.1	B.2	C
Hatch covers are handled with single spreader	N/A	N/A	N/A	N/A	✓
Hatch cover handling takes 5 minutes	N/A	N/A	N/A	N/A	✓
Tandem spreader is used for two 40ft. containers	✓	✓	✓	✓	✓
Spreader change takes 5 minutes	✓	✓	✓	✓	✓
Two containers in tandem move have same tier	✓	✓	✓	✓	✓
Two containers in tandem move have adjacent rows	✓	✓	✓	✓	✓
Handling is done tier by tier	✓	✓	✓	✓	✓
Handling sequence is possible	✓	✓	✓	✓	✓

Table 4.3: Validation of the scenarios.

As verification process of the model, it should be verified that the solution provided by the model leads to the shortest handling time of the bay. In all scenarios in the case study in chapter 5, the optimal solution provided by the model outperforms the traditional solution based on the total handling time of the bay. It can be questioned however whether an even shorter time is possible. When looking at the handling sequences provides by the model, spreader changes to tandem spreader occur right before the most amount of tandem cycles can be performed which is the optimal moment. Consequently, the handling time will not decrease by adding additional spreader changes or changing the moment of the spreader change. Therefore the solution provided by the model yields indeed the lowest handling time.

5 Case Study

In the case study, the handling time of a bay when using the optimal spreader strategy is compared to the handling time of that bay when the spreader changes are done in the traditional way as explained in section 4.1. This is done for multiple bay configurations each varying in the amount of containers and the location of the containers on the ship. As the cycle times are based on the wind speed and the weight of the containers, sensitivity analyses are conducted for each scenario to observe the behaviour of the optimal spreader switching strategy under different circumstances. Another factor that could change the behaviour of the optimal spreader switching strategy is the skill level of the crane operator. As the setdown of the container on the ship is always done manually by the operator, the duration of this part has an effect on the whole cycle time duration and thus also on the spreader switching strategy. As some operators struggle more with the setdown part on the ship of tandem moves than other operators, a 10% increase in cycle time duration for tandem moves is taken in the sensitivity analyses for operators with a 'low' skill level.
The scenarios in the case study are chosen to be discharge scenarios only due to several reasons. First of all, at the time of performing the case studies, the large majority of tandem operations in current practice are discharge moves as this type of move is used for a longer time in operation. Tandem load moves were until recently only used in a pilot phase and tandem loading above deck is still not possible. Furthermore, the handling time of loading a bay is more often influenced by other factors than the cycle times compared to the unloading process of a bay. For instance in case of unloading at any point of time, there just needs to be an empty AGV at the crane and it does not matter which one it is. But in case of loading, an AGV carrying a specific container is required at the crane. Therefore in load scenarios, the chances of a crane waiting for an AGV are higher compared to unload scenarios. Also in case of loading, a container can be set down on the ship with a slight offset from its correct location which prevents the twist locks from locking. When this is not noticed on time and other containers are already loaded on top of that container, those containers need to be unloaded temporarily again in order to reposition that specific container.
The bay design used is a middle bay of a Maersk triple-E ship as this type of bay is handled quite often and leaves room to vary in different variables such as the number of containers, the location of the containers etc.

5.1. Scenario A

Suppose a bay contains 58 full containers, each having a weight pf around 25.000kg that needs to be discharged. The containers are all located in one section of the bay below a hatch cover with tiers ranging from 2 to 24 and the rows from 12 to 20. A visualization of the bay with the containers to be unloaded can be seen in Figure 5.1. In subsection 5.1.1, this bay needs to be unloaded while the ship is lying starboard side to the quay which means that the section with the containers is close to the waterside. Then in subsection 5.1.2, the same bay needs to be unloaded but this time the ship is lying port side to the quay which means that the cycles are shorter. Concerning the wind conditions for both scenarios, the average wind speed at the coast of the Netherlands is used, which is 7.5 m/s.

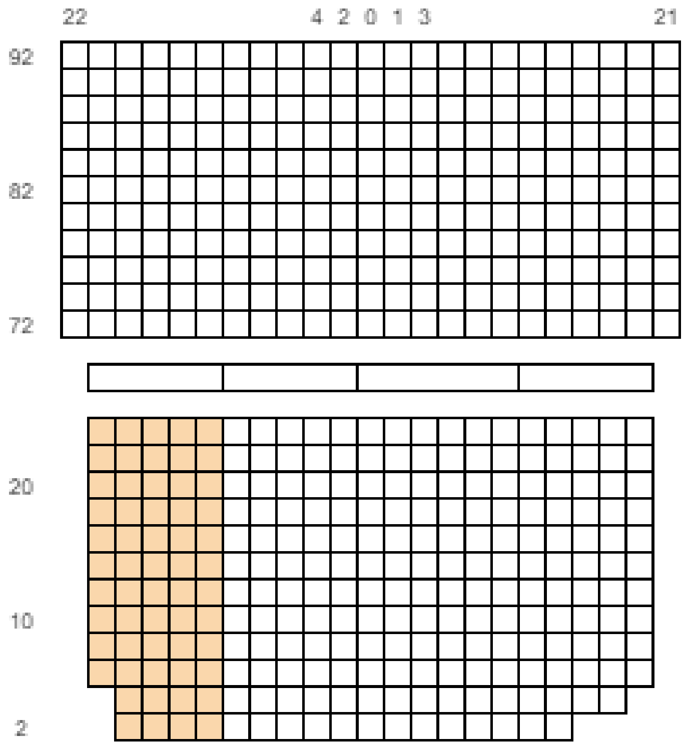


Figure 5.1: Containers in a bay that need to be unloaded.

5.1.1. A.1 Starboard Side to Quay

As the crane has just removed the hatch cover in order to be able to start the unloading process, the crane is attached with the single spreader. As the number of rows is odd, the optimal solution unloads the first container with the single spreader, indicated in red in Figure 5.2 as handling a single container with the tandem spreader takes more time. Then the crane operator changes the spreader to the tandem spreader and the unloading process is done tier by tier and from the lower numbered rows to the higher numbered rows. The containers marked as dark gray are performed in a tandem way and the containers marked in light gray are performed single but with the tandem spreader. The total handling time for the bay is 97 minutes which includes changing back to the single spreader at the end in order to place the hatch cover back.

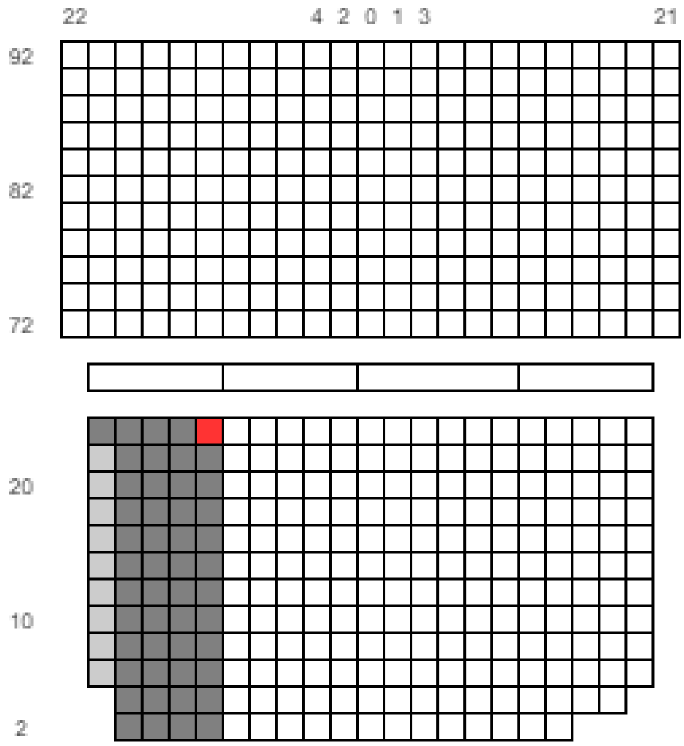


Figure 5.2: The optimal spreader switching strategy. Red container is handled with single spreader, dark gray containers are handled in pairs with tandem spreader and light gray containers are handled individually with tandem spreader.

In current practice, called the traditional way, the number of possible tandem cycles would be considered as too low to switch to the tandem spreader resulting in the whole bay being handled with single cycles. In Figure 5.3 the handling time for the two different strategies is visualized. The first container is handled for both strategies with the single spreader which means the elapsed time after the first container is handled is the same. Then the optimal solution changes to the tandem spreader resulting in a stagnation of the number of handled containers for five minutes while the the amount of containers handled for the traditional strategy keeps increasing. After the change is made, the optimal solution makes up for the lost time and at around 40 minutes and 20 handled containers it is already ahead of the traditional solution. When the optimal solution has handled all containers and changed back to the single spreader after 97 minutes, the traditional strategy has only handled 48 containers. It takes the traditional strategy 21 minutes extra in order to finish all containers in 118 minutes.

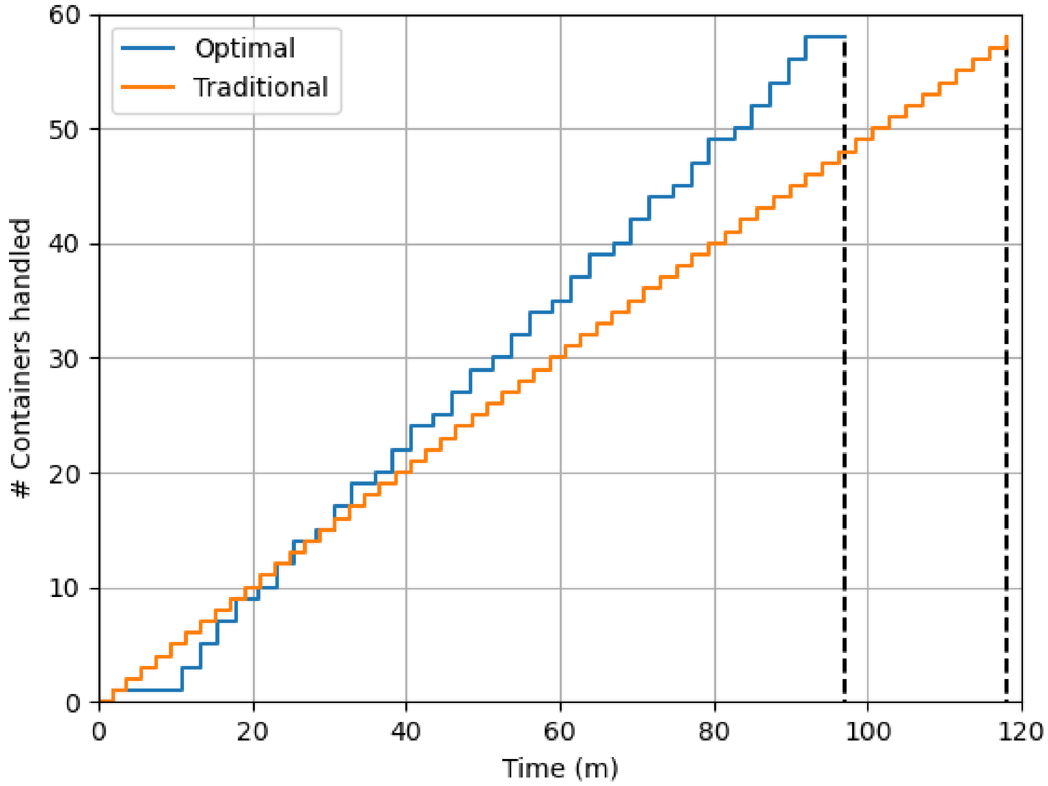


Figure 5.3: Comparison current situation and optimal strategy.

As described earlier, the containers in the bay were assumed to be full (around 25.000kg each) and an average wind speed occurring at the coast of the Netherlands was taken (7.5m/s). Furthermore the skill level of the crane operator was assumed to be high. When the same number of containers and location on the ship as visualized in Figure 5.1 are used but now with different combinations of wind speed, weight of the containers, and the skill level of the crane operator, the optimal moments to change spreaders stay the same but only the handling time differs. Table 5.1 shows that time savings can vary from 15 to 25 minutes for different conditions of wind, weight of the containers and the crane operator's skill level. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions as explained in subsection 3.1.5. The weight of an empty 40ft. container is around 3750kg. Lastly, a low skill level of the crane operator results in a 10% increase in cycle time duration of tandem moves as explained earlier.

Operator Skill	Container	Wind	Traditional	Optimal	Difference
High	Empty	Average	121	96	25
High	Empty	Strong	122	98	24
High	Full	Strong	118	98	20
High	Full	Average	118	97	21
Low	Full	Average	118	103	15

Table 5.1: Handling time in minutes for both strategies for different wind and container conditions.

5.1.2. A.2 Port Side to Quay

This time the ship is lying port side to the quay which means that the cycles are shorter since the containers are also loaded on the port side of the ship as can be seen in Figure 5.1. Figure 5.4 shows the optimal unloading strategy in order to minimize the handling time which is similar to the strategy in subsection 5.1.1. As the crane is equipped with the single spreader at the start, the first container indicated in red is handled with this single spreader as the number of rows is odd and unloading a single container with a tandem spreader takes more time. Then the spreader change takes place and the remainder of the containers in the bay are handled with the tandem spreader. At the end, the crane needs to switch back to the single spreader in order to place the hatch cover back in place which brings the total handling time of the bay to 88 minutes.

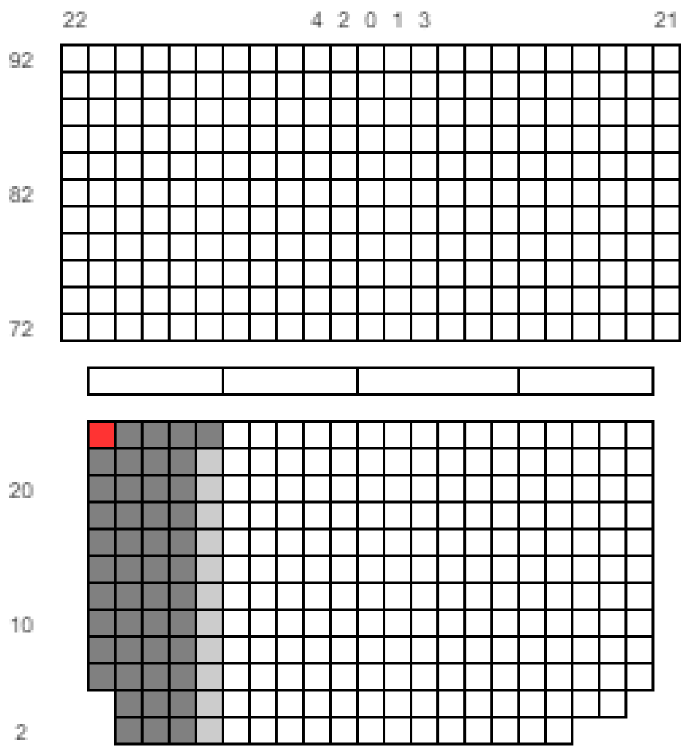


Figure 5.4: The optimal spreader switching strategy. Red container is handled with single spreader, dark gray containers are handled in pairs with tandem spreader and light gray containers are handled individually with tandem spreader.

As the number of containers is the same as in subsection 5.1.1, the traditional handling of the bay will be done again with the single spreader only as the number of possible tandem cycles is considered to be too low. Because the containers are located close to the quay in this scenario, the cycles will be shorter which results in less time saving for tandem moves. This can also be seen in Figure 5.5 which shows the handling process of the bay for the traditional way and the optimal way as explained above. The shorter cycles result in a later moment at around 60 minutes at which the optimal solution has made up for the lost time of changing the spreader. Also the difference in the total handling time of the bay for both strategies is smaller compared to subsection 5.1.1. The optimal solution has handled all containers and changed back to the single spreader in 88 minutes. The traditional strategy is then already at 53 containers and is finished ten minutes later at 98 minutes.

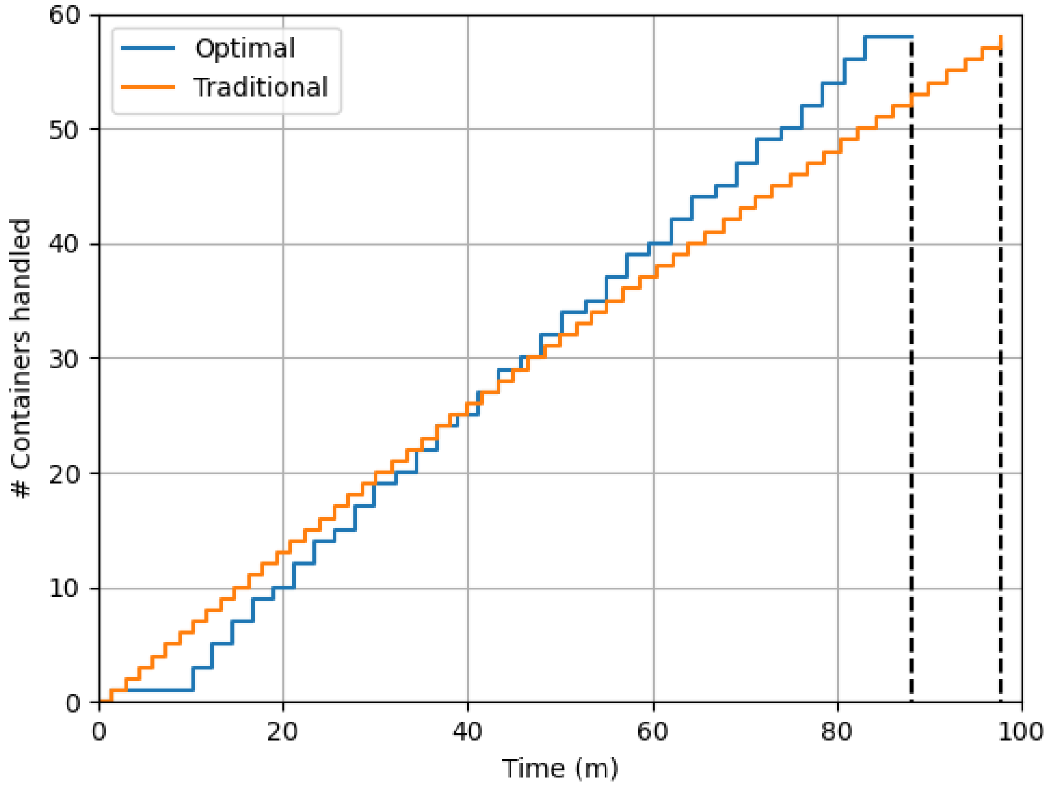


Figure 5.5: Comparison current situation and optimal strategy.

Under different circumstances concerning the wind conditions, the weight of the containers and the skill level of the crane operator, the handling sequence of the optimal solution does not change. However, the handling time of the whole bay does change slightly. Those handling times for the traditional situation and the optimal solution for different combinations of wind speed and container weights can be seen in Table 5.2. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions as explained in subsection 3.1.5. The weight of an empty 40ft. container is around 3750kg. A low skill level of a crane operator leads to a 10% increase in cycle time duration for tandem moves as was explained earlier.

Operator Skill	Container	Wind	Traditional	Optimal	Difference
High	Empty	Average	98	86	12
High	Empty	Strong	104	90	14
High	Full	Strong	102	91	11
High	Full	Average	98	88	10
Low	Full	Average	98	93	5

Table 5.2: Handling time in minutes for both strategies for different wind and container conditions.

5.2. Scenario B

In this scenario, 54 full containers need to be unloaded from a specific part of a bay as can be seen in Figure 5.6. During the handling process of a bay, the wind conditions are assumed to be normal which is 7.5 m/s as it is the average occurring wind speed at the coast of the Netherlands. The first step of unloading the bay consists of unlocking the twistlocks of the containers in tiers 88, 86 and 84 with a lashing cage or gondola as explained in subsection 2.1.2. For the containers located in the lower tiers, the unlocking process can be done by people on the ship. The scenario starts right after the unlocking process is finished. At this moment, the crane is equipped with the single spreader as it is required in order to lift the lashing cage. After all the containers are unloaded, the crane must be equipped with the single spreader as the next move is assumed to be a move for which the single spreader is required. In subsection 5.2.2, this scenario is simulated for a ship lying starboard side to the quay and in subsection 5.2.2 for a ship lying port side to the quay.

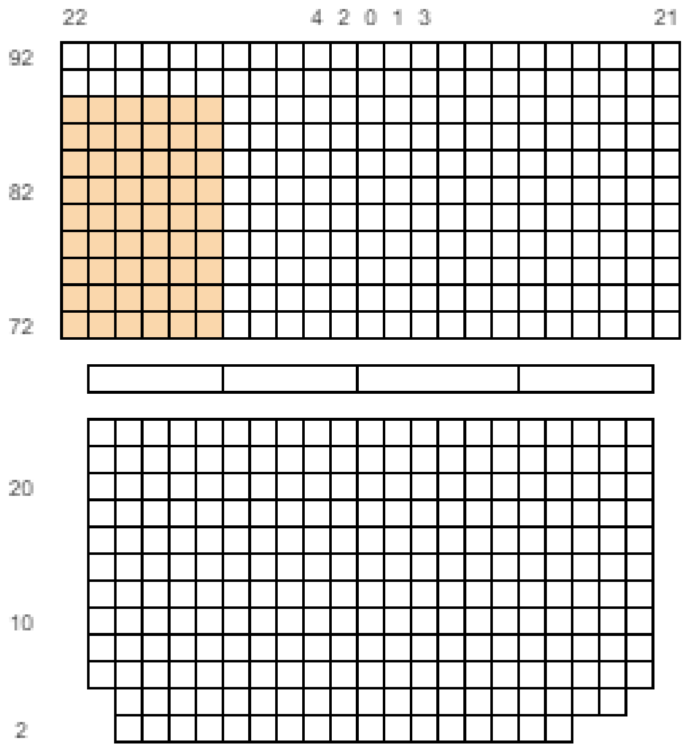


Figure 5.6: Containers in a bay that need to be unloaded.

5.2.1. B.1 Starboard Side to Quay

In this subsection of the scenario, the ship is lying starboard side to the quay which means that the cycles are relatively long as the containers are located at the waterside of the ship. The entire unloading process of the bay will be done with the single spreader in current practice as the number of possible tandem cycles is considered too low in order to make the spreader change worthwhile. This means that the unloading of the first container can start immediately because the crane is equipped with the single spreader at the start of the unloading process. At the end, the crane is also already equipped with the single spreader so the unloading process ends right after the last container is unloaded. This unloading process as it is done in current practice is visualized by the Traditional line in Figure 5.7. The total time for unloading all 54 containers is 91 minutes.
However, the optimal solution calculated by the model does use a different unloading strategy which leads to a shorter handling time of the bay. This strategy consists of changing right at the start to the tandem spreader and then unloading all containers with tandem cycles. At the end the spreader needs to changed back to the single spreader. This process is visualized with the Optimal line in Figure 5.7 in which the spreader changes at the start and end can be observed. The total handling time of the bay when applying this strategy is 73 minutes, which is 18 minutes shorter than for the traditional strategy.

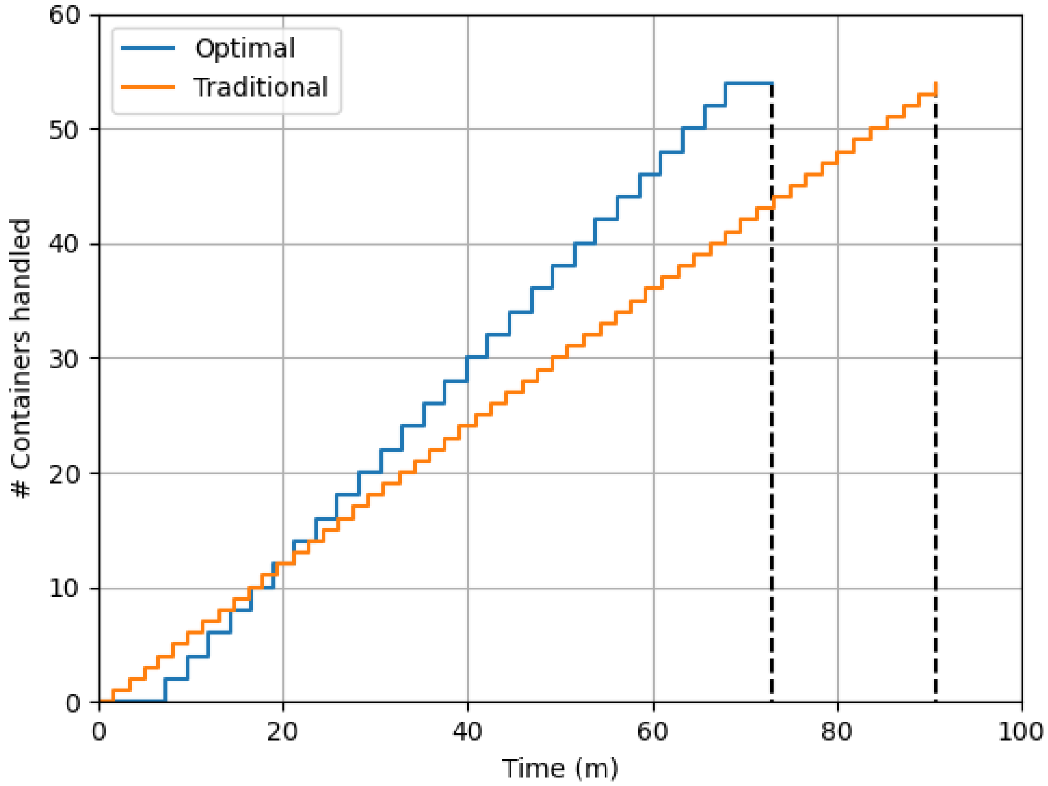


Figure 5.7: Comparison current situation and optimal strategy.

This scenario was performed with full containers, average wind conditions as explained above and a crane operator with a high skill level. Under different circumstances, both the traditional and the optimal strategy stay the same but the handling times differ slightly. Those handling times for several combinations of container weight, wind speed and crane operator's skill level can be seen in Table 5.3. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions as explained in subsection 3.1.5. As previously stated, the weight of an empty 40ft. container is around 3750kg, and a crane operator's low skill level results in a 10% increase in cycle time duration of tandem moves.

Operator Skill	Container	Wind	Traditional	Optimal	Difference
High	Empty	Average	91	72	19
High	Empty	Strong	93	73	20
High	Full	Strong	92	73	19
High	Full	Average	91	73	18
Low	Full	Average	91	79	12

Table 5.3: Handling time in minutes for both strategies for different wind and container conditions.

5.2.2. B.2 Port Side to Quay

This time the ship is lying port side to the quay which means that the cycles are shorter than for the starboard scenario as the containers are also located on the port side of the ship. Because the number of containers that need to be unloaded is still the same and considered too low to use tandem operations, all containers will be unloaded with single moves in current practice. This is visualized by the Traditional line in Figure 5.8. As can be seen, the unloading process can start immediately since the crane is already equipped with the single spreader and at the end there is no extra time needed to change to

the single spreader again. The total handling time of the bay by using this unloading strategy is 70 minutes.
The optimal solution, however, does change to the tandem spreader at the start in order to unload the 54 containers in 27 tandem cycles and changes back to the single spreader at the end. This strategy is visualized in Figure 5.8 and has a total handling time of 69 minutes. Since this is only 1 minute faster than the traditional solution, one may wonder if this optimal strategy should be preferred over the traditional strategy as two spreader changes increase the risk of potential delays. For instance when a spreader change takes much longer than an average spreader change, the one minute time benefit is already lost.

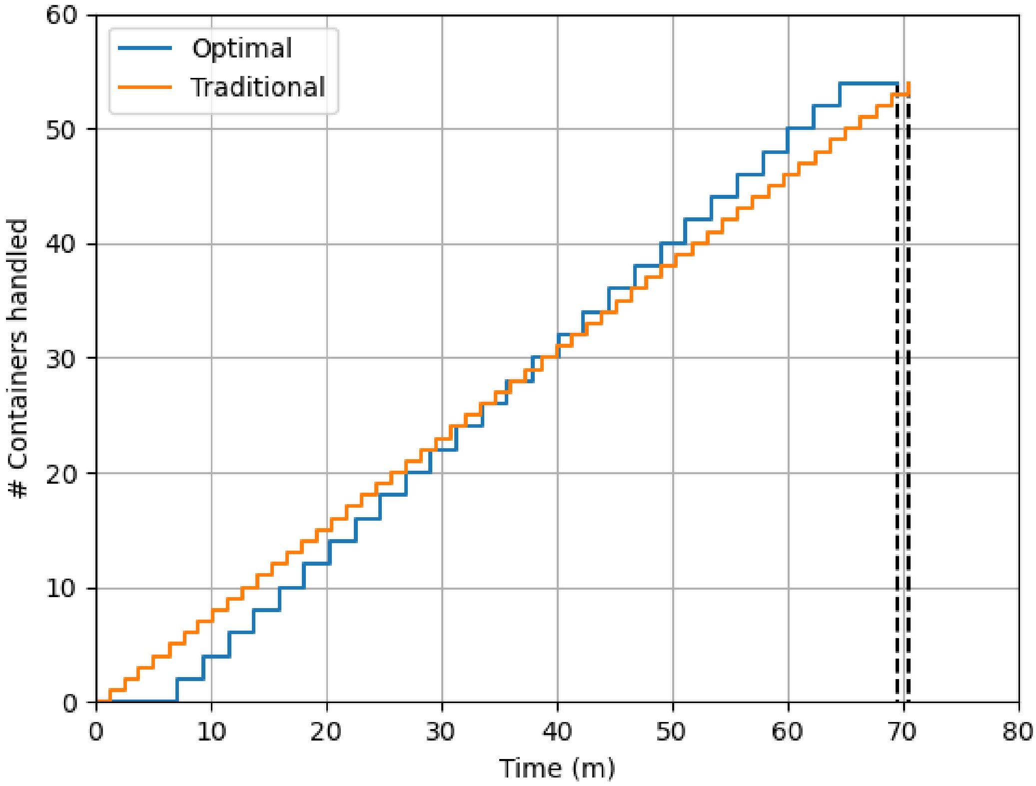


Figure 5.8: Comparison current situation and optimal strategy.

In case of empty containers and different wind conditions, both the traditional and optimal strategy stays the same but the handling times differ slightly. Table 5.4 shows those handling times for different combinations of the weight of the containers and the wind conditions. In a scenario with a crane operator with a low skill level however, the optimal solution is the same as the traditional solution which means that all containers are handled with single moves. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions as explained in subsection 3.1.5. The weight of an empty 40ft. container is around 3750kg and a low skill level of a crane operator leads to a 10% increase in cycle time duration of tandem moves as explained earlier.

Operator Skill	Container	Wind	Traditional	Optimal	Difference
High	Empty	Average	71	69	2
High	Empty	Strong	73	70	3
High	Full	Strong	72	70	2
High	Full	Average	70	69	1
Low	Full	Average	70	70	0

Table 5.4: Handling time in minutes for both strategies for different wind and container conditions.

5.3. Scenario C

In this scenario, 126 empty containers need to be unloaded of which 54 above deck and 72 below deck as can be seen in Figure 5.9. The average wind speed occurring at the coast of the Netherlands, which is 7.5 m/s, is taken as the wind condition during the handling process of this bay. For this specific ship, the twistlocks of the containers in tiers 72 to 82 can be unlocked by people on the ship. In order to unlock the twistlocks of the containers in tiers 84 to 88, a lashing cage or gondola needs to be used as explained in subsection 2.1.2. The scenario starts right after the operation with the lashing cage is performed which means that the twistlocks of the containers in tiers 84 to 88 are unlocked. At this point, the crane must be equipped with the single spreader as this spreader is needed to handle the lashing cage.

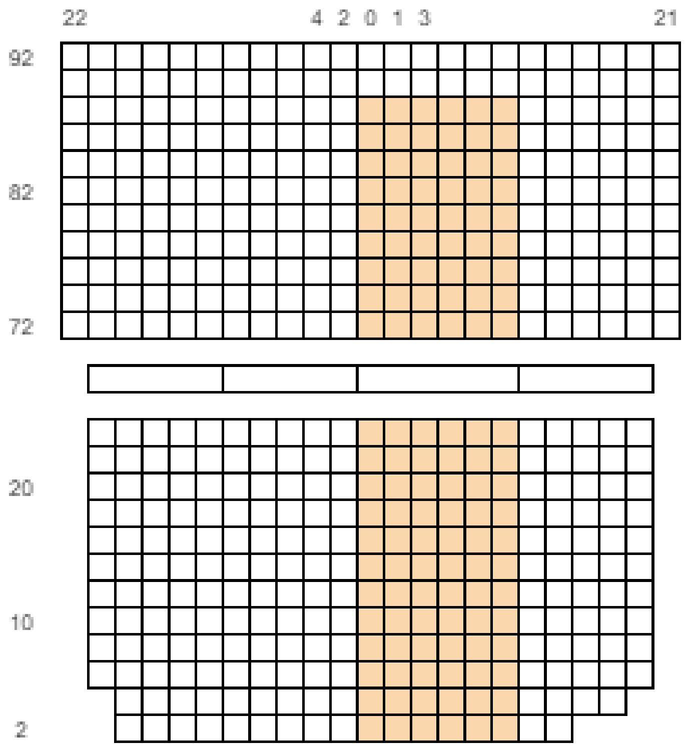


Figure 5.9: Containers in the bay to be discharged. The ship is lying port side to quay.

After all containers above deck are unloaded, the hatch cover needs to be removed in order to unload the remaining containers below deck. As the crane must be equipped with the single spreader to be able to lift a hatch cover, there can only be 27 tandem cycles performed above deck before the crane needs to switch back to the single spreader. Below deck there can only be 36 tandem cycles performed before the crane needs to switch back again to the single spreader in order to place the hatch cover back. In current practice, those numbers of tandem cycles are considered too low to make the spreader change worthwhile and therefore this whole bay is handled by using single moves. The traditional line in Figure 5.10 shows that this process would take 224 minutes which includes the handling of the hatch cover at around 85 minutes and at the end but does not include the lashing cage procedure at the start. However the optimal solution, indicated by the optimal line in the figure shows that the single spreader is changed to the tandem spreader right at the start and 27 tandem cycles are performed above deck. Then around 70 minutes, there is a 15 minutes window in which there are no containers handled. This is the case because the hatch cover needs to be removed so the crane must switch back to the single spreader, which takes five minutes and removing the hatch cover takes another five minutes. Then the last five minutes consist of switching back to the tandem spreader in order to perform 36 tandem cycles below deck. At the end there is another time window of 10 minutes without handling any containers which is changing back the single spreader and placing the hatch cover back. This whole process takes 174 minutes which is 50 minutes less than the traditional solution takes.

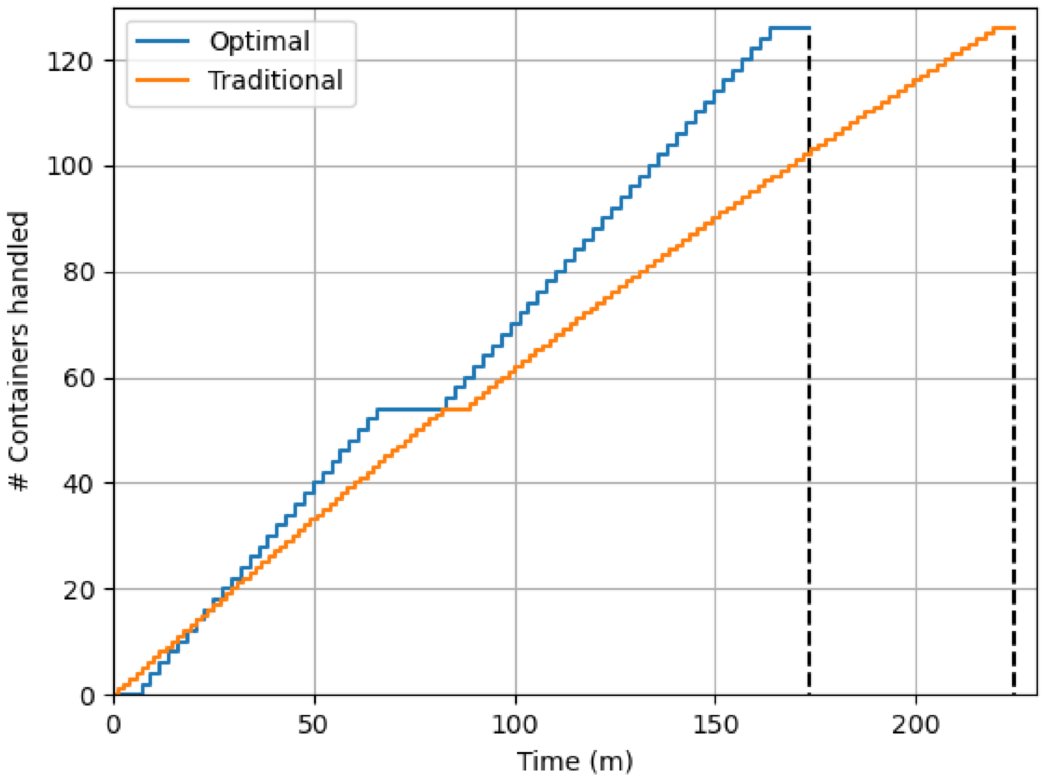


Figure 5.10: Comparison current situation and optimal strategy.

As said before, the results obtained above were performed under average wind conditions with empty containers and a high skill level of the crane operator. For different combinations of those variables, both the traditional and optimal strategies stay the same but the handling times change. In Table 5.5, the handling times for the different conditions can be observed, varying from 36 to 61 minutes difference between the traditional and optimal solution. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions as explained in subsection 3.1.5. The weight of an empty 40ft. container is around 3750kg and a low skill level of crane operator leads to an additional 10% in cycle time duration for tandem moves as explained earlier.

Operator Skill	Container	Wind	Traditional	Optimal	Difference
High	Empty	Strong	237	176	61
High	Full	Average	225	176	49
High	Full	Strong	235	177	58
High	Empty	Average	224	174	50
Low	Empty	Average	224	188	36

Table 5.5: Handling time in minutes for both strategies for different wind and container conditions.

5.4. Summary Case Study

The first scenario involved the unloading process of 58 containers from a bay below deck. Since there are only 34 tandem cycles that can be performed, the unloading process is done with single moves only in current practice. The optimal solution, however, does make the switch to the tandem spreader and saves 10 to 18% in handling time, depending on whether the ship is lying port side or starboard side to the quay.

In the second scenario, 54 containers needed to be unloaded from a bay above deck. When the ship is lying port side to the quay and the containers are located on the port side of the bay as well, the cycles become quite short which means that the time saving of performing tandem cycles is less than in cases with longer cycles. As a consequence, the optimal solution which uses tandem moves is only slightly faster than the traditional solution which uses only single moves. When the ship is turned around and lies starboard side to the quay, the optimal solution reduces bay handling time by 20% when compared to the traditional solution.

The last scenario consisted of the unloading process of 54 containers above deck, 72 containers below deck and the removal of a hatch cover before continuing the unloading process below deck. The traditional solution handled all containers with single moves while the optimal solution performed multiple spreader changes in order to perform tandem moves which led to a handling time decrease of 22%.

An overview of the different scenarios is given in Table 5.6. As can be seen from this table, the time difference between scenarios A and B depends on the location of the containers in the bay. When the containers are located on the quay side of the ship, the cycles are shorter than when the containers are located on the water side of the ship as the crane's trolley distance increases. This difference is especially remarkable for the Maersk Triple-E ship used in the case study as it is one of the widest container ships at 59 metres. When smaller ships are considered, the difference between a scenario with containers located on the quay side of the ship and a scenario with containers located on the water side of the ship is expected to be less.

	A.1	A.2	B.1	B.2	C
Ship to quay	Starboard	Port	Starboard	Port	Port
Side containers in bay	Port	Port	Port	Port	Middle-Starboard
Above/Below deck	B	B	A	A	Both
# Containers	58	58	54	54	126: 54(A)&72(B)
Possible tandem cycles	34	34	27	27	36
Traditional (minutes)	118	98	91	70	224
Optimal (minutes)	97	88	73	69	174
Difference (minutes)	-21	-10	-18	-1	-50
Percentage difference	-18%	-10%	-20%	-1%	-22%

Table 5.6: The results obtained for the different scenarios.

The main KPI used on the terminal is Crane Moves Per Hour (CMPH) which indicates how many billable moves (containers) the crane has handled on average per hour. This KPI is not used in the case study as the cases are performed at bay level. Therefore, many non-billable moves of the crane are excluded such as gantry driving between bays, lowering the boom etc. causing an unrealistically high CMPH. As those moves are necessary, the CMPH is mostly calculated at ship level. By making some assumptions, the impact on the CMPH of the optimal spreader switching strategy can be estimated roughly.

First of all when looking at the case study, there are around 20 cycles or 40 containers needed to make up for the lost time of a spreader change for the optimal solution. When the number of containers is 100 or more, tandem operations are currently performed which is also the optimal solution. Therefore, time can be saved for bays with 40 to 100 40ft. containers, divided into above and below deck due to the hatch cover removal. When assuming the handling time of those containers is on average 100 minutes with the traditional solution and a 10% shorter handling time with the optimal spreader switching strategy, 10 minutes per bay, either above or below deck, is saved. Table 4.1 shows the division of the 40ft. containers over the bays and divided into above deck and below deck. As can be seen from this table, it occurs 14 times for ships 1 and 3 and 12 times for ship 2 that there can be handled 40 to 100 40 ft. containers in a row with the tandem spreader. Due to the time savings on the handling time of those containers, the total crane hours decrease as can be seen in Table 5.7 by the ”Total Crane Hours New”. Due to the decreased working hours of the cranes on a ship, the CMPH decreases as well. On average, a CMPH increase of 0.2 is observed which is satisfactory considering no money needs to be spend in order to obtain this increase. This estimation is done for Maersk Triple-E ships which have a length of 400 metres. When smaller ships are considered, the CMPH increase is expected to be less as time is saved per bay by using the optimal spreader switching strategy and smaller ships have less bays.

As previously stated, this CMPH increase estimate should be regarded as a rough estimate because it is subject to change for a variety of reasons. For instance in real operation, it can occur that a crane drives between two or more bays in a working sequence to make the change to the tandem spreader more worthwhile. Also the time increase of 10% for only sections with 40 to 100 40ft. containers is a rough estimation. Further research is recommended in order to know the precise impact on the CMPH of the optimal spreader switching strategy. Nevertheless, an increase in CMPH will be observed as there are certain sections with fewer than 50 possible tandem cycles for which a spreader change would result in a shorter handling time.

	Ship 1	**Ship 2**	**Ship 3**
Total Moves	4428	6932	6008
Total Crane Hours	219.37	437.87	219.37
CMPH	20.2	15.8	27.4
# 40-100 40ft. containers	14	12	14
Total Crane Hours New	217.04	435.87	217.04
CMPH New	20.4	15.9	27.7
CMPH gain	0.2	0.1	0.3

Table 5.7: Estimation of impact of optimal spreader switching strategy on CMPH.

This CMPH increase of on average 0.2 can be translated to the number of containers handled in a day. An increase of 0.2 CMPH means that every hour, 0.2 extra moves can be made by a crane. A move can either be one container in case of a single lift or two containers in case of a twin or tandem lift. So, based on the number of cranes working on a given day, which is determined by the number of vessels at the quay, the cranes' technical availability, and the type of lifts, the number of extra containers that can be handled per day can be estimated by multiplying 0.2 by 24 (hours) and the number of cranes. This estimation is done in Table 5.8.

	# Cranes									
	1	2	3	4	5	6	7	8	9	10
Single	4,8	9,6	14,4	19,2	24	28,8	33,6	38,4	43,2	48
Twin or Tandem	9,6	19,2	28,8	38,4	48	57,6	67,2	76,8	86,4	96

Table 5.8: Amount of containers that can be handled extra per day.

6

Conclusions and Recommendations

This chapter provides conclusions and recommendations about the main findings of the conducted research. In section 6.1, the research is concluded and answers are given to the research question as defined below.

How can a quay crane's cycle time prediction model be developed and used to calculate the optimal spreader switching strategy?

Then section 6.2 gives recommendations on how the results could be improved in the future and practical recommendations on how the spreader switching moment should be determined.

6.1. Conclusions

In this thesis, two models are developed to predict the cycle time of a quay crane based on the location of the container on the ship, the weight of the load, the type of move and the wind speed. Those input variables are obtained with a literature review and a data analysis. The first model is a linear regression model yielding a Mean Absolute Percentage Error (MAPE) of 11.2%. This means that the average predicted cycle time duration deviates on average by 11.2% from the actual cycle time duration. As a linear regression model is only able to capture linear relationships between variables which is not necessarily the case for the variables influencing the cycle time, an artificial neural network is developed as well. This model consists of a hidden layer between the input and the output layer with 10 neurons and sigmoid as activation function resulting in a slightly lower MAPE value of 10.64%. When predicting the test dataset, 56% of the predictions have an error rate below 10% and 85% of the predictions below 20%. With the development of the models and the related research about the input factors, the first part of the research question is answered. This also covers the lack of a cycle time prediction model in the literature which can be used as an input to various models, such as turnaround time prediction models for vessels and tandem performance models.
The second part of the research question is answered by the development of a Mixed-Integer Linear Programming (MILP) which identifies the optimal moments to change between single and tandem spreaders when loading or unloading a bay. This model uses cycle time predictions from the cycle time prediction model developed earlier as one of the parameters. In the case study, the handling times of different bay layouts under varying circumstances concerning wind speed and weight of the containers are calculated for both the current handling strategy and the optimal handling strategy calculated by the model. The current handling strategy consists of switching to the tandem spreader when 50 tandem cycles can be performed in succession. In the scenarios, bay layouts are tested in which the possible number of tandem cycles is lower such that the bay is handled with the single spreader only. However, the optimal shows that even with a limited number of possible tandem cycles, switching to the tandem cycle can be beneficial in some cases. This depends mainly on the containers' location in a bay. For certain bay layouts, the handling time can decrease by up to 22% when the spreader is switched at optimal moments compared to the current strategy. A rough estimation is made as well for the impact on the CMPH of Maersk Triple-E ships by using this model, which is on average an increase of 0.2 CMPH. Considering the solution does not require any physical changes nor additional money, this

seemingly small increase in CMPH is satisfactory. The case study also shows that for a certain number of containers in a bay, the decrease in discharge time of the bay by using tandem operations can vary from 1% to 20% based on the cycle times which are influenced by the location of the containers, the wind conditions and the weight of the containers. When taking a fixed value as cycle time, as is done in current literature about tandem performance models, those differences cannot be observed meaning that the performance of tandem operations is not modelled realistically.

6.2. Recommendations

The different scenarios have shown that the time decrease is highly dependent on the location of the containers on the ship. In certain scenarios, a time decrease of 20% is observed by using the optimal spreader switching strategy while there are only 27 possible tandem cycles that can be performed in succession. As in current practice tandem operations are only used when 50 tandem cycles can be performed in a row, this case would have been handled with the single spreader only. On the other hand, a scenario is observed in which there are also 27 possible tandem cycles in succession but a time increase of only 1% is observed as the locations of the containers on the ship are different compared to the previous scenario. This leads to both practical and scientific observations. Concerning the practical observation, a fixed threshold of 50 possible tandem cycles in succession to make the switch to the tandem spreader worthwhile, which is used currently, is far from the optimal solution. In fact, a fixed value cannot be used at all as the time saved by tandem moves depends heavily on the cycle times. Therefore, the recommendation is made to use the spreader switching strategy model developed in this report for each bay in order to know whether a spreader switch is worth it and when the switch needs to be done. In terms of scientific observation, when a constant value is taken as cycle time and used as an input to tandem performance models in literature, the differences based on the cycles times revealed in the case study cannot be captured. By using the cycle time prediction model as input instead, the accuracy of the models will likely improve. This does not only hold for tandem performance models, but also for other models in literature that use cycle times as input such as turnaround time prediction models.

At the time of writing this report, the obstacle path of a quay crane's cycle was not available. This obstacle path consists of the current containers on the ship, the obstacles, over which the crane needs to go. For instance when a container needs to be loaded on the water side of the ship and in the middle of the ship there is a high stack of containers for a different port, the cycle of the quay crane will take more time as it needs to go higher than normal. In order to achieve more accurate cycle time predictions, it is recommended to include this aspect in the future. Furthermore, when loading a container on the ship while there is already a container located next to it, the set down becomes easier as that container can be used as guidance which leads to a shorter cycle time duration. As this information was also not easily available at the time of writing this report, it is not included in the cycle time prediction model but the inclusion of this aspect may lead to more accurate cycle time predictions.

In this research, the operation of a quay crane is optimised assuming that there are no quay-side capacity restraints. This is done because the cranes used in the research are dual trolley cycle cranes which have a platform that acts as a buffer between the ship and the quay. However, the capacity of this buffer is limited to two containers so there are certainly scenarios possible in which the limit is reached. For instance when an AGV is heavily delayed such that the crane has already used the buffer of the platform and has to wait for the AGV. Therefore, it is recommended to include the quay-side constraints in future research in order to obtain a more realistic view.

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A

Scientific Paper

Optimising quay crane operations based on data-driven cycle time prediction

Laurens Gerlach

***Abstract*—Quay cranes on modern container terminals have the possibility to lift two 40ft. containers side by side. In order to be able to perform this type of lift, the crane must be equipped with a tandem spreader. As this type of spreader cannot be used for performing certain lifts, such as the handling of hatch covers, switches between single spreader and tandem spreader are inevitable. However, there is no method in current literature nor in practice to determine when the spreader changes should be performed. Therefore, the aim of this research is to develop a model that calculates the optimal moments to switch spreaders. As the performance of tandem lifting depends on the cycle times, a cycle time prediction model is developed first. This Artificial Neural Network model predicts the cycle time based on the type of lift, the actual position of the container(s) on the ship, the weight of the load and the current wind speed. The predictions yield a Mean Absolute Percentage Error of less than 11%. Afterwards, the cycle time prediction model is used to develop an optimal spreader switching strategy model in the form a of Mixed Integer Linear Programming model. A case study, in which several different bay layouts of a container ship need to be handled, shows a decrease in handling time of up to 22% compared to the traditional spreader switching strategy.**

***Index Terms*—Quay Crane, Tandem Move, Container Terminal, Spreader Change, Cycle Time**

I. Introduction

In 2019, 825 million TEUs of containers were handled in ports worldwide [on Trade and Development (2022)]. In order to minimize the handling time and maximize the profit, container terminals are constantly aiming to improve the efficiency of container handling. One of the ways to improve the efficiency is by increasing the moves per hour of a quay crane. This can be done by loading or unloading two 40ft. containers at the same time, which is called a *tandem move*. Tandem moves require the quay crane to be equipped with a tandem spreader which is different than the single spreader. As changing between the single spreader and tandem spreader takes time, it is not always beneficial to make the spreader change to perform tandem moves. In fact, there is a certain number of containers needed that can be performed after the spreader change in order to make up for the lost time of the spreader change.

In current practice, a fixed number of possible tandem cycles is taken as a threshold value to make the decision for a spreader change. However, the time saving of a tandem move instead of two single moves depends on the cycle time. For instance, a tandem move of two 40ft. containers takes 160 seconds and a single move for those containers takes 120 seconds. Then the time saved by performing the tandem move instead of two single moves is 80 seconds. In case when the containers are located closer to the quay which makes the cycle times shorter, for instance 120 seconds for tandem move and 80 seconds for a single move, the time saved by performing the tandem move instead of two single moves is in this case only 40 seconds. This means that when the cycle times are shorter, there are more cycles needed after the spreader change in order to make the spreader change beneficial. This aspect, however, is not taken into consideration in current practice.

Also in current literature, the performance of tandem moves is often simulated by using fixed values as cycle times. As the performance of tandem moves depends on the cycle times as explained above, the model may provide inaccurate estimations for the performance increase of tandem operations. Accurate cycle time predictions are not only useful for tandem performance models but also for other models that include cycle times as an input variable. Unfortunately, a model that predicts the cycle time of a quay crane cannot be found in literature.

The aim of this research paper is to handle the problems described above by answering the following research question: *How can a quay crane's cycle time prediction model be developed and used to calculate the optimal spreader switching strategy?*

The structure of the paper is as follows. In chapter II, an overview of the performed literature review is presented. Then in chapter III, the methodology is presented which explains the methods used to solve the research question. The next chapter, chapter IV, provides the results and is followed by a case study in chapter V. Lastly, the conclusions of the research are drawn in chapter VI.

II. Literature Review

The literature review is divided into two parts. The first part consists of literature about tandem operations in section II-A. Then literature about turnaround time prediction models is analysed in section II-B.

A. Tandem Operations

Tandem operations consists of lifting two 40 ft. containers, four 20 ft. containers or one 40 ft. container and two 20 ft. containers according to Bartosek and Marek (2013). By using tandem operations, containers are placed side by side as opposed to twin operations where containers are placed end-to-end. Theoretically, tandem operations can double the quay crane's performance since double the number of containers are loaded or unloaded simultaneously compared to the traditional way. However, there are many more factors involved in real operations preventing the crane from doubling its performance when performing tandem lifts. Models can

Citation	Spreader change	yard trucks	hatch covers	Cycle time	Loading/ unloading	SQC with platform	Change stowage plan
Kong et al. (2021)	No	Yes	No	1.5 minutes for both single and tandem cycle	Both	No	Yes
Huang and Li (2017)	Yes	No	Yes	2 minutes for both single and tandem cycle	Both	Yes	No
Lashkari et al. (2017)	Yes	No	No	1.5 for single and 1.8 for tandem	Unloading	No	No
Ding et al. (2017)	Yes	No	No	Fixed values	Both	No	No
This paper	Yes	No	Yes	Cycle time prediction model	Both	Yes	No

TABLE I: Literature review table for tandem operations.

Citation	ship type	Model	Case study	Crane cycle time	Factors
Stepec et al. (2020)	All	Machine learning	Yes	No	Cargo type, cargo tonnage, day/hour of entry and berth
Li et al. (2013)	All	BP, RBF and Linear	Yes	No	Line of ship, type of ship, berth and month
Li and He (2020)	Container	Deep learning	Yes	2 minutes	Fundamental points and quantity configurations
Lee et al. (2021)	Container	Multi-layer perceptron model	No	1.5 minutes for unloading and 2.5 minutes for loading	type of the container, bay cluster movement, work type change, employee shift, single/twin lift and container full/empty
Dhingra et al. (2017)	Container	two-level stochastic model	No	Exponentially distributed	Crane assignment and scheduling and interaction amongst terminal equipment
This paper	Container	Machine learning	Yes	Cycle time prediction model	Location of containers on the ship, type of lift, wind speed and container weight

TABLE II: Literature review table for turnaround time prediction models.

be found in literature that simulate the actual increase in performance of tandem lifts compared to single lifts. First of all, the paper by Kong et al. (2021) uses Mixed-Integer Linear Programming to optimize tandem operations. Since quay cranes without a platform are used in this research, the cooperation between yard trucks and crane is very important because two yard trucks at the same time are required in order to perform a tandem lift. When one of the yard trucks is delayed, a decision has to be made whether the crane will perform a single lift or wait for the delayed yard truck to perform a tandem lift. This is one part of the optimization. The other part of the optimization is the container slot planning. An optimal stowage plan is made such that the number of possible tandem operations is maximized.

In the research conducted by Huang and Li (2017), a method is proposed to group containers into tandem lifts in order to minimize the spreader changes and intra-bay movements of the crane. A reduction of 40 to 50% in vessel completion time can be obtained by applying this method. However, cycle times are set to two minutes for both single lifts and tandem lifts which does not match reality.

The paper by Lashkari et al. (2017) proposes a new mathematical model to optimize the unloading sequence of a bay. One of the possible pitfalls of this research is its theoretical point of view. First of all, the removal of hatch covers is not taken into consideration while it has a big influence on the unloading strategy as removing of a hatch cover can only be done by a single spreader. Furthermore, the

unloading process does not follow a tier-by-tier order which is done in practice due to several reasons such as the weight distribution on the ship and the unlocking process of the twistlocks using a gondola. Another drawback of the research are the fixed values for cycle times of 1.5 minutes for single lifts and 1.8 minutes for tandem lifts.
Very similar to the research just mentioned is the work done by Ding et al. (2017). The main difference is that this paper also includes the possibility of performing a dual cycle which means loading and unloading at the same time. The cycle times are fixed values again varying based on the type of lift and cycle and taking spreader changes into account.
Table I presents an overview of the literature analysed above.

B. Turnaround Time Prediction Models

Predicting the berthing time of a ship is something which is widely researched. The paper by Stepec et al. (2020) uses a machine learning based system to predict the turnaround time for vessels in the port of Bordeaux. There are several features considered of which the cargo type and tonnage appeared to be the most important. For certain cargo types, the model can estimate the turnaround time of a vessel with an error rate below 10%. Therefore this model offers a good prediction for a specific vessel type.
A similar approach is taken in the paper by Li et al. (2013) which designs three different neural networks to predict the berthing time of a ship. The three networks are; Back Propagation (BP), Radial Basis Function (RBF) and Linear (L). Those networks are then applied in a case study for the Port of Valencia and the RBF showed the highest accuracy. However, the output of the model is a berthing time number from 1 to 4 which indicates a large time time span of eight hours. So 1 means a berthing time of 0-8 hours, 2 means a berthing time of 8-16 hours etc. While this gives a broad indication of a vessel's berthing time, an accurate prediction is not made. Also the data used to train the neural networks only consist of four factors; the line of the ship, the type of the ship, the berth at which the ship is handled and the month of berthing. In reality, the berthing time of a ship is affected by more factors but those were not available for the authors of the paper. However, by including more factors, more realistic predictions might be made.
Smaller time spans and more factors are taken into account in the paper by Li and He (2020). Deep learning is applied to predict the Liner Berthing Time (LBT) in time ranges of half an hour. As this is way harder than predicting the LBT in time range of eight hours as done in the previous paper, the results are much worse. Only one third of the results are predicted correctly with an error range of two hours.
In the paper by Lee et al. (2021), the quay crane's working time is predicted using a multi-layer perceptron model. The factors that are taken into account are type of the container, bay cluster movement, work type change, employee shift, single or twin lift and whether the container is full or empty. The results are then compared to the conventional cycle time estimates of 1.5 minutes of unloading and 2.5 minutes for loading. Compared to those, the method is capable of reducing error rate up to 54%.
Not only machine learning techniques but also stochastic models are used in order to estimate vessel handling time. Dhingra et al. (2017) proposes a two-level stochastic model of which the higher level represents the quay crane assignment and scheduling and the lower level models the dynamic interactions amongst the terminal equipment such as the quayside, stackside and vehicle transport processes. While this model is useful to examine the effect of the factors on the handling time of a vessel, accurate predictions are lacking. This partly caused by two assumptions that are made: (1) only 20 ft. standard containers with identical shape and size are used in the simulation and (2) the time it takes to load or unload all the containers in a zone is exponentially distributed.
Table II presents an overview of the literature analysed above.
Although this paper does not make a direct turnaround time prediction model, the turnaround time of a container ship can be predicted by using the cycle time prediction model.

C. Contributions

In existing literature, many models have been developed to assess the performance of tandem operations on container terminals. Those models often include cycle times of the quay cranes for which an average value is taken or sampled from a distribution. The duration of a cycle, however, depends heavily on certain factors such as for example the type of lift, the location of the containers on the ship and the weather conditions. By not including this aspect in tandem performance models, the results may differ significantly from reality. This paper introduces a prediction model which predicts the cycle time of a quay based on several factors. Afterwards, the cycle time prediction model is used as an input to another model in order to calculate the optimal spreader switching strategy.

III. Methodology

The methodology is divided into two parts. First of all, the methods used to develop the cycle time prediction model are explained in section III-A. Then the development of the optimal spreader switching strategy is explained in section III-B.

A. Cycle Time Prediction Model

First of all, a linear regression model is made to predict the cycle time of a quay crane. The model's input factors are based on a literature review and data analysis, and result in a total of six input parameters: the wind speed, the weight of the container(s), the trolley position of the crane, the hoist position of the crane, the type of lift and whether the container is located above or below deck. As it is unsure whether those variables have linear relationships, an artificial neural network is developed as well to predict the cycle times. This model consists of an input layer of size 10, a hidden layer with ten neurons and sigmoid as activation function, and an output layer of size 1.

B. Optimal Spreader Switching Strategy

In order to determine the optimal moments to change between single and tandem spreaders, a Mixed-Integer Linear Programming model is used. The objective function of this model is to minimize the sum of all cycle times in a bay plus the time that is used to change spreaders. Several constraints are introduced such that the proposed handling strategy of the model is possible in real life. For instance, containers in lower tiers need to be handled first in case of loading, hatch covers handling requires the crane to be equipped with the single spreader etc.

IV. Results

This chapter provides the results of the cycle time prediction model and the optimal spreader switching strategy in their according sections. As input data for the cycle time prediction model, more than 86.000 cycles of dual trolley quay cranes are used. This data is gathered from ten cranes during more than two months (around November 2021) on the fully automated container terminal APM Terminals at Maasvlakte II. Each cycle has a duration, which is the target variable, and six dependent variables; namely the current wind speed, the weight of the load, the trolley position, the hoist position, the type of move and whether the container is located above or below deck. Based on those variables, the prediction of a cycle time is made. The cycle time prediction model is then used as an input to the Mixed-Linear Integer Programming model to determine the optimal spreader switching strategy.
In order to evaluate the model that calculates the optimal spreader switching strategy, a case study is performed in which several different bays of a container ship need to be unloaded. This is done under different circumstances concerning the berthing side of the ship, the skill level of the operator, the weight of the containers and the wind speed. The handling times of the bays by using the optimal spreader switching model are compared to the handling times of the bays when the spreader changes are done in the traditional way which is explained in chapter V.

A. Cycle Time Prediction Model

Based on a literature review of cycle time prediction models used in external fields, both a linear regression model and an artificial neural network are chosen to predict the cycle times of a quay crane. In order to determine the input variables, a data analysis and a literature review are performed. Those variables are the wind condition [m/s], the weight of the load [kg], the location of the container on the ship [trolley position, hoist position and above/below deck], and the type of move [single/tandem discharge, single/tandem load and twin load/discharge]. The original dataset of historical cycles used consists of 86.125 observations and a split of 80:10:10 is applied in order to create the training, validation and testing dataset respectively. In the following subsections, the linear regression model and artificial neural network model are implemented and compared in the last subsection.

1) Linear Regression Model: First of all a neural network without any hidden layers is constructed where the input variables are directly connected to the output layer. This means that a weight is assigned to each input variable which transforms the model to a linear regression model, as stated in Hastie et al. (2001). The training phase of the model runs for as long until there is no improvement made for fifteen epochs. For this model, it occurs at around 2500 epochs with a MAPE value of 11.2%. Similar MAPE values are also observed for the validation and test dataset, respectively 11.15% and 11.09%. According to Lewis (1982), those MAPE values can be considered as good predictions and close to highly accurate predictions (<10%). Concerning the MSE, a value of 311.49 is obtained. By taking the square root of this value (17.65), it indicates how many seconds the prediction deviates from the actual cycle time. Table III shows the weights of the variables. Tandem discharge and tandem load were identified as longest cycle types in that section and therefore also have assigned the highest weight by the linear model. The trolley and hoist position are of equal importance but the hoist position is a negative value as the higher the hoist position, the less hoist distance is required.

Variable	**Weight**
Wind speed	6.89
Weight	4.08
Trolley Position	25.89
Hoist Position	-26.77
Single Load	7.63
Tandem Discharge	38.76
Tandem Load	33.27
Twin Discharge	12.99
Twin Load	21.11
Above deck	7.70

TABLE III: The weights assigned by the Linear Regression model to the variables.

2) Artificial Neural Network Model: Due to the uncertainty in linearity of the input variables, an extra layer is added to the model such that it is no longer a linear regression model. This layer is a so-called 'dense' layer which is the most commonly used layer in ANN. Dense layers are deeply connected to its previous layer as all neurons of the layer are connected to every neuron of the previous layer. For this layer, the best number of neurons and the activation function need to be determined. A general accepted rule of thumb is that the optimal number of neurons is usually between the size of the input and the size of the output layer, according to Heaton (2008). In this case, the size of the input layer is 10 and the size of the output layer is 1. Concerning the activation function, the used library Keras provides 9 different functions, namely relu, sigmoid, softmax, softplus, softsign, tanh, selu, elu and exponential. This means that there are 90 different combinations possible as activation function and number of neurons. In order to find the best combination, several possibilities are tried and compared on MAPE and

MSE value. Then the combination that provides the lowest MAPE and MSE values is chosen. Based on the results of a grid search, the activation function sigmoid with 10 neurons provides both the lowest MSE and the lowest MAPE values, 287.93 and 10.64 respectively, and thus used as the hidden layer. According to Lewis (1982), the MAPE score lies between highly accurate forecasting and good forecasting. The square root of the MSE, which is 16.97, tells the average time the prediction deviates from the actual cycle time.

3) Comparison of the Models: When comparing the ANN model to the regression model, a slight improvement in both MAPE and MSE value can be observed. This holds for all three datasets, test train and validate. This slight improvement of the ANN over the LR model is also visible in Figure 1. Besides the MAPE and MSE values, the models can be verified by this graph as well. The percentage difference between the actual cycle time and the predicted cycle time is plotted on the x-axis. The y-axis indicates the percentage of the test data. For instance when looking at an error rate of 10% on the x-axis, it can be seen that around 52% of the predicted cycles by the Linear Regression model has an error rate below 10%. For the Artificial Neural Network model, the number of cycles predicted with an error rate below 10% is slightly higher, approximately 56% of the data as can be seen in the graph.

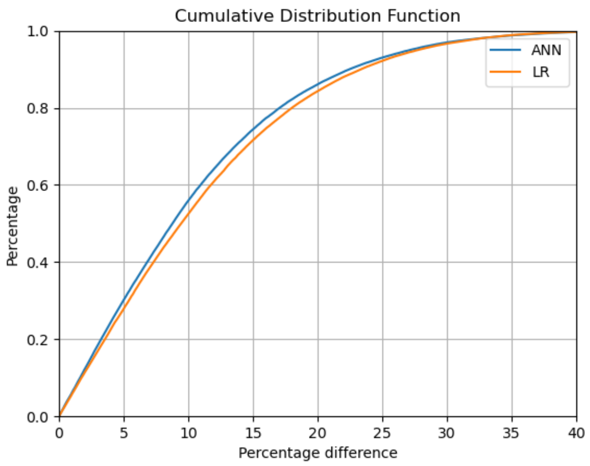

Fig. 1: Comparison of the LR model and ANN model based on the percentage error.

B. Optimal Spreader Switching Strategy

First of all, the sets, constants and variables needed for the model are defined.

There are two sets needed; the set of all containers and hatch covers in the bay that need to be handled, indicated with the letter I and the set of all cycles, including both single cycles and possible tandem cycles, indicated with the letter J. Then there are two constants, the predicted cycle time of each cycle denoted as P_j and a binary constant C_{ij} which is 1 if container i belongs to cycle j.

Concerning the variables, the model uses six binary variables and one continuous variable. The binary variables are X_j which is 1 if cycle j is used, CS_{jk} which is one if cycle j is followed by cycle k, TS_j and SS_j are 1 if cycle j is performed with a tandem spreader or a single spreader respectively, SC_j is 1 if the crane has changed spreaders before cycle j and lastly STS_j is 1 if a single container is handled with a tandem spreader. The continuous variable is CT_j which stands for the elapsed time so far after cycle j is performed. An overview of all the sets, constants and variables described above can be found in Table IV.

Constants and sets	
I	Containers and hatch covers index set
J	Cycles index set
$H \subset J$	Set of hatch cover cycles
P_j	Predicted time of cycle j
C_{ij}	is 1 if container i belongs to cycle j
Variables	
$X_j \in \{0,1\}$	Cycle j is used
$CS_{jk} \in \{0,1\}$	Cycle j is followed by cycle k
$TS_j \in \{0,1\}$	Cycle j is performed with tandem spreader
$SS_j \in \{0,1\}$	Cycle j is performed with single spreader
$SC_j \in \{0,1\}$	Spreader is changed before cycle j
$STS_j \in \{0,1\}$	Single container is handled with tandem spreader
CT_j	Elapsed time so far after cycle j is performed

TABLE IV: Sets, constants and variables of the MILP model.

The goal of the model is to minimize the handling time of a whole bay as described above and is expressed in the objective function (1). The first part of this objective function consists of the sum of the predicted cycle times of the performed cycles while taking a 50% time penalty into account when a single container is handled with the tandem spreader. The second part of the objective function adds 5 minutes for each spreader change. As a container can belong to multiple cycles, for instance a single cycle and two tandem cycles, constraint (2) ensures that each container only belongs to one performed cycle. Constraint (3) states that when two containers belong to a performed cycle, the tandem spreader must have been used. Then constraint (4) is used to make sure that each cycle is either performed with a single spreader or a tandem spreader. Each cycle has one previous cycle except for the first one which has no previous cycles. This is constrained in (5) and (6). Similar to those constraints are constraints (7) and (8) which state that each cycle is followed by one other cycle except the last cycle which has no next cycle. Constraint (9) defines the elapsed time so far after a cycle is performed which is the elapsed time at the previous cycle plus the predicted cycle time duration of the current cycle. Either constraint (10a) or (10b) for load or discharge respectively is included to make sure that the handling of the bay is done tier by tier. Constraint (11) is used to set STS to one when a cycle with one container is performed with the tandem spreader. When a cycle is performed with a tandem spreader and the previous cycle with a single spreader, the variable SC must be one which is ensured with constraint (12a) and constraint (12b) for the other way around. As hatch covers need to be handled with a single spreader, constraint (12c) is used to make sure that cycles handling a hatch cover are performed with a single spreader.

$$min \sum_{j \in J} (X_j * P_j + P_j * 0.5 * STS_j + 300 * SC_j) \quad (1)$$

s.t.

$$\sum_{j \in J} C_{ij} * X_j = 1 \quad \forall i \in I \quad (2)$$

$$\sum_{i \in I} C_{ij} * X_j \leq 1 + TS_j \quad \forall j \in J \quad (3)$$

$$SS_j + TS_j = X_j \quad \forall j \in J \quad (4)$$

$$\sum_{k \in J} CS_{kj} = X_j \quad \forall j \in J \setminus \{0\} \quad (5)$$

$$\sum_{j \in J} CS_{j0} = 0 \quad (6)$$

$$\sum_{j \in J} CS_{kj} = X_k \quad \forall k \in J \setminus \{|J| - 1\} \quad (7)$$

$$\sum_{j \in J} CS_{(|J-1|)k} = 0 \quad (8)$$

$$CT_k \geq CT_j + P_k - M * (1 - CS_{jk}) \quad \forall j, k \in J \quad (9)$$

$$CT_j \geq CT_k \quad \forall j, k \in J \quad \text{and} \quad Tier_j > Tier_k \quad (10a)$$

$$CT_j \geq CT_k \quad \forall j, k \in J \quad \text{and} \quad Tier_j < Tier_k \quad (10b)$$

$$\sum_{i \in I} C_{ij} - M * (1 - TS_j) \leq STS_j + M * (\sum_{i \in I} C_{ij} - 1) \quad \forall j \in J \quad (11)$$

$$SS_j + TS_k - M * (1 - CS_{jk}) \leq SC_j + 1 \quad \forall j, k \in J \quad (12a)$$

$$TS_j + SS_k - M * (1 - CS_{jk}) \leq SC_j + 1 \quad \forall j, k \in J \quad (12b)$$

$$SS_j = 1 \quad \forall j \in H \quad (12c)$$

V. Case Study

In the case study, the handling time of a bay when using the optimal spreader strategy is compared to the handling time of that bay when the spreader changes are done in the traditional way when the switch to the tandem spreader is done when at least 50 tandem cycles can be performed afterwards. This means that there should be at least 100 40ft. containers that can be handled in succession with the tandem spreader without a move or action that requires the single spreader. Those moves or actions are the handling of hatch covers, lashing cage operations or the handling of 20ft. containers.
This is done for multiple bay configurations each varying in the number of containers and the location of the containers on the ship. As the cycle times are based on the wind speed and the weight of the containers, sensitivity analyses are made for each scenario to observe the behaviour of the optimal speader switching strategy under different circumstances. Another factor that could change the behaviour of the optimal spreader switching strategy is the skill level of the crane operator. As the setdown of the container on the ship is always done manually by the operator, the duration of this part has an effect on the whole cycle time duration and thus also on the spreader switching strategy. As some operators struggle more with the setdown part on the ship of tandem moves than other operators, a 10% increase in cycle time duration for tandem moves is taken in the sensitivity analyses for operators with a 'low' skill level.
The scenarios in the case study are chosen to be discharge scenarios only due to several reasons. First of all, at the time of performing the case studies, the large majority of tandem operations in current practice are discharge moves as this type of move is used for a longer time in operation. Tandem load moves were until shortly only used in a pilot phase and tandem loading above deck is still not possible. Furthermore, the handling time of loading a bay is more often influenced by other factors than the cycle time durations compared to the unloading process of a bay. For instance in case of unloading at any point of time, there just needs to be an empty AGV at the crane and it does not matter which one it is. But in case of loading, an AGV carrying a specific container is required at the crane. Therefore in load scenarios, the chances of a crane waiting for an AGV are higher compared to unload scenarios. Also in case of loading, a container can be set down on the ship with a slight offset from its correct location which prevents the twistlocks from locking. When this is not noticed on time and other containers are already loaded on top of that container, those containers need to be unloaded temporarily again in order to reposition that specific container.
The bay design used is a middle bay of a Maersk triple-E ship as this type of bay is handled quite often and leaves free to vary in different variables such as the number of the containers, the location of the containers etc.

A. Scenario A

Suppose a bay that contains 58 full containers with each having a weight around 25.000kg that need to be discharged. The containers are all located in one section of the bay below a hatch cover with tiers ranging from 2 to 24 and the rows from 12 to 20 as can be seen in Figure 2. Concerning the wind condition for both scenarios, the average wind speed at the coast of the Netherlands is used, which is 7.5 m/s. At the start of the scenario, the hatch cover is just removed which means that the crane is equipped with the single spreader. After all containers are unloaded, the crane must be equipped again with the single spreader in order to place the hatch cover back in place.

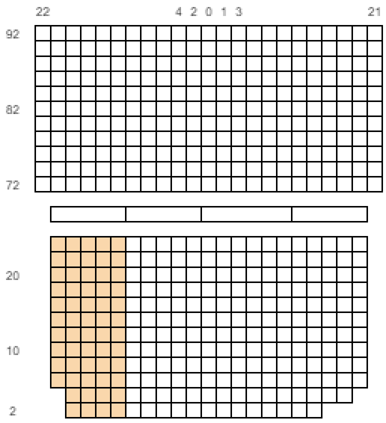

Fig. 2: Containers in a bay that need to be unloaded in Scenario A.

In current practice, called the traditional way, the number of possible tandem cycles would be considered as too low to switch to the tandem spreader resulting in the whole bay being handled with single cycles. However, the optimal solution makes the switch to the tandem spreader after the first container is unloaded with the single spreader. The remainder of the bay is then handled with the tandem spreader. As the number of rows are odd, a single container needs to be unloaded with the tandem spreader in each tier except for the first one. The cycle time of handling a single container with a tandem spreader is assumed to take 1.5 times longer than handling that container with the single spreader. When the ship is lying starboard side to the quay, the handling time of the bay by using the optimal solution takes 97 minutes including switching back to the single spreader at the end. When all containers are unloaded with the single spreader as would be done in current practice, the handling time would take 21 minutes longer. When the ship is lying port side to the quay, the cycles become shorter. The optimal solution still makes the change to the tandem spreader but the time savings are less. This, as well as other variations in other variables can be seen in Table V.

Side to quay	Operator skill	Container	Wind	Trad.	Opt.	Dif.
Starboard	High	Empty	Average	121	96	25
Starboard	High	Empty	Strong	122	98	24
Starboard	High	Full	Strong	118	98	20
Starboard	High	Full	Average	118	97	21
Starboard	Low	Full	Average	118	103	15
Port	High	Empty	Average	98	86	12
Port	High	Empty	Strong	104	90	14
Port	High	Full	Strong	102	91	11
Port	High	Full	Average	98	88	10
Port	Low	Full	Average	98	93	5

TABLE V: Handling time in minutes for both strategies under different circumstances.

B. Scenario B

This scenario is similar to the previous scenario but this time the containers that need to be unloaded are located above deck as can be seen in Figure 3. The first step of unloading the bay consists of unlocking the twistlocks of the containers in tiers 88, 86 and 84 with a lashing cage or gondola. For the containers located in the lower tiers, the unlocking process can be done by persons on the ship. The scenario starts right after the unlocking process is finished. At this moment, the crane is equipped with the single spreader as it is required in order to lift the lashing cage. After all the container are unloaded, the crane must be equipped with the single spreader as the next move is assumed to be a move for which the single spreader is required.

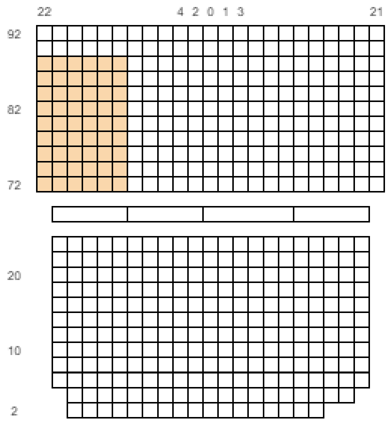

Fig. 3: Containers in a bay that need to be unloaded in Scenario B.

When the ship is lying starboard side to the quay the cycles are relatively long as the containers are located at the waterside of the ship. The whole unloading process of the bay will be done with the single spreader in current practice as the number of possible tandem cycles is considered to be too low in order to make the spreader change worth it. This means that the unloading of the first container can start immediately because the crane is equipped with the single spreader at the start of the unloading process. At the end, the crane is also already equipped with the single spreader so the unloading process ends right after the last container is unloaded. The total time for unloading all 54 containers is 91 minutes.

However, the optimal solution calculated by the model does use a different unloading strategy which leads to a shorter handling time of the bay. This strategy consists of changing right at the start to the tandem spreader and then unloading all containers with tandem cycles. At the end the spreader needs to changed back to the single spreader. The total handling time of the bay when applying this strategy is 73 minutes, which is 18 minutes shorter than for traditional strategy.

When the ship is lying port side to the quay, the cycles become shorter which means that the time savings become less. Under certain circumstances, for instance a crane operator with a low skill level, the optimal solution consists of unloading all containers with the single spreader as well. The handling times under different circumstances can be seen in Table VI.

Side to quay	Operator skill	Container	Wind	Trad.	Opt.	Dif.
Starboard	High	Empty	Average	91	72	19
Starboard	High	Empty	Strong	93	73	20
Starboard	High	Full	Strong	92	73	19
Starboard	High	Full	Average	91	73	18
Starboard	Low	Full	Average	91	79	12
Port	High	Empty	Average	71	69	2
Port	High	Empty	Strong	73	70	3
Port	High	Full	Strong	72	70	2
Port	High	Full	Average	70	69	1
Port	Low	Full	Average	70	70	0

TABLE VI: Handling time in minutes for both strategies under different circumstances.

C. Scenario C

In this scenario, 126 empty containers need to be unloaded of which 54 above deck and 72 below deck as can be seen in Figure 4. The average wind speed occurring at the coast of the Netherlands, which is 7.5 m/s, is taken as the wind condition during the handling process of this bay. For this specific ship, the twistlocks of the containers in tiers 72 to 82 can be unlocked by people on the ship. In order to unlock the twistlocks of the containers in tiers 84 to 88, a lashing cage or gondola needs to be used. The scenario starts right after the operation with the lashing cage is performed which means that the twistlocks of the containers in tiers 84 to 88 are unlocked. At this point, the crane must be equipped with the single spreader as this spreader is needed to handle the lashing cage.

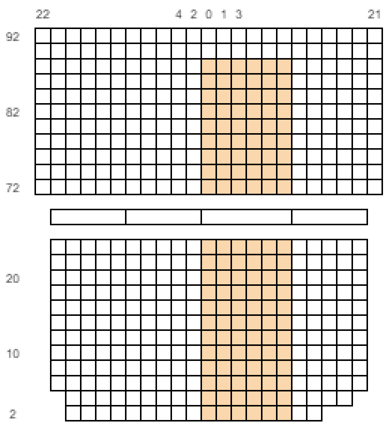

Fig. 4: Containers in the bay to be discharged in Scenario C. The ship is lying port side to quay.

After all containers above deck are unloaded, the hatch cover needs to be removed in order to unload the remaining containers below deck. As the crane must be equipped with the single spreader to be able to lift a hatch cover, there can only be 27 tandem cycles performed above deck before the crane needs to switch back to the single spreader. Below deck there can only be 36 tandem cycles performed before the crane needs to switch back again to the single spreader in order to place the hatch cover back. In current practice, those numbers of tandem cycles are considered too low to make the spreader change worthwhile and therefore this whole bay is handled by using single moves. The traditional line in Figure 5 shows that this process would take 224 minutes which includes the handling of the hatch cover at around 85 minutes and at the end but does not include the lashing cage procedure at the start.

However the optimal solution, indicated by the optimal line in the figure shows that the single spreader is changed to the tandem spreader right at the start and 27 tandem cycles are performed above deck. Then around 70 minutes, there is a 15 minutes window in which there are no containers handled. This is the case because the hatch cover needs to be removed so the crane must switch back to the single spreader, which takes five minutes and removing the hatch cover takes another five minutes. Then the last five minutes consist of switching back to the tandem spreader in order to perform 36 tandem cycles below deck. At the end there is another time window of 10 minutes without handling any containers which is changing back the single spreader and placing the hatch cover back. This whole process takes 174 minutes which is 50 minutes less than the traditional solution takes.

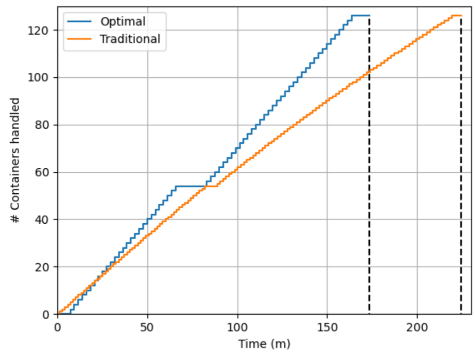

Fig. 5: Comparison current situation and optimal strategy.

As said before, the results obtained above were performed under average wind conditions with empty containers and a high skill level of the crane operator. For different combinations of those variables, both the traditional and optimal strategies stay the same but the handling times change. In Table VII, the handling times for the different conditions can be observed, varying from 36 to 61 minutes difference between the traditional and optimal solution. A strong wind speed is assumed to be 17.7 which is the maximum wind speed under which the crane can still operate without restrictions. The weight of an empty 40ft. container is around 3750kg and a low skill level of crane operator leads to an additional 10% in cycle time duration for tandem moves as explained earlier.

Side to quay	Operator skill	Container	Wind	Trad.	Opt.	Dif.
Port	High	Empty	Strong	237	176	61
Port	High	Full	Average	225	176	49
Port	High	Full	Strong	235	177	58
Port	High	Empty	Average	224	174	50
Port	Low	Empty	Average	224	188	36

TABLE VII: Handling time in minutes for both strategies for different wind and container conditions.

D. Summary Case Study

The first scenario involved the unloading process of 58 containers from a bay below deck. Since there are only 34 tandem cycles that can be performed, the unloading process is done with single moves only in current practice. The optimal solution, however, does make the switch to the tandem spreader and saves 10 to 18% in handling time, depending on whether the ship is lying port side or starboard side to the quay.

In the second scenario, 54 containers needed to be unloaded from a bay above deck. When the ship is lying port side to the quay and the containers are located on the port side of the bay as well, the cycles become quite short which means that the time saving of performing tandem cycles is less than in cases with longer cycles. As a consequence, the optimal solution which uses tandem moves is only slightly faster than the traditional solution which uses only single moves. When the ship is turned around and lies starboard side to the quay, the optimal solution reduces bay handling time by 20% when compared to the traditional solution.

The last scenario consisted of the unloading process of 54 containers above deck, 72 containers below deck and the removal of a hatch cover before continuing the unloading process below deck. The traditional solution handled all containers with single moves while the optimal solution performed multiple spreader changes in order to perform tandem moves which led to a handling time decrease of 22%. An overview of the different scenarios is given in Table VIII.

	A.1	A.2	B.1	B.2	C
Ship to quay	Starboard	Port	Starboard	Port	Port
Side containers in bay	Port	Port	Port	Port	Middle-Starboard
Above/Below deck	Below	Below	Above	Above	Both
# Containers	58	58	54	54	126
Possible tandem cycles	34	34	27	27	36
Traditional (minutes)	118	98	91	70	224
Optimal (minutes)	97	88	73	69	174
Difference (minutes)	-21	-10	-18	-1	-50
Percentage difference	-18%	-10%	-20%	-1%	-22%

TABLE VIII: The results obtained for the different scenarios.

VI. Conclusions

This chapter provides conclusions and recommendations about the main findings of the conducted research. In section VI-A, the research is concluded and answers are given to the research question as defined below.

How can a quay crane's cycle time prediction model be developed and used to calculate the optimal spreader switching strategy?

Then section VI-B gives recommendations how the results could be improved in the future and practical recommendations how the spreader switching moment should be determined.

A. Conclusions

In this paper, two models are developed to predict the cycle time of a quay crane based on the location of the container on the ship, the weight of the load, the type of move and the wind speed. Those input variables are obtained with a literature review and a data analysis. The first model is a linear regression model yielding a Mean Absolute Percentage Error (MAPE) of 11.2%. This means that the average predicted cycle time deviates on average by 11.2% from the actual cycle time. As a linear regression model is only able to capture linear relationships between variables which is not necessarily the case for the variables influencing the cycle time duration, an artificial neural network is developed as well. This model consists of a hidden layer between the input and the output layer with 10 neurons and sigmoid as activation function resulting in a slightly lower MAPE value of 10.64%. When predicting the test dataset, 56% of the predictions have an error rate below 10% and 85% of the predictions below 20%. With the development of the models and the related research about the input factors, the first part of the research question is answered. This also covers the lack of a cycle time prediction model in literature which can be used as an input to various models, such as turnaround time prediction models for vessels and tandem performance models.

The second part of the research question is answered by the development of a Mixed-Integer Linear Programming (MILP) which identifies the optimal moments to change between single and tandem spreaders when loading or unloading a bay. This model uses cycle time predictions from the cycle time prediction model developed earlier as one of the parameters. In the case study, the handling times of different bay layouts under varying circumstances concerning wind speed and weight of the containers are calculated for both the current handling strategy and the optimal handling strategy calculated by the model. The current handling strategy consists of switching to the tandem spreader when 50 tandem cycles can be performed in succession. In the scenarios, bay layouts are tested in which the possible number of tandem cycles is lower such that the bay is handled with the single spreader only. However, the optimal shows that even with a limited number of possible tandem cycles, switching to the tandem cycle can be beneficial in some cases. This depends mainly on the containers' location in a bay. For certain bay layouts, the handling time can decrease by up to 22% when the spreader is switched at optimal moments compared to the current strategy. The case study also shows that for a certain number of containers in a bay, the decrease in discharge time of the bay by using tandem operations can vary from 1% to 20% based on the cycle times which are influenced by the location of the containers, the wind conditions and the weight of the containers. When taking a fixed value as cycle time, as is done in current literature about tandem performance models, those differences cannot be observed meaning that the performance of tandem operations is not modelled realistically.

B. Recommendations

The different scenarios have shown that the time decrease is highly dependent on the location of the containers on the ship. In certain scenarios, a time decrease of 20% is observed by using the optimal spreader switching strategy while there are only 27 possible tandem cycles that can be performed in succession. As in current practice tandem operations are only used when 50 tandem cycles can be performed in a row, this case would have been handled with the single spreader only. On the other hand, a scenario is observed in which there are also 27 possible tandem cycles in succession but a time increase of only 1% is observed as the locations of the containers on the ship are different compared to the previous scenario. This leads to both practical and scientific observations. Concerning the practical observation, a fixed threshold of 50 possible tandem cycles in succession to make the switch to the tandem spreader worthwhile, which is used currently, is far from the optimal solution. In fact, a fixed value cannot be used at all as the time saved by tandem moves depends heavily on the cycle times. Therefore, the recommendation is made to use the spreader switching strategy model developed in this report for each bay in order to know whether a spreader switch is worth it and when the switch needs to be done. In terms of scientific observation, when a constant value is taken as cycle time and used as an input to tandem performance models in literature, the differences based on the cycles times revealed in the case study cannot be captured. By using the cycle time prediction model as input instead, the accuracy of the models will likely improve. This does not only hold for tandem performance models, but also for other models in literature that use cycle times as input such as turnaround time prediction models.

At the time of writing this report, the obstacle path of a quay crane's cycle was not available. This obstacle path consists of the current containers on the ship, the obstacles, over which the crane needs to go. For instance when a container needs to be loaded on the water side of the ship and in the middle of the ship there is a high stack of containers for a different port, the cycle of the quay crane will take more time as it needs to go higher than normal. In order to achieve more accurate cycle time predictions, it is recommended to include this aspect in the future. Furthermore, when loading a container on the ship while there is already a container located next to it, the set down becomes easier as that container can be used as guidance which leads to a shorter cycle time duration. As this information was also not easily available at the time of writing this report, it is not included in the cycle time prediction model but the inclusion of this aspect may lead to more accurate cycle time predictions.

In this research, the operation of a quay crane is optimised assuming that there are no quay-side capacity restraints. This is done because the cranes used in the research are dual trolley cycle cranes which have a platform that acts as a buffer between the ship and the quay. However, the capacity of this buffer is limited to two containers so there are certainly scenarios possible in which the limit is reached. For instance when an AGV is heavily delayed such that the crane has already used the buffer of the platform and has to wait for the AGV. Therefore, it is recommended to include the quay-side constraints in future research in order to obtain a more realistic view.

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B

Bad Weather Procedure

Level 4 - Stopfase
De stopfase is een weerfase waarbij rekening gehouden moet worden met een (naderende) periode van zeer zware stormachtige weersomstandigheden. In deze weerfase moeten alle veiligheidsmaatregelen zijn genomen en wordt de gehele terminal operatie uit veiligheidsoverwegingen stilgelegd en de terminal gesloten.
De stopfase gaat in zodra: - Er binnen 2 uur een windkracht 9 Beaufort of hoger wordt verwacht. - Er binnen 2 uur windstoten ? 28 m/s worden verwacht. - Er een windwaarschuwing wordt afgegeven van Level 4 of hoger.
De stopfase blijft van kracht zolang: - Er een wind wordt voorspeld of gemeten ? 9 Beaufort. - Er windstoten worden voorspeld door de meteoroloog en/of gemeten ? 28 m/s op de centrale windmeter over de laatste 30 minuten.
De stopfase eindigt als: - De windwaarschuwing level 4 wordt ingetrokken door de meteoroloog. - De wind is afgenomen tot onder 9 Beaufort. - De windstoten zijn afgenomen tot onder 28 m/s.

Technische limieten

Technische limieten automatisch equipment		
SQC	? 17,7 m/s	Normaal bedrijf zonder beperkingen.
	17,8 - 25 m/s	Lagere operationele snelheid en acceleratie (automatisch).
	25,1 - 28 m/s	Kraan gaat automatisch (tijdelijk) uit operatie. Indien nodig tegen de wind in naar stormpot en optoppen .
	? 28,0 m/s	Kraan geborgd op stormpotten en opgetopt op tie downs. Portal trolley op stormpositie en manueel geborgd. LOTO-proc. toepassen op zowel SQC en op portal trolley.
QC	? 17,7 m/s	Normaal bedrijf zonder beperkingen.
	17,8 - 25 m/s	Lagere operationele snelheid en acceleratie (manueel PCE).
	25,1 - 28 m/s	Kraan tijdelijk uit operatie, indien nodig naar stormpot.
	? 28,0 m/s	Kraan geborgd op stormpotten en volledig opgetopt.
RGC	? 20,7 m/s	Normaal bedrijf zonder beperkingen.
	20,8 - 25 m/s	Lagere operationele snelheid en acceleratie (automatisch).

	25,1 - 28 m/s	Kraan tijdelijk uit operatie, indien nodig naar stormpositie.
	? 28,0 m/s	Kraan (gantry en trolley) geborgd op stormpinnen.
ARMG	? 17,7 m/s	Normaal bedrijf zonder beperkingen
	17,8 - 25 m/s	Normaal bedrijf zonder beperkingen
	25,1 - 28 m/s	Stack kraan naar stormpositie indien nodig.
	? 28,0 m/s	Stackkraan geborgd op stormvergrendeling op TP's.
Gondel		Geen constructie-technische limiet equipment (info fabrikant)
	Operationele werkwijze	1. Individuele dekman geeft mbt uitvoering van zijn eigen werkzaamheden aan of dit veilig kan worden uitgevoerd en meldt dit aan Shiftco/ME. Als werkzaamheden – naar eigen inschatting - niet veilig uitgevoerd kunnen worden dan stopt hij/zij de gondelwerkzaamheden. 2. RCO beoordeelt of SQC veilig bediend kan worden. Indien de SQC niet veilig bediend kan worden dan staakt hij/zij de werkzaamheden. *NB medewerkers kunnen altijd – indien de werkzaamheden in hun ogen niet veilig verricht kunnen worden – de werkzaamheden onderbreken/niet aanvangen melden dit bij hun direct leidinggevende).*

Let op: Bovengenoemde waardes zijn windstoten!

Windlimieten voor de SQC-kraan (Bron: Kalmar manual):

Volledige operationele snelheid en acceleratie.	0-17.7 m/s
Lagere operationele snelheid en acceleratie. Niet operationele kranen op stormpennen zetten (4 totaal); Niet operationele kranen main spreader volledig ophalen en op 20'[1]. Niet operationele kranen optoppen tot 55 graden.	17.8 – 25 m/s
Acties en consequenties: 1. Kraan schakelt (tijdelijk) automatisch uit tijdens operatie; 2. Indien noodzakelijk kraanrijden naar stormput tegen de wind in over max. 300m. en vervolgens op stormpennen zetten. 3. Indien nodig SQC optoppen naar 55 graden (=tot max. 28 m/s) 4. Portal trolley naar waterzijde en vergrendeld met stormpen (=tot max. 28 m/s). (handmatig aan te brengen aan bakboordzijde) 5. LOTO procedure uitgevoerd waarbij SQC als geheel voorzien wordt van slot (uitschakelen en vergrendelen) en portal trolley ook wordt vergrendeld (separate vergrendeling).	25.1 – 28 m/s
Acties en consequenties: 1. Kraan moet geborgd zijn op stormpennen (4 totaal); 2. Tie-Downs dienen bevestigd te zijn; 3. Klap is opgetopt op 55 graden (normale klap-op cyclus) 4. Portal trolley staat compleet aan waterzijde op de stormpen (handmatig aan te brengen aan bakboordzijde); 5. LOTO procedure is uitgevoerd (kraan als geheel vergrendeld & portal trolley separaat vergrendeld).	>28 m/s

Bovenstaande windsnelheden zijn windstoten gemeten door de windmeters op de SQC's welke geplaatst zijn bovenop het A-frame op ca. 100 meter hoogte.

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[1] Zie bijlage E voor tijdelijke regeling.

Hervatting van de SQC werkzaamheden na een slechtweer situatie:

C

Linearity of Wind Speed

The visualizations in this appendix show the non-linear relationship between wind speed and cycle time. Until a certain wind speed, the cycle times do not increase much as can be seen in the graphs. When this point is reached, the cycle times increase rapidly. This is also in line with the perception of the Remote Crane Operators (RCOs). Furthermore, it can also be technically explained as the operation speed of the cranes will be lowered when the wind speed exceeds 17.7 m/s (Appendix B).

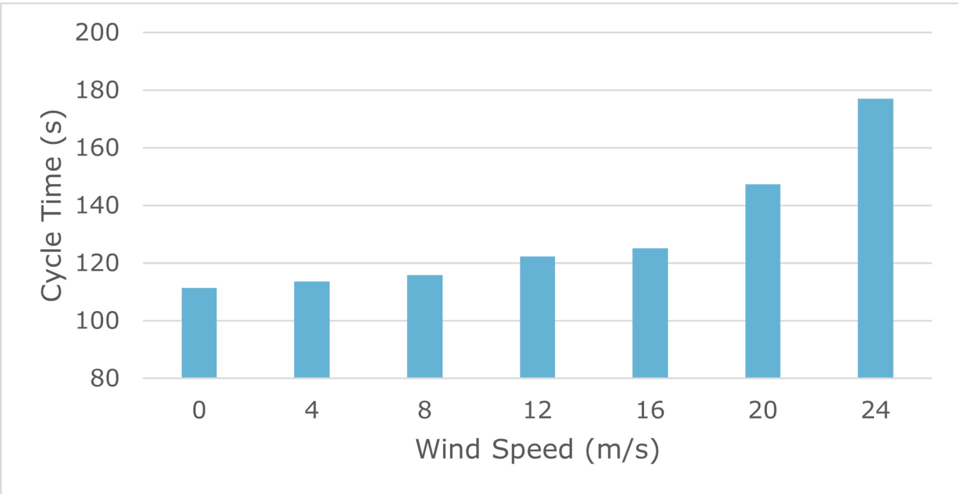

Figure C.1: Average cycle time of single discharge for different wind speeds.

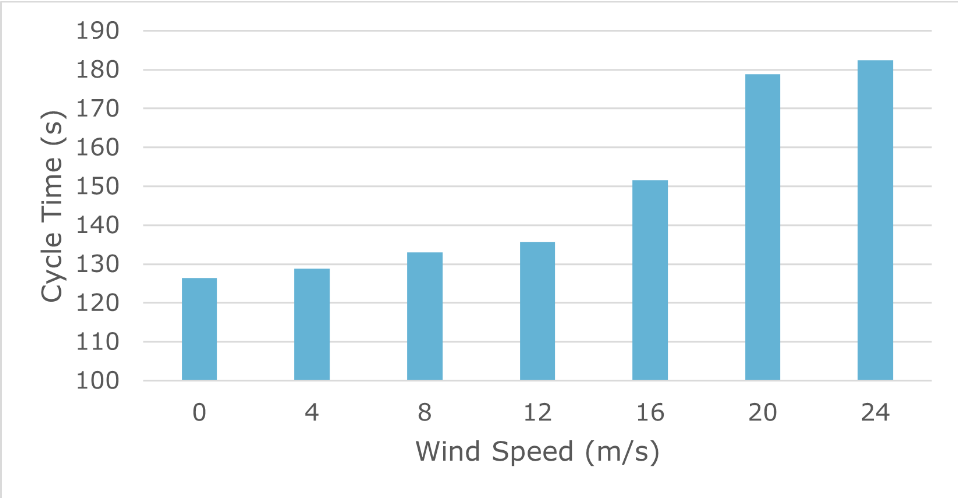

Figure C.2: Average cycle time of single load for different wind speeds.

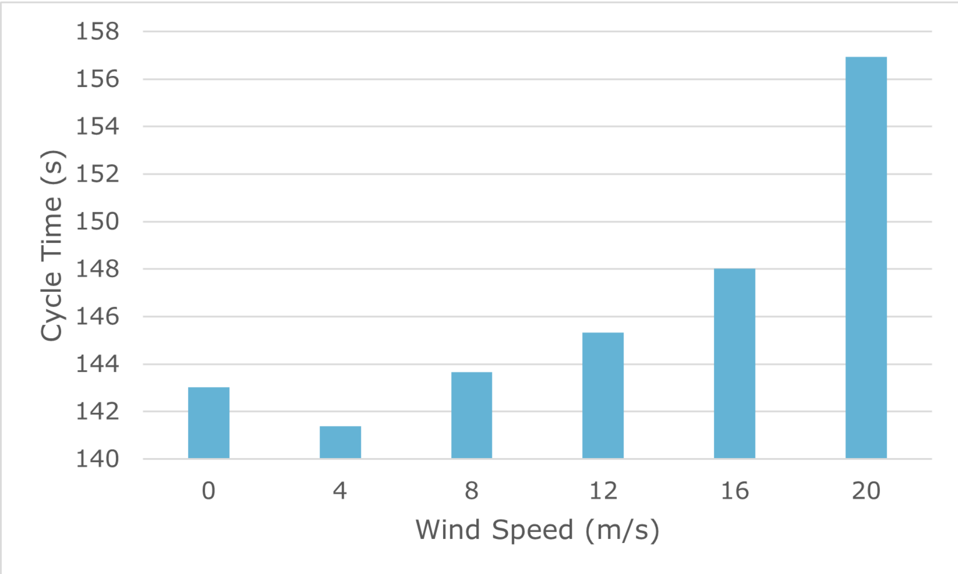

Figure C.3: Average cycle time of twin discharge for different wind speeds.

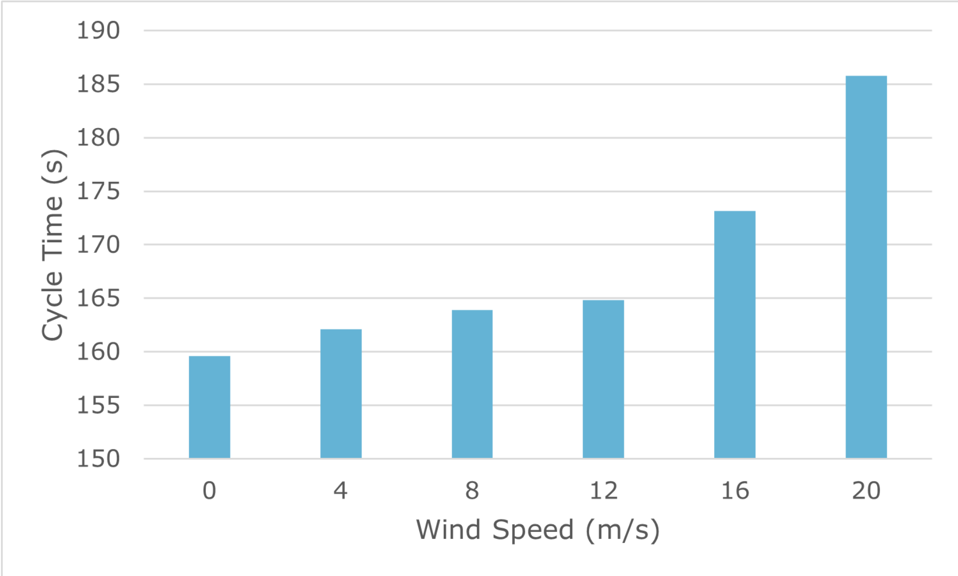

Figure C.4: Average cycle time of twin load for different wind speeds.

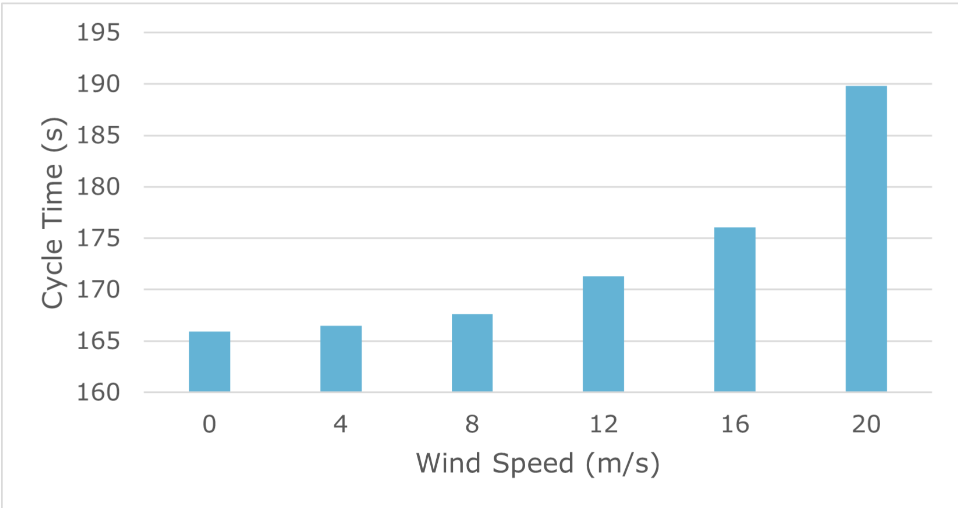

Figure C.5: Average cycle time of tandem discharge for different wind speeds.

D

Code Cycle Time Prediction Model

```
# Regression Example With Boston Dataset: Baseline
from numpy.random import seed
seed(1)
import tensorflow
tensorflow.random.set_seed(1)
from keras.models import Sequential
from keras.layers import Dense
from keras.callbacks import EarlyStopping
# from keras.wrappers.scikit_learn import KerasRegressor
from keras.metrics import MeanSquaredError
# from sklearn.model_selection import cross_val_score
# from sklearn.model_selection import KFold
from sklearn.preprocessing import MinMaxScaler
from sklearn.model_selection import train_test_split
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np
from sklearn.metrics import mean_absolute_percentage_error
from sklearn.metrics import mean_squared_error
from keras.utils.vis_utils import plot_model
# from matplotlib import pyplot
# from sklearn.preprocessing import StandardScaler
import seaborn as sns
import matplotlib.pyplot as plt
from keras.metrics import MeanAbsolutePercentageError

# load dataset
df = pd.read_excel("data_cycles_st.xlsx", engine='openpyxl').dropna()

dummy_variables = pd.get_dummies(df[['MoveKindCycleKey', 'AboveBelowDeck']], drop_first=True)
num_features = df[['MainTrolleyCycleDuration', 'windSpeed', 'totalWeight', 'TrolleyPosition',
     'HoistPosition']]

cat_features = dummy_variables.values
dataset = np.concatenate((num_features, cat_features), axis=1)

# split into input (X) and output (Y) variables
col = len(dataset[0])
X = dataset[:,1:col]
Y = dataset[:,0]
sc = MinMaxScaler()

X = sc.fit_transform(X)

X_train, X_rem, y_train, y_rem = train_test_split(X, Y, train_size=0.8)
X_val, X_test, y_val, y_test = train_test_split(X_rem, y_rem, test_size=0.5)
col = len(X_train[0])

def create_model():
    model = Sequential()
```

```
    model.add(Dense(10, kernel_initializer='normal', activation='sigmoid'))
    model.add(Dense(1, kernel_initializer='normal'))
    model.compile(optimizer='nadam', loss='mean_absolute_percentage_error', metrics=['mean_squared_error'])
    return model

def model_linear():
    model = Sequential()
    model.add(Dense(1))
    model.compile(optimizer='nadam', loss='mean_absolute_percentage_error', metrics=['mean_squared_error'])
    return model


model = create_model()
model_linear = model_linear()

callback = EarlyStopping(monitor='loss', patience = 15)
history = model.fit(X_train, y_train,
          batch_size = 512,
          epochs = 3,
          verbose = 2,
          validation_data=(X_val, y_val),
          callbacks = [callback])
history_linear = model_linear.fit(X_train, y_train,
          batch_size = 512,
          epochs = 3,
          verbose = 2,
          validation_data=(X_val, y_val),
          callbacks = [callback])



predictions = model_linear.predict(X_test)
predictions_lin = model_linear.predict(X_test)
print('MAPE validation:', min(history_linear.history['val_loss']))
print('MAPE training:', min(history_linear.history['loss']))
print('MAPE testing:', mean_absolute_percentage_error(y_test, predictions_lin.ravel()) * 100)
print('MSE validation:', min(history_linear.history['val_mean_squared_error']))
print('MSE training:', min(history_linear.history['mean_squared_error']))
print('MSE test:', mean_squared_error(y_test, predictions_lin.ravel()))


predic = predictions.ravel()
predic_lin = predictions_lin.ravel()
diff_perc = [abs((predic[i] - y_train[i]) / y_train[i] * 100) for i in range(len(y_train))]
diff_perc_lin = [abs((predic_lin[i] - y_train[i]) / y_train[i] * 100) for i in range(len(y_train))]


sorted_dif = np.sort(diff_perc)
sorted_dif_lin = np.sort(diff_perc_lin)
y = 1. * np.arange(len(sorted_dif)) / (len(sorted_dif) - 1)
y_lin = 1. * np.arange(len(sorted_dif_lin)) / (len(sorted_dif_lin) - 1)
plt.grid()
plt.xlim([0,40])
plt.ylim([0,1])
plt.title('Cumulative Distribution Function')
plt.xlabel('Percentage difference')
plt.ylabel('Percentage')
plt.plot(sorted_dif,y, label='ANN')
plt.plot(sorted_dif_lin, y_lin, label='LR')
plt.legend()
print(np.mean(diff))
```

E

Code Spreader Switching Strategy Model

```python
from gurobipy import *
import numpy as np
from numpy.random import seed
from tensorflow.keras.models import load_model
from pickle import load
seed(1)

model = load_model('Prediction_model.h5', compile=False)
scaler = load(open('scaler.pkl', 'rb'))

# Define Trolley Positions for each row
trolley_positions = {
    '22':6.34,
    '20':8.94,
    '18':11.54,
    '16':14.14,
    '14':16.74,
    '12':19.34,
    '10':21.94,
    '8':24.54,
    '6':27.14,
    '4':29.74,
    '2':32.34,
    '0':34.94,
    '1':37.54,
    '3':40.14,
    '5':42.74,
    '7':45.34,
    '9':47.94,
    '11':50.54,
    '13':53.14,
    '15':55.74,
    '17':58.34,
    '19':60.94,
    '21':63.54
}

# Define Hoist Positions for each tier
hoist_positions = {
    '2':-13.77859333,
    '4':-10.95614,
    '6':-8.29493,
    '8':-5.97247,
    '10':-3.18002,
    '12':-0.530376667,
    '14':2.119266667,
    '16':4.76891,
```

```
    '18':7.418553333,
    '20':10.06819667,
    '22':12.71784,
    '24':15.36748333,
    '72':20.61197429,
    '74':23.40143952,
    '76':26.19090476,
    '78':28.98037,
    '80':31.85064,
    '82':35.62018,
    '84':37.34876571,
    '86':40.13823095,
    '88':42.92769619,
    '90':45.71716143,
    '92':48.50662667
}

# Method to make the predictions
def make_predictions(cycles):
    prediction_list = []
    for i in range(1, len(cycles) - 1):
        cycle = cycles[i]
        single_prediction = []
        single_prediction += [cycle.get_wind(), cycle.get_weight(), cycle.get_trolley_pos(), cycle.get_hoist_pos()]

        if(cycle.amount_of_containers() == 1 and cycle.get_container1().get_move() == 'Load'):
            single_prediction += [1,0,0,0,0]
        if(cycle.amount_of_containers() == 2 and cycle.get_container1().get_move() == 'Load'):
            single_prediction += [0,0,1,0,0]

        if(cycle.get_container1().get_above_below() == 'Below'):
            single_prediction.append(1)
        else:
            single_prediction.append(0)
        prediction_list.append(single_prediction)

    to_predict = np.asarray(prediction_list)
    to_predict = scaler.transform(to_predict)
    predicted_values = model.predict(to_predict).ravel()
    predicted_values = np.insert(predicted_values, 0, 0)
    predicted_values = np.append(predicted_values, 0)

    return predicted_values

# Class to create cycles
class Cycle:
    def __init__(self, wind, container1 = None, container2 = None):
        self.wind = wind
        self.container1 = container1
        self.container2 = container2

    def get_container1(self):
        return self.container1

    def get_container2(self):
        return self.container2

    def get_wind(self):
        return self.wind

    def get_weight(self):
        if(self.container2 == None):
            return self.container1.get_weight()
        else:
            return self.container1.get_weight() + self.container2.get_weight()

    def get_tier(self):
        return self.container1.get_tier()
```

```

    def container_in_cycle(self, con):
        return (self.container1 == con or self.container2 == con)

    def get_trolley_pos(self):
        if(self.container2 == None):
            return trolley_positions[str(self.container1.get_row())]
        else:
            return (trolley_positions[str(self.container1.get_row())] + trolley_positions[str(self.container2.get_row())])/2

    def get_hoist_pos(self):
        return hoist_positions[str(self.container1.get_tier())]

    def amount_of_containers(self):
        if(self.container1 is not None and self.container2 is not None):
            return 2
        else:
            return 1

    def __eq__(self, other):
            if not isinstance(other, Cycle):
                # don't attempt to compare against unrelated types
                return NotImplemented

            return self.wind == other.wind and ((self.container1 == other.container1 and self.container2 == other.container2) or (self.container1 == other.container2 and self.container2 == other.container1))


# Class to create containers
class Container:
    def __init__(self, id_con = None, weight = None, tier = None, row = None, aboveBelow = None, move = None):
        self.id_con = id_con
        self.weight = weight
        self.row = row
        self.tier = tier
        self.aboveBelow = aboveBelow
        self.move = move

    def get_id(self):
        return self.id_con

    def get_above_below(self):
        return self.aboveBelow

    def get_weight(self):
        return self.weight

    def get_move(self):
        return self.move

    def get_row(self):
        return self.row

    def get_tier(self):
        return self.tier

# Method to check if two cycles are tandemable
def is_tandemable(c1, c2):
    return c1.get_tier() == c2.get_tier() and abs(c1.get_row()-c2.get_row()) <= 2 and c1.get_move() == c2.get_move()

# Method to make cycle from one or more container(s)
def make_cycles(containers, c_start, c_end):
    new_cycles = []
    for container1 in containers:
        for container2 in containers:
            cycle = Cycle(7.5, container1)
            if(cycle not in new_cycles):
```

```
                new_cycles.append(cycle)

            if(is_tandemable(container1, container2) and container1 != container2):
                cycle = Cycle(7.5, container1, container2)
                if(cycle not in new_cycles):
                    new_cycles.append(cycle)

    new_cycles.insert(0, Cycle(1, c_start))
    new_cycles.append(Cycle(1, c_end))

    return new_cycles


containers = []
for tier in [2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24]:
    # for row in [11,13,15,17]:
    for row in [11, 13, 15, 17]:
        if(not(tier==2 and row == 19) and not(tier==4 and row == 19)):
            containers.append(Container('tier:{0}, row:{1}'.format(tier, row), 3750, tier,
                row, 'Below', 'Load'))

c_dummy_start = Container('start', 0,-1,0, 'Below', 'Load')
c_dummy_end = Container('end', 0,2000,0, 'Below', 'Load')

cycles = make_cycles(containers, c_dummy_start, c_dummy_end)

containers.insert(0, c_dummy_start)
containers.append(c_dummy_end)

predicted_values = make_predictions(cycles)
# Create sets and constants
I = len(containers)
J = len(cycles)

tiers = []
for j in range(J):
    tiers.append(cycles[j].get_tier())


C = np.zeros((I, J))
for i in range(I):
    for j in range(J):
        C[i,j] = cycles[j].container_in_cycle(containers[i])

CC = np.zeros(J)
for j in range(J):
    CC[j] = cycles[j].amount_of_containers()

P = np.zeros(J)
for j in range(J):
    P[j] = predicted_values[j]


model = Model ('SWS')

# Create variables
X = {}
for j in range(J):
    X[j] = model.addVar(vtype = GRB.BINARY)

CS = {}
for j in range(J):
    for k in range(J):
        CS[j,k] = model.addVar(vtype = GRB.BINARY)

TS = {}
for j in range(J):
    TS[j] = model.addVar(vtype = GRB.BINARY)

SS = {}
for j in range(J):
```

```
    SS[j] = model.addVar(vtype = GRB.BINARY)

# Current time at cycle j
CT = {}
for j in range(J):
    CT[j] = model.addVar (vtype = GRB.CONTINUOUS, lb=0)

# Spreader change
SC = {}
for j in range(J):
    SC[j] = model.addVar(vtype = GRB.BINARY)

# Single with tandem spreader
STS = {}
for j in range(J):
    STS[j] = model.addVar(vtype = GRB.BINARY)


# Objective function
model.setObjective (quicksum (X[j]*P[j]+P[j]*0.5*STS[j] for j in range(J)) + 300 * quicksum(
    SC[j] for j in range(J)) )
model.modelSense = GRB.MINIMIZE
model.update ()

# Constraints

# Each container is handled once
for i in range(I):
    model.addConstr(quicksum(C[i,j] * X[j] for j in range(J)) == 1)

# If containers in cycle is 2 then cycle must be performed with tandem spreader
for j in range(J):
    model.addConstr(quicksum(C[i,j] * X[j] for i in range(I)) <= 1 + TS[j])

# Each cycle is either performed with single spreader or tandem spreader
for j in range(J):
    model.addConstr(SS[j] + TS[j] == X[j])

# Constraint 1: Each location has 1 incoming edge, except for the first node
for j in range(1, J):
    model.addConstr(quicksum(CS[k,j] for k in range(J)) == X[j])

# Constraint 2: Each location has 1 outgoing edge, except for the last node
for k in range(0, J - 1):
    model.addConstr(quicksum(CS[k,j] for j in range(J)) == X[k])

# Constraint 3: The first node does not have incoming edges
model.addConstr(quicksum(CS[j,0] for j in range(J)) == 0)

# Constraint 4: The last node does not have outgoing edges
model.addConstr(quicksum(CS[J - 1,k] for k in range(J)) == 0)

# Constraint 5: Defining the current time
for j in range(J):
    for k in range(J):
        model.addConstr((CS[j,k] == 1) >> (CT[k] == CT[j] + P[k] + SC[j]))

# All cycles in tier t have a later handling time than cycles in tier t-1
for j in range(J):
    for k in range(J):
        if(cycles[j].get_tier() < cycles[k].get_tier()):
            model.addConstr((CS[j,k] == 1) >> (CT[j] >= CT[k]))

for j in range(1,J-1):
    for k in range(1,J-1):
        if(cycles[j].get_tier() == cycles[k].get_tier() and cycles[j].get_container1().
            get_row() > cycles[k].get_container1().get_row()):
            model.addConstr((CS[j,k] == 1) >> (CT[j] >= CT[k]))

# Identify single containers handled with tandem spreader
for j in range(J):
```

```
    model.addConstr(quicksum(C[i,j] for i in range(I)) - 2 * (1-TS[j]) <= STS[j] + (quicksum(
        C[i,j] for i in range(I)) - 1) * 3)

# Keep track of spreader changes
for j in range(J):
    for k in range(J):
        model.addConstr(SS[j] + TS[k] - 3*(1-CS[j,k]) <= SC[j] + 1)
        model.addConstr(TS[j] + SS[k] - 3*(1-CS[j,k]) <= SC[j] + 1)

# Set type of spreader a crane is equiped with before starting
model.addConstr(TS[0] == 0)


# ---- Solve ----
model.setParam( 'OutputFlag', True) # silencing gurobi output or not
model.setParam ('MIPGap', 0.01);       # find the optimal solution
model.setParam('IntFeasTol', 1e-9)
model.optimize ()
print('Total time:', model.objVal)
```