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MASTER THESIS

Automated berth planning and quay crane allocation at a Dutch container terminal

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I hope you enjoy reading this thesis!

Rob van Schooten
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Management Summary

Company X, is an operator of container terminals in the Rotterdam harbour. The company handles container vessels of various sizes from various origins, ranging from barges from Germany to deep-sea vessels from China. Currently, the planning department is responsible for allocating the available capacity to the vessels that visit the terminal. Each vessel is allocated a place and period along the quay as well as quay cranes (QCs) to service the vessel. Furthermore, an (un)loading plan is made for each vessel.

In literature, the planning problems are known as the Berth Allocation Problem (BAP), Quay Crane Allocation Problem (QCAP) and Quay Crane Scheduling Problem (QCSP). The BAP determines which vessel arrives at which moment and where it is moored. The QCAP entails allocating (QCs) to vessels to service them. The QCSP plans the (un)loading order and locations of the containers in the vessel. The outcomes of the three plans depend on each other which makes it complex to construct an optimal solution.

Currently, all planning is done manually, however, the company wants to switch from manual planning to automatic planning. As most of the work is done manually, it is difficult to judge the quality of the plans. Furthermore, manual planning is time-consuming thus requiring many worker hours and making it difficult to evaluate multiple scenarios. The scope for this study is the BAP and QCAP, the QCSP is not included as this is too complex for problems of realistic size. To find a solution for automatic planning, the main research question is

"How can berth planning and quay crane allocation for Company X be automated by an algorithm?"

Through interviews with several people in the company, we identified all features of the BAP and QCAP applicable to the case of Company X. By using the input, we also formulated an objective function that considers and balances the interests of each department of the company, customers, and other stakeholders. Additionally, we investigated the current processes and provided insight into which information is available at which moment. The main decisions in the BAP are at which moment and place a vessel is moored. In the QCAP it is determined which QCs are allocated to which vessel at which moment.

We conducted a literature review to obtain solution methods for the BAP and QCAP. We searched for applications with similar features as the case of Company X. Based on this review and our insights, we proposed a solution method that first solves the BAP and then the QCAP. We proposed two solution methods for the BAP. The first solution is Tabu Search while the second is a newly proposed heuristic, named Priority Rules.

The Tabu Search implementation plans all vessels in an initial solution and then moves and swaps vessels to investigate the solution space. The Priority Rules heuristics plans vessels sequentially based on a preconfigured list of rules and priorities. We solved the QCAP with a newly formed QC allocation heuristic that divides the available QCs over the vessels such that each vessel departs before the departure time determined in the BAP. To align the berth and crane plan better, we introduced refinements. These refinements slightly change vessel arrivals, departures and mooring positions for example.

As with the proposed heuristics, it is uncertain if the optimal solution is reached, it is desirable to construct a solution method that is guaranteed to find the optimal solution. Therefore, we formulated a linear programming (LP) model with the features and objective of Company X that is guaranteed to provide the optimal solution if it is given enough time. As the runtime of the LP model is too long for problem instances of realistic size, we compare the solutions of the proposed heuristic with the exact outcomes for small problem instances. The heuristics are tuned separately for these small problem instances to enable a fair comparison. The total cost of the combination of Priority Rules and QC allocation is 54% higher than the exact solution. For the combination of Tabu Search and QC allocation, this is 32.8%.

To evaluate the performance of the heuristics on problem instances of a realistic size we performed multiple experiments. First, we tuned the individual elements of the solution method. We determined the rules and priorities for the Priority Rules heuristic. For Tabu Search we evaluated multiple configurations for the tabu list length and number of iterations. Subsequently, we tested various configurations for the application of refinements.

Using ten problem instances of a realistic size of one week with approximately fifty vessels, we evaluate the performance of the heuristics. Unfortunately, it is not possible to compare the outcomes with actual plans as too many simplifications were made. So, to provide insight into the performance of the heuristic we used two benchmarking methods. The low benchmark (LB) is the total cost when there are no delays or deviations from the preferred mooring position. The high benchmark (HB) is based on the Priority Rules heuristic but only uses the ETA as the priority.

As we proposed two solutions methods for the BAP, we first compared the outcomes of Tabu Search with Priority Rules. In this experiment, the performance of both heuristics is poor, Priority Rules is outperformed by the benchmarking method in 7 of the 10 cases, while Tabu Search is outperformed in 8 of the 10 cases. In the next experiment that we performed, we compared the combination of Tabu Search with the QC allocation heuristic and Priority Rules with the QC allocation heuristic.

TABLE 1: Experiment outcomes Priority Rules realistic problem instances BAP and QCAP

Problem instance	**PR Value**	**TS Value**	**LB Value**	**HB Value**
1	215.740,4	283.857,3 (12.593,0)	52.275	194.186,4
2	275.320,8	274.375,8 (7.469,6)	67.950	289.142,3
3	205.992,6	245.518,5 (20.494,1)	54.975	213.180,1
4	182.267,9	217.033,3 (9.922,5)	50.925	225.531,1
5	245.316,1	317.417,7 (4.1067,9)	54.450	253.676,3
6	258.550,0	264.261,3 (10.736,6)	51.075	285.070,1
7	206.823,8	292.382,9 (49.862,2)	53.700	273.828,5
8	275.335,0	294.877,3 (8.397,6)	58.500	273.649,8
9	275.216,1	322.129,9 (22.692,9)	52.350	364.338,9
10	335.679,0	323.810,2 (11.998,9)	45.675	334.514,0

Table 1 provides the outcomes of the experiment for the BAP and QCAP. The performance of the combination with Tabu Search is still worse than the benchmark. However, the performance of the combination with Priority Rules has significantly improved compared to the benchmark. The total cost of the ten problem instances is 14.5% higher for Tabu Search than for Priority Rules. The performance in all ten problem instances is better for Priority Rules than HB, the total cost of HB is 9,3% higher in the ten problem instances.

We conclude that both heuristics can make valid berth and crane plans for the problem discussed in this research. However, compared to the benchmarking methods the performance is poor and further improvement is needed. Furthermore, the set of features discussed in this problem is a significant simplification of reality. Therefore, the outcomes are not directly usable.

Based on the outcomes of this research and the acquired insights we recommend to:

- Investigate other solution methods, for example, genetic algorithms as discussed in the literature review;
- Increase the number of features incorporated in the solution methods to close the gap with reality and make the plans usable in reality;

- Investigate if the discussed solution methods are usable for the long-term plan where the QCAP is not included.

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Glossary and Abbreviations

Container moves	Total number of containers to be loaded, unloaded or restowed
QC team	Crew of three people that can operate a QC
Bollard	A pole on the quay that is used to secure a vessel's mooring lines
Berth plan	Plan that contains a mooring position and timeslot for every vessel
Crane plan	Plan that contains for each vessel which QC(s) will service the vessel at which moments
Bay plan	Plan that shows which container is placed on which position in the vessel as well as the order of (un)loading
Deep-sea vessel	Ocean-going vessels that operate around the globe
Feeder vessel	Vessels that operate mainly within Europa and Scandinavia
Barge	Vessels that sail between inland terminals
Window	Contractually agreed time window in which the vessel is guaranteed service
In window	If the vessel arrives in the port within the contractually agreed period, it is in window
Pro forma schedule	Weekly schedule that contains the contractually agreed windows
Port stay	Total time that a vessel is present at the terminal
Yard	Place on the terminal where containers are stored, the yard is divided in sub stacks
Call	A visit of a vessel to a terminal
Shipping line	Company that operates multiple container vessels
QC split	Maximum number of QCs that can work on a vessel simultaneously, based on safety protocols and practical reasons
QC set up	A QC is not immediately operable, the QC set-up includes the crew traveling to the QC, starting it and preparing service
QC hour	Allocation of one QC to a vessel for one hour
Quay section	Space along the quay between two bollards
Time section	Period of time
Shift	QC teams work in shifts of multiple time sections
Berth	A predefined space along the quay where a vessel is serviced

ETA	Estimated time of arrival
ETD	Estimated time of departure
STA	Scheduled time of arrival
STD	Scheduled time of departure
PTA	Preferred time of arrival
PTD	Preferred time of departure
ATA	Actual time of arrival
ATD	Actual time of departure
QC	Quay crane
AGV	Automated guided vehicle
ASC	Automated stacking crane

OPC	Operational planning center
BAP	Berth allocation problem
QCAP	Quay crane allocation problem
QCSP	Quay crane scheduling problem
BP	Bruto production (per hour)

Chapter 1

Introduction

This chapter provides an overall introduction to the company and port processes. It provides context on the assignment, such as the background information, problem statement, research questions and scope. Section 1.1 describes the company Company X and the new planning system. Section 1.2 discusses terminal processes. Section 1.3 provides an introduction to the planning process on a container terminal. In Section 1.4 we identify the problems and select a core problem. Section 1.5 discusses the research approach, sets the objective, outline and scope, and provides the research questions.

1.1 About Company X

In this public version of the thesis the name of the company is replaced by 'Company X'. The names of other parties involved are replaced by fictional names. Furthermore, a number of details are removed or redacted. All changes are made with the readability of the report in mind, to minimize the impact of the anonymization.

Company X's mother company is one of the biggest players in the container terminal industry in Europe. With three container terminals in the port of Rotterdam and four other terminals in the hinterland, Company X can offer seamless services to its customers. Since the founding of the company, Company X focuses on improvement and innovation. As the biggest container harbour in Europe, Rotterdam handles almost 15 million TEU per year (Rotterdam, 2021). Company X handles a significant portion of this volume, with the largest vessels in the world visiting the terminal on a daily basis.

The terminal of Company X is a multi-user terminal, which means that multiple container shipping companies visit the terminal and that the terminal owner is independent of the container shipping companies. The terminals in the port of Rotterdam are well connected with other modalities such as truck and rail.

Company X is part of a larger concern, which is one of the biggest port operators on the globe. Within the network of terminals of the group, knowledge is shared and improvements are taken over from each other. Company X contributes with its department Improvement & Development, where many innovations and improvement projects are initiated and performed. One of the projects currently in progress involves the development of a new planning system. This thesis reports the research performed for an efficient berth and crane planning system and the validation of this, through a proof of concept.

1.1.1 New planning system

Company X's parent company is currently developing a new planning system for its container terminals in Asia, Europe and South America. The first version is a manual system in which the planner must manually plan the vessels. The approach is to develop this basic solution further step by step. This involves the following steps:

1. Schedule manually
2. Manual scheduling but with checks and warnings from the computer system
3. Decision Support for manual planning, where the system suggests changes to the plan to improve the efficiency
4. Automated planning, where the planner can intervene but the system makes the plan

Steps 1 & 2 are currently under development. The checks and warnings of Step 2 involve, amongst others, checking if the height of the allocated QCs is sufficient, if the the commercial agreements are achieved, and if the draft is not too much, etc. These checks only consider the information given and do not provide alternatives in case of infeasibility.

With the introduction of decision support in Step 3, the planner receives advice on, for example, adding an extra QC to service the vessel, such that it can be served on time, or allocating the vessel to another mooring position in anticipation of a later arriving vessel. This advice should result in more efficient plans. With the automated planning from Step 4, an algorithm runs in the background that continuously processes all input and generates efficient plans. The planner can intervene, but will mainly influence the plan by adjusting the input.

The approach is divided into multiple steps to ensure that automation can be embedded in the organisation. Changing the process from manual to automated immediately is a big step that is difficult to implement in the organisation. This thesis is the first concept for steps three and four. The focus is on step four, in a later stage step three can be derived from step four.

1.2 Container terminals

This section provides a general introduction to the context of a container terminal.

1.2.1 Types of vessels

Most deep-sea terminals are visited by three classes of vessels: deep-sea vessels, feeder vessels and barges. In addition to these visits on the water-side, there is often a road and rail connection. Deep-sea vessels are the enormous container vessels, operated by various container shipping companies. These vessels sail around the world in a standard schedule, called a service. A service is set up by a container shipping company, or an alliance of container shipping companies, and connects multiple terminals on different continents at a set frequency.

The containers that arrive or depart on these deep-sea vessels are transhipped by feeder vessels, barges, trucks and trains. Feeder vessels sail to other regions in and around Europe such as Scandinavia and England. Barges provide the distribution closer to the Netherlands, via the Rijn and Maas rivers for example.

1.2.2 Terminal process

During a visit of a vessel, which is also denoted as a call, containers are unloaded, loaded, or restowed, which is changing the position of a container on the vessel. Vessels moor along the quay on the waterside, at their allocated mooring position. A predefined mooring space along the quay is called a berth. The quay is divided into sections using so-called bollards, which are markings every 25 meters along the quay. Deep-sea and feeder vessels are brought from the sea to the quay with the help of a pilot and tugs.

Figure 1.1 provides an overview of the most important elements that are present on the terminal. The Quay Cranes (QCs) and Automated Guided Vehicles (AGVs) are used to service a vessel. The QCs are mounted on rails along the quay and have a specific reach along the quay.

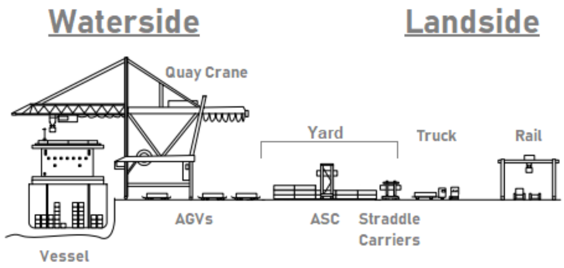


FIGURE 1.1: Overview of elements on a container terminal

Since they are mounted on rails, they cannot pass each other. The yard is the place where all containers are stored while they wait for further transport. A container is put on or taken from the yard by an Automated Stacking Crane (ASC).

At the landside, a container is transported from/to the yard by a straddle carrier. The straddle carrier can pick up one container at a time and put this on a truck or an internal transport wagon, to drive it to the train yard. On the waterside, a container is transported by an AGV. The ASC puts a container on the AGV, which will drive it to the QC. The QC then picks it up from the AGV and puts it on the vessel. For unloading, an empty AGV drives to the QC to be loaded with a container, which it will then bring to the yard.

There is much more to a terminal than the explanation provided here. This can for example be found in Christiansen et al. (2007). All relevant processes are explained in more detail later in this report.

1.3 Planning processes

There are three 'steps' in making the plan for handling the vessels that arrive at the terminal, Figure 1.2 shows these three steps. The first step is to determine where a vessel can moor along the quay. This 'problem' is known as the Berth Allocation Problem (BAP). Once the place of mooring is known, the QCs to service the vessel can be assigned, this is known as the Quay Crane Allocation Problem (QCAP). The third planning step uses the two earlier steps to make a (un)loading plan for the vessel, also called the vessel plan. This problem is known as the Quay Crane Scheduling Problem (QCSP). The three problems interact with each other, namely, the mooring position determines which QCs can be allocated, which in turn determines how fast a vessel can be serviced. Based on the service time the next vessel can be scheduled.

1.3.1 Berth Allocation Problem

Berth planning is the process of assigning vessels that want to visit the terminal to a place in the plan. A place consists of a moment in time and a location. If a vessel wants to call at a port, the container shipping company announces the vessel to the planner. Based on the information provided by a container shipping company, the planner tries to find the best place in the current plan given the objective and constraints. The planner needs to find a mooring position where the vessel fits physically, where suitable equipment is available and a moment when there is enough time to service the vessel until the next vessel arrives.

Figure 1.3 provides an example of a berth plan: on the vertical axis the time is given and the horizontal axis represents the quay. The top of the figure provides the quay division, using the numbers of the bollards. Every rectangle is a vessel, the longer the rectangle the longer the service time. The width of the rectangle represents the width of the vessel. The smallest blocks with a QC number represent QC maintenance.

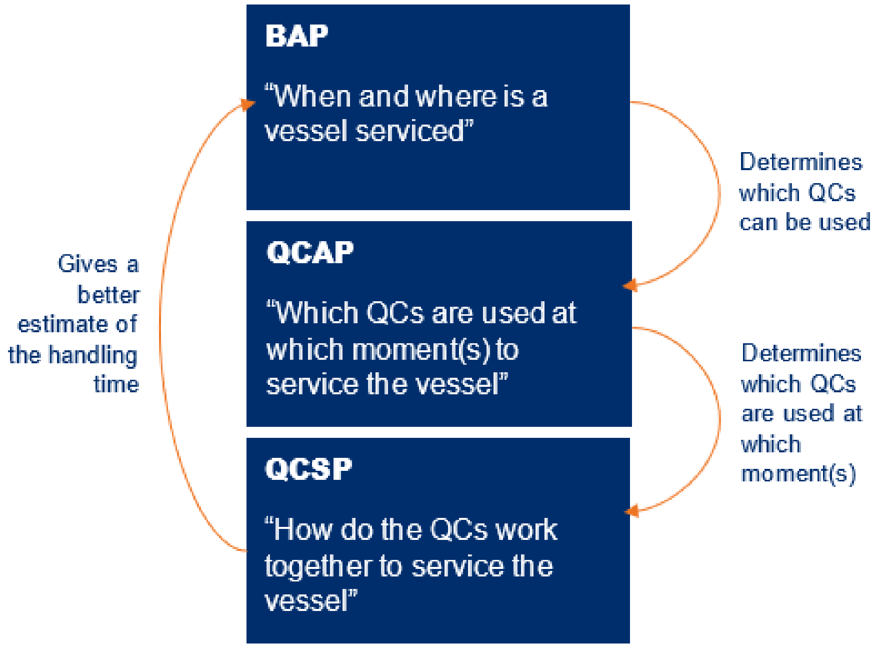


FIGURE 1.2: Overview of three steps in the planning process for a container terminal

1.3.2 Quay Crane Allocation Problem

Along the quay, there are multiple QCs with different properties, therefore, not every QC is suitable for every vessel. Furthermore, the reach along the quay of each QC is restricted. To operate a QC, a QC team of three people is needed. The number of available QC teams depends on how much personnel is available. QCs also need maintenance, therefore, they are not always available. Given the berth plan and the availability of QC teams and QCs, a crane allocation plan is made to meet the objective as good as possible.

1.3.3 Quay Crane Scheduling Problem

The quay crane schedule determines the order in which containers are (un)loaded by which QC and where they are placed in the vessel. Once the berth and crane plan are known, the bay plan can be made. The bay plan assures that the vessel stays in balance during service and that QCs do not get in conflict while (un)loading the vessel. The complete bay plan gives a reliable estimate of the total handling time.

1.3.4 Complete process

There are many constraints to making a complete plan, which make the planning process complex. In addition, it is also a very dynamic activity. There is a constant flow of new or updated information that might require taking an action. There is a constant trade-off between several options, to meet the objective as good as possible. The plan is the guideline for the actual operation and a realistic plan results in on-time performance and fewer delays.

In practice, planning is often performed by humans. There are several software tools to support a planner in its decision-making, but the intelligence typically comes from the human planner. A human is very capable of taking all constraints into account while also being creative when necessary. But the human planner will never be able to evaluate all possible solutions to

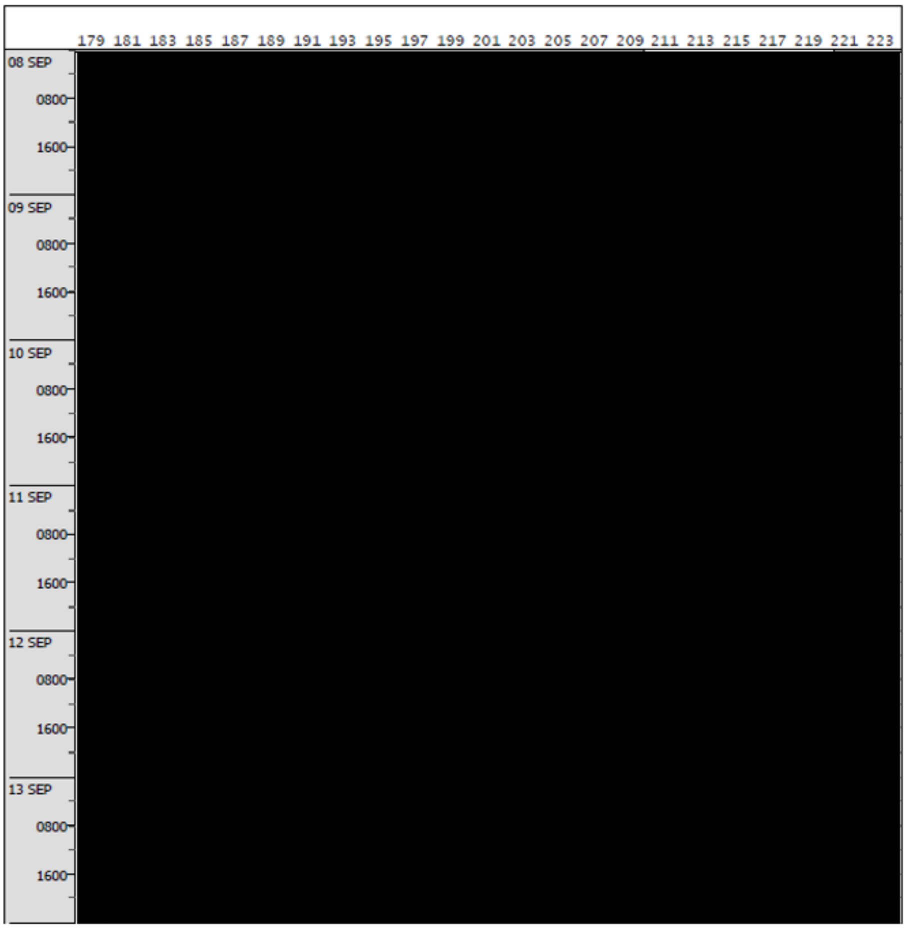


FIGURE 1.3: Example of a berth plan (without QCs)

the planning problem. Especially the step towards an optimal plan will not be made by the human planner, a human planner is satisfied with a realistic and workable plan.

A lot of research on these planning processes is available, see for example the literature reviews of Bierwirth and Meisel (2010)(2015). However, none of these solution methods is currently used by Company X.

1.4 Problem identification

By making a problem cluster it becomes clear what the causes and effects of the identified problems are. All problems mentioned in this section are put together in a structured overview based on the methodology of Heerkens, Winden, and Tjooitink (2021). Figure 1.4 shows this problem cluster. Each arrow originates in a cause and points to an effect. The problems that do not have incoming arrows are called root causes, when these problems are solved they will affect the subsequent problems as well.

1.4.1 Quantification of objective and constraints

To make a good plan, it is important to know the (soft) constraints and the objective. However, in the case of Company X, this is not always clear. Imagine a barge that fits in two places, but both places have a disadvantage. For one place fifty containers have to be moved from one side of the quay to the other, but the barge can be serviced immediately. The other place does not require moving the containers over a long distance but is only available after two hours, which

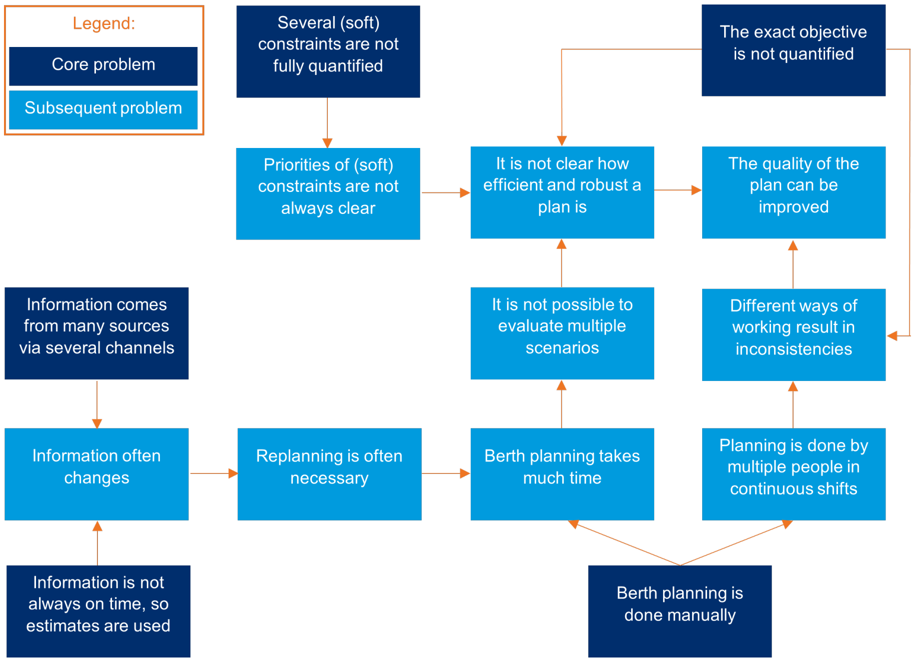


FIGURE 1.4: Problem cluster of planning department of Company X

means that the barge will get a delay. If the costs of movements and delays are not known by the planner, it is impossible to determine which solution results in the lowest cost.

To evaluate a plan, it is important to have a quantified objective function. This makes the quality of a plan measurable. The goal can be to minimize delays, to serve every vessel as quick as possible, or to make a trade-off between cost and service level. At this moment, there is no such quantified objective available. The planner makes the trade-offs and creates a plan that feels like the best trade-off between all priorities for them.

1.4.2 Working manually

In the current approach at Company X, all planning is done manually, there is no 'cleverness' incorporated in the software tool that the planning department uses. The division of time for a planner is roughly 75% information processing and updating, and 25% replanning the plan (Planner, personal communication, September 7, 2021).

One planner is appointed for each class of vessels but these planners share the same resources. Aligning the usage of resources between the various classes requires time from all planners. Furthermore, each planner has its way of working and planners work in shifts of eight hours. After every shift, an information transfer of the current state is needed. Due to the changes in personnel and different ways of working, inconsistencies in the plan arise.

1.4.3 Information flows

Another aspect of planning is the constant flow of new and updated information. Information comes from many sources, such as the operator of a vessel, the booker of a container or internal systems. A significant portion of these processes is automated, however, part of the information is still exchanged by mail or phone. Processing this information takes a significant portion of the planners' time. Part of the information is based on preliminary forecasts, which are regularly updated. It often occurs that updates in information results in replanning of the current plan. As a consequence of these circumstances, a significant portion of the planners' time goes to waste, as the work is later redone.

1.4.4 Core problem selection

As it is currently not clear what the exact objective is, it is difficult to evaluate the quality of a plan. Furthermore, due to the unclarity inconsistencies arise in the plan. Because all the planning is performed manually, the time of the planners is limited. Therefore, it is currently not possible to work out multiple problem instances under various objectives. For the management, it would be interesting to get insight into multiple problem instances focused on various objectives. This would also enable a better comparison of several plans, which in turn provides insight into the quality of the plan.

These problems give rise to the feeling that the quality of the plan can be improved. Many aspects can be improved, however, part of the situation, which is that decisions have to be made in advance while factors are still uncertain, cannot be changed easily. Even with improvements, some information cannot be made available earlier and disruptions regularly occur. Therefore it is useful if plans can be formed faster, such that more problem instances can be evaluated.

The core problem addressed in this research is "Berth planning is done manually", improving this problem will affect the consequent problems. To form a good plan we need the information on the constraints and objectives. Therefore, we also invest time in the core problems "Several (soft) constraints are not fully quantified" and "The exact objective is not qualified". The information that we gain in improving these problems is used for improving the planning process.

1.5 Research approach

In this section, we introduce the approach to solve the core problem that we identified in Section 1.4.4. We first discuss the objective and outline of the research. Next, we set the scope of the research. Based on these inputs we form the research questions.

1.5.1 Research objective and outline

The research objective is twofold. First, the relevant constraints and objectives for the plan should be identified and quantified. A part of the constraints are hard constraints, the other part concerns soft constraints. Furthermore, some factors play a role but cannot be translated into constraints, or are accomplished via other constraints. Second, we develop an algorithm that can construct a valid plan that is (close to) optimal. Valid in this case means to adhere to all hard constraints. Optimal entails the best balance between all interests from a Company X perspective, fulfilling the objective as good as possible.

Once all applicable constraints are identified, it is possible to select a solution method. The solution method should be able to incorporate as many constraints as possible. Furthermore, the solution method should be able to differentiate between hard and soft constraints. Figure 1.5 shows the step by step outline of the research.

1.5.2 Scope

This assignment takes place at Company X. This research is part of an innovation project of the mother company of Company X, in which many other ports participate. However, this study will focus only on the terminal in Rotterdam, factors that are not relevant for Rotterdam, such as irregular layouts of quays will not be included in the study. Furthermore, specific customer agreements will not be incorporated into the solution. Taking all exceptions and customizations into account would make it impossible to come up with a proof of concept in six months.

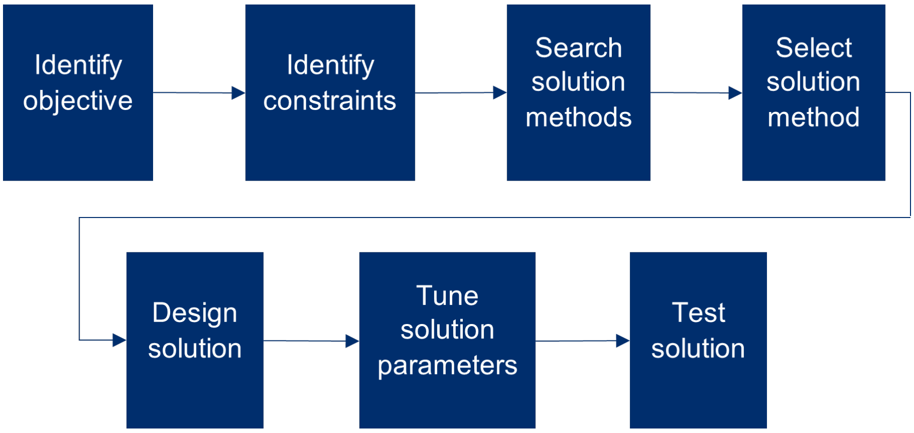


FIGURE 1.5: Outline of steps in this research

The terminal is used by multiple container shipping companies and all container shipping companies have the same priority. This forms a representative situation for research on berth planning and quay crane allocation.

The planning department requires information from many sources to form a complete plan. A study on how this information comes available and the reliability of the information would be very interesting, however, such a study is also very time consuming, as historical data has to be analysed and interviews need to be held to find out the processes for obtaining this information. Since many sources provide information, this process has to be done several times. Therefore, in this research, the information (e.g., number of container moves and number of QC teams available) is assumed to be known. Examining how the information is obtained and how reliable it is, is outside the scope of this research. A data study of the plans itself is included in the research, as this may reveal problems in the current situation. Furthermore, it gives a basis for a comparison with a plan made by a new solution.

In another innovation project the planning for barges is improved. A system that combines all information makes a plan in the best interest of all parties. Barges are relatively small and can be serviced by only one QC simultaneously, therefore, it is sufficient to reserve a part of the quay for barges after which the system will plan the individual barges. As this process is already set up, barges are not included in the study. To keep the situation realistic, the quay, QCs and QC teams for barges will be deducted from the available resources.

As mentioned in Section 1.3, the planning process consists of three steps. In the available literature, these steps are studied individually as well as combined. The literature shows that combining all three steps results in a complex problem, as the three steps influence each other. To keep the scope of this project reasonable, the QCSP is not included in this study. We assume that estimates of handling times suffice.

1.5.3 Research questions

The main research question of this research is:

"How can berth planning and quay crane allocation for Company X be automated by an algorithm?"

To structure the research and to support a step by step approach, we formulate research subquestions. The research subquestions result in the outline of the research. To understand the current situation and to find the objective and constraints for the BAP and QCAP as currently used by Company X, we formulate the following questions.

1. What does the current problem context look like?

   (a) What is the size of the operations on the terminal?
   (b) What does the current planning process look like?
   (c) Who are the stakeholders of the plan?
   (d) How dynamic is the environment of the planning?
   (e) What is the current performance of the planning department?

2. Which objective and constraints are relevant when making a plan?
   (a) What is the objective of the plan?
   (b) Which constraints are taken into account for the terminal?
   (c) What other limitations/influences are taken into account in the plan?

To form an overview of the current problem context, we study the data on the current operations on the terminal and more specifically the performance statistics of the planning department. To get insight into the current planning process, informal interviews and observation sessions take place with the planning employees. In these interviews, we will also discuss the current process and the objectives and constraints that are taken into account.

Furthermore, we will informally interview other people in the organisation to incorporate their views and opinions. Together this gives a complete and balanced overview of the current planning process, objectives and constraints. To be able to work with the constraints and compare solutions using an objective function, we should define and quantify the constraints that we identified. Quantifying in this case means clearly defining if the constraint is soft or hard and what the boundaries are. Furthermore, we study where the information comes from. Additional information comes from the data warehouse: Company X has a large data warehouse that stores data on many aspects of the organisation.

Given the objectives and constraints, we can select potential solution methods from the literature. We study the available literature on berth planning and QC allocation to get a view of which objectives and constraints are included and how they are prioritised in existing solution methods.

3. Which solution methods are suitable for the case of Company X?
   (a) Which constraints do existing works incorporate?
   (b) Which objective functions are used?
   (c) Which solution methods are used in these works?
   (d) What are the gaps and similarities between the Company X case and cases in literature?
   (e) Which solution method from the literature is most useful for the case of terminal?

Many studies on port planning problems exist in the literature, with a variety of solution methods. Studying the available literature gives an overview of existing implementations and lays the foundation for a solution method for Company X. We do not focus the literature study on the case of Company X, but keep a broad perspective as the available literature might offer objectives and constraints that are relevant for Company X but not yet present.

Next, we need to consider which solution method can best be applied to the situation of the terminal.

4. What does a solution method for Company X look like?
   (a) Which objectives and constraints should the solution method include?

(b) Which adaptation/additions should be made to the solution method(s) found in the literature to make it useful for the terminal?

(c) To what extent can the solution method support the constraints relevant for the terminal?

(d) To what extent can the solution method support the objective(s) relevant for the terminal?

(e) Which simplification and assumptions do we need to make to make the problem solvable?

By combining the insights on objectives and constraints, and the knowledge of the available solution methods, we can select the solution method that fits best to Company X. The solution method from the literature is possibly not a direct fit, therefore adaptations of the solution method will be needed. When selecting the solution method we will also look at its flexibility. Using the best solution method found, we design/adapt the solution method specifically for the situation of Company X.

Once we finalize the design of the solution method, it is useful to evaluate its performance. Does the solution method work, does it give a correct solution, and if it gives a correct solution, is it an improvement? Therefore we test the solutions constructed by the solution method.

5. What performance can be expected from the proposed solution method?

   (a) How valid are the constructed solutions?

   (b) What is the influence of the quay layout used in the solution method?

   (c) How well do the heuristics perform compared to an exact approach?

   (d) How well do the heuristics perform in realistic problem instances?

   (e) Can the initial outcomes of the heuristics be improved further by a dedicated improvement heuristic?

By comparing various plans with exact approaches and a simple heuristic used for benchmarking, we gain valuable insights into the performance. To be able to compare two plans, both methods should have the same constraints and objectives. The comparison compromises several aspects, such as efficient usage of resources and total cost.

Lastly, the research is finalized with conclusions, suggestions for future research and recommendations for Company X.

Chapter 2

Research context

The main goal of this chapter is to discuss the current problem context and answer the first research question: *'What does the current problem context look like?'*. Section 2.1 provides basic information on the day to day operations at the terminal and the current processes and parties involved. In addition, it also provides insight into the current performance and how often the inputs change. We also anser the second research question: *'Which objective and constraints are relevant when making a plan?'*. Section 2.2 discusses all constraints and the objective of the planning process. Finally, Section 2.3 provides a summary.

2.1 Current processes

In this section, we discuss the current process at the terminal. We first give an insight into the magnitude of the activities on the terminal. Next, we go more into detail on the steps in the planning process. We discuss the departments that are involved in making a plan and we construct a timeline for a single call. Furthermore, we discuss the usage of the available resources and the stakeholders.

2.1.1 Magnitude of activities

During an average week, [redacted] deep-sea and [redacted] feeder vessels visit the terminal, complemented with barge visits. The average port stay of a deep-sea vessel is 44 hours. Feeder vessels have smaller call sizes, resulting in an average port stay of 11 hours. The port stay is influenced by many factors; service time can be significantly less than the total port stay. Vessels might stay for bunkering, or they stay because they cannot arrive at the next terminal yet. This increases the port stay, even if the service was already completed.

In total around [redacted] containers are handled at the terminal in a week on average. These containers come and go via water, rail or road. Deep-sea is the most important waterside modality. On the landside, trucking is the most important modality. Barges and feeder vessels have comparable shares in the modal split.

2.1.2 Periods in the planning phase

The planning horizon can be divided into five phases, as shown in Table 2.1. A 'blueprint' for the long term plan is formed in the pro forma schedule. Figure 2.1 shows a (simplified) example of a pro forma schedule. Most deep-sea vessels sail in standard services, set up by an alliance of container shipping companies or an individual container shipping company. Each service has its route and calls at all ports on this route. An example of such a service is the AA1 service of container shipping company ABContainers, which operates between Asia and Europe. A fleet of multiple vessels sails in a service, such that every port on the route is visited once a week.

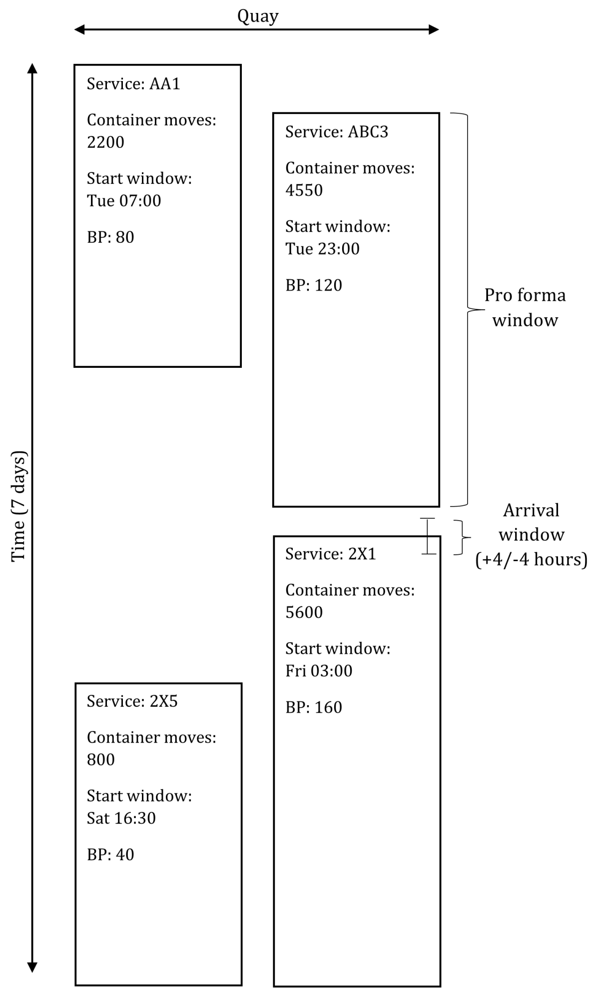


FIGURE 2.1: Simplified pro forma schedule with four vessels

These visits are planned at a specific moment every week, the so-called pro forma window. A pro forma window consists of the arrival time, i.e. the start of the window, the number of container moves and the BP. The arrival time is the arrival time at the port. If the vessel arrives in the port within a specified period around the arrival time, also called the arrival window, its arrival is registered as in window. The arrival time in the port is different from the arrival time at the terminal. If the vessel arrives in the port while there is no place for it at the terminal, it has to wait in the port.

A vessel that arrives in window is entitled to a contractually agreed BP. The BP is the 'bruto production', the number of container moves performed per hour. Based on the number of container moves of the vessel and the BP, the port stay is calculated. The port stay is the difference between the arrival time and the departure time. Using this data, the departure time can be calculated as the port stay added to the arrival time.

The contractual agreements for pro forma windows are made to improve reliability of both the container shipping company as well as the terminal. If vessel arrivals are reliable, Company X can produce a more reliable schedule. However, the pro forma windows are a soft constraint. In case the vessel does not arrive in window, the entitled minimum BP expires. In case the vessel arrival was in window and the departure time is not met by the terminal, Company X has to pay a higher penalty for the delays compared to a vessel that did not arrive in window.

The pro forma windows are contractually fixed and negotiated in contract negotiations between the container shipping company/alliance and the sales department of the terminal.

All these pro forma windows combined form the pro forma schedule. The pro forma schedule is repeated every week and forms the basis for the berth plan.

Approximately three months before a call of a deep-sea vessel, actual information comes in from the container shipping companies. Part of this information is which vessel will arrive, which means that the length of the vessel that visits the terminal is known. Furthermore, estimates of the number of container moves, the estimated time of arrival and the preferred departure time are included. In this period, the contractual information from the pro forma schedule is updated with the actual estimates. By updating the plan with actual estimates instead of contractual agreements, the planners get a better view of the current plan. If conflicts arise, planners can already intervene.

TABLE 2.1: Periods in the planning process

Period	**Considered period**	**Responsible department**	**Vessels included**	**Information available**	**Planning problem**
Pro forma schedule	Months in advance	Sales department	Deep-sea	Contractual agreements: container moves, BP, port stay, arrival and preferred departure time	BAP
Long term plan	Three months – seven days	OPC	Deep-sea	Estimated data: container moves, arrival and preferred departure time Actual data: vessel	BAP
Short term plan	Seven days – one day	OPC	Deep-sea, Feeder	Estimated data: containers to load, arrival and preferred departure time, available QC teams Actual data: containers to unload, QC/quay maintenance	BAP, QCAP
24-hour plan	One day – eight hours	OPC	Deep-sea, Feeder	Estimated data: arrival time Actual data: container moves, departure time, available QC teams, QC/quay maintenance	BAP, QCAP, QCSP
In operation	Eight hours – now	Execution department	Deep-sea, Feeder	Actual data: container moves, arrival and departure times, available QC teams, QC/quay maintenance	-

Starting seven days before the date on which the planning is done, feeder vessels are also included in the plan. Furthermore, an estimate for the number of QC teams that can be scheduled is now available and QC/quay maintenance is scheduled. In this phase, the plan is elaborated with the QC allocation. In the last phase before execution, most data is known and actual QC allocation is known, so the vessel planners make a bay plan, solving the QCSP. Once the plan is finalized it is sent to the Execution department.

2.1.3 Departments

There are three departments involved in the planning process. The Sales department has a minor role and determines the pro forma schedules, based on long term capacity estimates. The Operational Planning Center (OPC) is responsible for the planning up to eight hours before the current time. The Execution department is responsible for the period between now and the next eight hours. Every morning there is a meeting with representatives of both departments to discuss the next 24 hours. Every eight hours there is a hand-over from the OPC to the execution department.

The OPC has three functions: it plans the mooring positions; QC allocations and makes the bayplans. These three functions are split between two groups of people, one group is responsible for the mooring position and QC allocation, this group is called berth planners. The other group works out the bay plan and is called vessel planners. These two groups work together closely, as a vessel planner needs to know where the vessel is located and which QCs are assigned to make a bay plan. The outcome of this bay plan provide a reliable estimate of the handling time, which can be used to improve the berth and crane plan.

In the current situation, there are three berth planners on a day shift and two on an evening shift and at weekends. Each berth planner focuses on one type of call, deep-sea, feeder or barge, in the evening and at weekends the functions are combined. The two major tasks of the berth planner are receiving and updating all information and making the complete plan. The updates concern all kinds of information, ranging from delays to updates on the number of container moves. In addition to new information from the container shipping companies, internal information can also change, such as the number of available QC teams and QC/quay maintenance.

2.1.4 Timeline of a call

There is a timeline that every individual call follows. This timeline differs slightly between deep-sea and feeder vessels. Figure 2.2 visualizes a timeline of a deep-sea call.

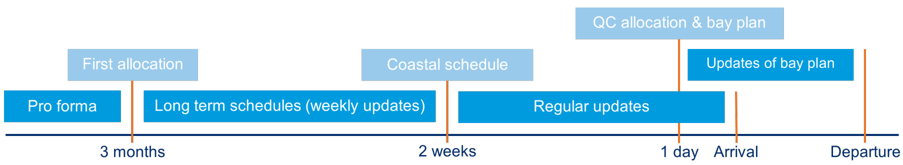


FIGURE 2.2: Timeline of a deep-sea call

The pro forma schedule forms the basis for the planning of deep-sea vessels. However, the pro forma windows in the schedule are placeholders, they need to be filled with actual vessels to form a plan. Approximately three months in advance, the container shipping company announces in the so-called long term schedule which vessel will arrive next. This is the moment that the vessel is scheduled in the planning software. The vessels are planned in their pro forma windows and the contractual number of container moves are entered.

Once a week, every container shipping company sends these long term schedules that contain all vessels that will call in the next three months. It contains information on the number of container moves, ETA, preferred departure and draft. The already scheduled calls are then updated with new information and new calls are entered into the planning software. Two weeks in advance, the planning receives the coastal schedule for the specific vessel. The coastal schedule contains a more reliable ETA, an update of the load estimates and information about the draft of the vessel at arrival. In most cases, the number of containers to unload is known, as the vessel has departed at the last terminal and does not call at any terminal on the route to the terminal.

The ETA estimate of the coastal schedule is very reliable in case the vessel comes from outside Europe directly to the terminal. If the vessel visits other ports in Europe before it visits the terminal, it is less reliable, as delays might develop in other ports. In the last two weeks before the actual arrival, minor updates in ETA and the number of container moves are received regularly via phone and email.

A week before the actual arrival, QCs can be allocated to the vessel to get a better view of the plan. If too few QC teams are available, the planned BPs cannot be achieved and the vessels have to be delayed. One day before the actual arrival, when the actual number of available QC teams is known, the berth planner finalizes the QC allocation for the vessel. Based on this allocation, the bay plan is made. The bay plan provides insight into the actual service time of the vessel, which helps the berth planner to further improve the plan. The berth planner uses the actual service time to update the plan, in case the service is finished earlier than expected other vessels can moor earlier. In case the service time is longer than expected, the berth planner has to delay other vessels or assign more QCs. In case the number of assigned QCs is changed, a new bay plan is made. This is a continuous loop between the number of assigned QCs and planned service time.

Compared to deep-sea vessels, feeder vessels travel shorter distances and call at more ports. This makes it a more dynamic type. Feeder calls are entered in the planning software seven days in advance. Feeder vessels can be announced earlier, but the calls are only entered seven days in advance to limit the number of changes that have to be processed. If a container shipping company announces a vessel, they share the ETA, preferred departure and the number of container moves.

FIGURE 2.3: Timeline of a feeder call

The berth planner plans the vessel on the first possible free position after the ETA. To estimate the service time, they use historical data and experience. In most cases, a feeder vessel is serviced by one or two QCs, which makes it relatively easy to predict service time. In the period until arrival, it often occurs that the ETA or the number of container moves change, these changes are constantly processed by the berth planner.

The process for the QC allocation and crane plan is the same as for the deep-sea vessels. Based on the crane plan, the berth planner can enter a better estimate for the actual service time. In case a conflict with another vessel arises or in case a free place comes available, the berth planner has to change the plan. Figure 2.3 provides an overview of the complete timeline for a feeder call.

The planning department also actively updates all container shipping companies on the current state of the plan. For feeder vessels, three times a day an overview of the current berth and crane plan for the next 72 hours is sent to all container shipping companies. For deep-sea vessels, every day an overview of the current berth and crane plan for the next two weeks is sent to all container shipping companies. In addition to the daily update, weekly conference calls take place with some container shipping companies. In these conference calls the coming period, as well as other notable things, are discussed.

2.1.5 Resources

To service vessels, two resources are required, QCs and QC teams to operate the QCs. The availability of resources changes every day. The QCs might be unavailable due to breakdowns, maintenance, while personnel can be unavailable due to being ill or having a day off. The planners receive information on the available resources regularly. The QC/quay maintenance is scheduled in a weekly meeting between the planner and the technical department. In some cases, maintenance or repairs cannot be delayed, but in most cases, the operation has priority over maintenance. Although the plan is made a week in advance, last moment changes, such as planning extra maintenance or putting a QC back into operation, can often be implemented.

For the number of QC teams, a forecast for the next seven days is available. For each shift, 21 in total, the expected number of available QC teams is provided. The forecast is based on absenteeism rate, requested days off and other data and is updated once a day by the HR department. Based on the available work, the resource planner orders the required number of QC teams. Once the actual number of available QC teams is known, the resource planner finalizes the berth and crane plan. If all requested QC teams are available, little has to be changed. However, when fewer QC teams are available QCs that were scheduled cannot be operated and changes in the plan have to be made. In some cases, this results in new crane plans, which in turn result in changes in service times.

2.1.6 Quay layout

A vessel can moor at any position along the quay at the terminal. However, the mooring lines are connected to the closest bollard, both at the front and back of the vessel. Bollards are large poles on the quay that vessels use to secure their mooring lines, these bollards are 25 meters apart from each other. We call the space between two consecutive bollards a quay section. As the mooring lines of vessels cannot cross each other, the space allocated to a vessel always consists of a set of consecutive quay sections that have no overlap with other vessels or mooring lines. In the example of Figure 2.4 Vessel 2 is allocated quay sections 10 to 15. Effectively, this setup forms a continuous quay layout with partitioning of 25 meters, the space between two bollards.

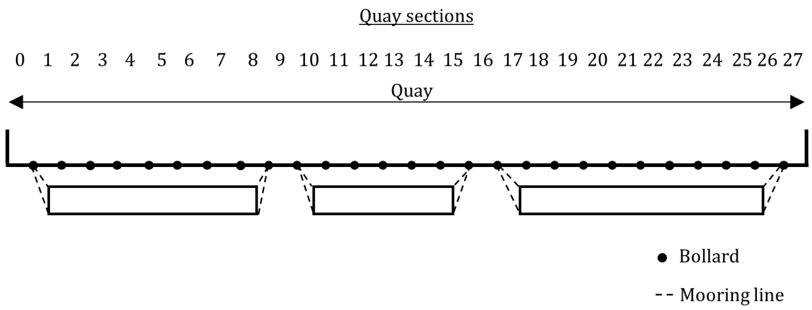


FIGURE 2.4: Quay layout with three vessels moored at bollards

Although the quay layout is continuous, the planners try to maintain a structure in the berth plan. Most of the time the deep-sea vessels are in the same positions. Feeder vessels and barges are interchanged sometimes. The main reason for this structure is the depth along the quay and the heterogenous QCs, not every QC can service every vessel optimally. It also occurs that two smaller vessels use the place of a large vessel. In case of disturbances or other exceptional circumstances, the structure is loosened and vessels are placed more flexibly.

2.1.7 Stakeholders

There are multiple stakeholders with an interest in the plan, both internally and externally. The most important stakeholder is the customer, the container shipping company, which is external. They desire the best service for the lowest cost. Good service for a container shipping company includes a mooring position available when the vessel arrives and quick service. An important factor is the reliability of the plan, container shipping companies do not want constantly changing arrival and departure times. In case the vessel has to wait it can reduce its speed to reduce fuel cost, but once it is delayed it is difficult to speed up again. Therefore, changes in the plan should be minimized.

Internal stakeholders are general management, the sales department, the maintenance department and the execution department. The general management is interested in meeting the agreements most efficiently. The agreements should be met, such that no penalties are received, but resource usage should be minimized to save expenses. For the maintenance department it is important to ensure high availability of the equipment, however, this requires maintenance. Therefore, the maintenance department needs to get enough time for maintenance. However, this means that the equipment is not available for servicing vessels.

The sales department makes the agreements with the customers. If these agreements are not met, the terminal is penalized and the customer is dissatisfied. If the agreements are not met too often, the customer might move to another terminal. Therefore, the sales department often prefers giving priority to vessels that tend to miss the agreements.

For the execution department, it is most important to have a workable plan. Too optimistic planning results in delays in practice. Furthermore, a plan with many changes in allocated QCs is undesired, as every change costs time. It is also desirable to spread the workload, such that all QC teams can be allocated the whole shift. Another desire is a reliable plan; last moment changes are undesirable and cost a lot of time to process.

2.1.8 Performance and dynamics

Company X monitors individual aspects, but there is no single KPI to evaluate the performance. Individual departments track their performance, but there is no overall objective that is tracked. This is partly due to the limited logging of data, the ETA of a vessel is stored only in a text field, for example, this data is not processed further. Based on the available data it is possible to draw several conclusions, we discuss the analysis of the data in more detail in Appendix B.

Deep-sea vessels arrive with a deviation of approximately two days in about half of the cases, the average is a delay of five days. For feeder vessels, approximately 80% has a deviation of two days. Unfortunately, it is not possible to determine if the delay was caused by Company X or had another cause. The scheduled time of arrival is updated 11.8 times for deep-sea vessels and 12.2 times for feeder vessels. The call sizes are relatively reliable, for both deep-sea and feeder vessels 80% of the calls have a deviation between the estimated and actual call size of less than 5%. The call size is changed approximately three times on average for both vessel types.

As the preferred time of departure is not stored, it is difficult to discuss the performance of that aspect. However, there is data available about the scheduled time of departure: 92% of the deep-sea vessels have a maximum delay of five hours while 80% of the feeder vessels have a delay of fewer than 50 minutes. This shows that planners are very good at estimating service times or build in sufficient slack. The average QC split for deep-sea vessels is 3.4 and for feeder vessels 1.2, however, it is not possible to indicate performance from this, as there are too many influences on the QC availability that lay outside the scope of planning.

Another KPI that provides some insight into the performance is the quay occupancy. The usage of available capacity (length * minutes) fluctuates between 70% and 90%. A higher occupancy is not always better, if vessels have a long port stay it might cause severe delays while at the same time the quay occupancy is high. Therefore, it is infeasible to conclude anything based on the quay occupancy.

2.2 Factors and constraints

The main goal of this section is to get insight into the objective and all factors that a planner takes into account when making a plan. First, we discuss the factors related to the plan, which we divide into two categories, “location and time” and “service time”. We translate most of these factors into constraints, for some factors we indicate that they are based on experience and difficult to translate into a constraint. Based on the factors we construct and quantify the objective function next.

2.2.1 Factors related to the plan

A factor is an aspect that is taken into account by a planner when making a plan. Most of these factors can be directly translated into constraints. However, some of these factors represent (part of) the objective function or cannot be translated into (hard) constraints as they are based on/require experience or expectations.

To structure the overview of factors, two groups are made. The first group, location and time, concerns factors that determine when and where a vessel is placed or moved to in the plan. Figure 2.5 provides an overview of all these factors. The second group, service time, involves the time that it takes to service a vessel, Figure 2.6 shows these factors.

The two groups are tightly connected and interact with each other. If a long service time is expected the vessel might not fit in a specific place in the plan, but at the same time, the service time is partially determined by the place in the plan. On the other hand, if a vessel is placed in a certain place in the plan it might result in a longer service time, as fewer resources are available at that moment.

2.2.2 Location and time

The group of factors concerning location and time can be subdivided into four categories. The first category of factors that a planner has to take into account for scheduling a vessel is the physical constraints. The most obvious factor is the length of the vessel. The vessel should fit between other vessels along the quay. In case ShoreTension (a dynamic mooring system[1]) is used, extra length along the quay is needed to moor the vessel. In addition to the length, the width also plays a role, as not all QCs can span over the broadest vessels. The third factor concerning the physical dimensions is the draft of the vessel. The waterways to the quay are deep enough, however, the depth along the quay is limited. Therefore, not every vessel fits in every position. The draft is important during arrival and departure, but also during service. If the vessel is loaded on one side first, it will be heavier on that side and it might touch the ground, which should be prevented. Another factor that is relevant in this respect is the tide, a vessel loaded to full height in combination with high tide might not fit under a QC.

The second category of factors covers the resources on the quay. An obvious factor is the availability of the quay, it regularly occurs that the quay needs to be maintained and therefore some sections of the quay might be unavailable. The same holds for the QCs, which need regular maintenance and repairs as well. In case a QC stands still due to maintenance it is called

[1] https://shoretension.com/

'dead'. The planner needs to think about where these dead QCs are placed, as it influences the range of movement of other QCs. The quay has a limited number of AGV lanes, as each QC needs one or two AGV lanes, and the number of QCs that can work on a vessel simultaneously is limited.

The yard spans from the start to the end of the quay and is divided into sub stacks, with one ASC per sub stack. As soon as a vessel is entered into the system, a range of sub stacks close to the mooring position of the vessel is selected. All containers that arrive for this vessel will be stored in this range, such that the driving distance for the AGVs is as short as possible. If a vessel is moved along the quay, the selected range will adapt as well. However, the containers already present in the yard will not follow immediately, the system of ASCs and AGVs needs time to move these containers. Moving the containers costs time and resources, which are taken away from the capacity for loading and unloading vessels that are currently present. These cost are also known as housekeeping cost.

Apart from the place of storage of the containers, the number of containers is also relevant. If the yard is close to its capacity, productivity will drop quickly. Therefore, calls, where many containers are unloaded, should be alternated with load calls. This is extra important for reefers, special containers that need a power supply to maintain a set temperature inside the container. The number of reefer plugs on the terminal is limited, therefore close attention needs to be paid to the occupancy of the reefer plugs. It is undesirable to have multiple vessels unloading many reefers at the same time.

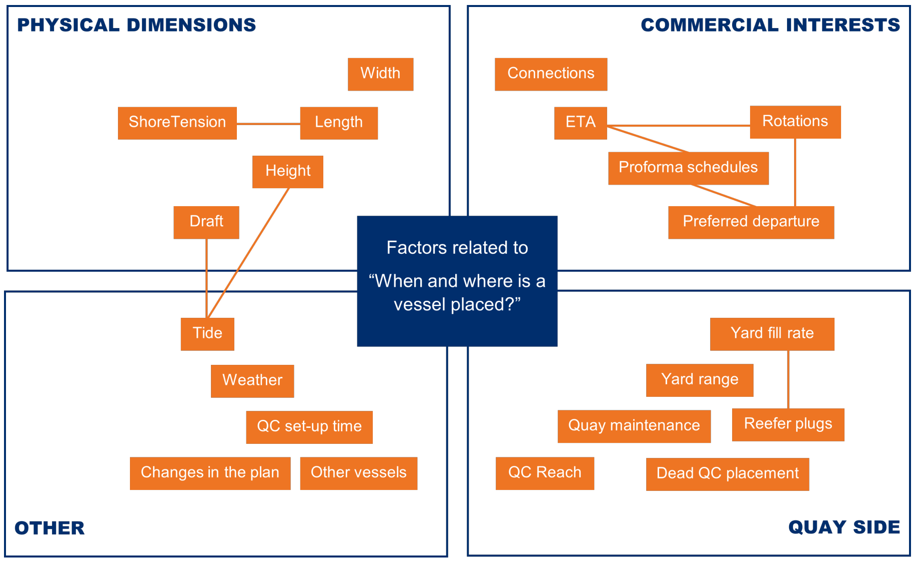


FIGURE 2.5: Factors related to 'When and where'

The third category of factors concerns the factors related to commercial interests. The most important factor is the pro forma schedule, the agreements from the pro forma schedule should be fulfilled. Two other factors are the ETA and the preferred departure time. Planning a vessel before the ETA does not make sense, as the vessel will not have arrived yet. The preferred departure time is the time that the vessel wants to depart to the next port. It often happens that a vessel cannot be serviced in another port yet, this extends the preferred departure time.

In some cases, the ETA and preferred departure time also depend on the rotation of a vessel. Some vessels visit several terminals in the same port, the order in which they do this is called the rotation. The container shipping companies try to create the most efficient sequence to visit all terminals, often resulting in a departure time at one terminal close to the planned arrival time at the next terminal. The planner has to make sure that these plans are realistic and sailing time is not underestimated. Another factor related to commercial interests is connections. In some cases, one vessel loads a big portion of the containers that are unloaded from another vessel. Therefore, the loading vessel must have a place in the plan after (or during) the unloading vessel.

There are a few other factors that are relevant but do not fit in a category. The QC set up is one of these factors. If a new QC crew starts working on a vessel, they need to start up the QC. This includes walking to the QC, starting it and moving it in the correct position along the vessel. If this is done just before the end of the shift, the setup will take longer than the actual working time, which is inefficient. Therefore, it should be prevented that QC teams work on vessels for short periods, unless it concerns finishing the service of a vessel.

The weather also influences the plan, there are regulations for when vessels can arrive, be serviced or depart. In some cases operations have to be stopped or delayed due to the weather. Planners also take into account which other vessels are in the plan. They prefer to put vessels of the same container shipping company or alliance behind each other, as a container shipping company also harms itself when it delays the previous vessel.

The tide also plays a role for the terminal and is closely related to the draft of a vessel. There are two issues related to the tide: fully loaded vessels at high tide might not fit under the QCs, therefore these vessels need to moor at low tide. On the other hand, fully loaded vessels are often heavy, which means they have a high draft. Therefore, they might not be able to moor at low tide because the quay along the mooring position is too shallow.

Before making a change, the planner considers if the benefits outweigh the disadvantages. An example of a disadvantage is that in case a vessel is replanned to another position, all containers that are in the yard already need to be moved. This means that AGVs need to move all containers, which results in extra traffic and possible delays if there are many containers to move.

Another example is the arrival time of a vessel, deep-sea vessels prefer to sail as slow as possible to save fuel. If the start of service is delayed two days before the planned arrival time while the vessel has almost arrived, the vessel could have sailed slower and saved more fuel. Therefore it is important to consider the disadvantages of making changes, reliability and consistency of the plan are important for all parties.

2.2.3 Service time

The group of factors concerning service time can be divided into two categories. The first category of factors that a planner has to take into account for determining the service time concerns the QCs. First, QCs should be available to service a vessel. Inoperable QCs, due to maintenance or repairs, cannot be scheduled for service. If QCs are available they should be of the right type. Not all QCs can service all vessels, as there are weight and height restrictions. Moreover, not all QCs are equally efficient for every vessel. A barge can be served by a deep-sea QC, but it is not very efficient which results in low production. The third factor is the maximum QC split, which is the maximum number of QCs that can work on a vessel simultaneously. In some cases, scheduling extra QCs is not useful, as they do not all fit next to the vessel or because all containers are located in the same bay in the vessel.

Another relevant factor is the number of container moves, this largely determines the service time. More container moves mean a longer service time. There is a slight difference between loading and unloading containers, unloading is faster than loading. In principle, the number of container moves follows from the pro forma schedule or the announcement. For servicing vessels, QC teams are needed, this is another factor. A vessel cannot be serviced if there are no QC teams available.

For calls visiting based on the pro forma schedule, there are contractual agreements about the BP. These contractual agreements are a factor that the planner has to take into account, if the production is achieved it is not necessary to appoint more resources. In case the planner does not have sufficient resources the 'pain' is often divided equally. This means that the resources are shared over the vehicles in proportion, such that the delays are approximately equal. The contractual productions can be used to determine priorities.

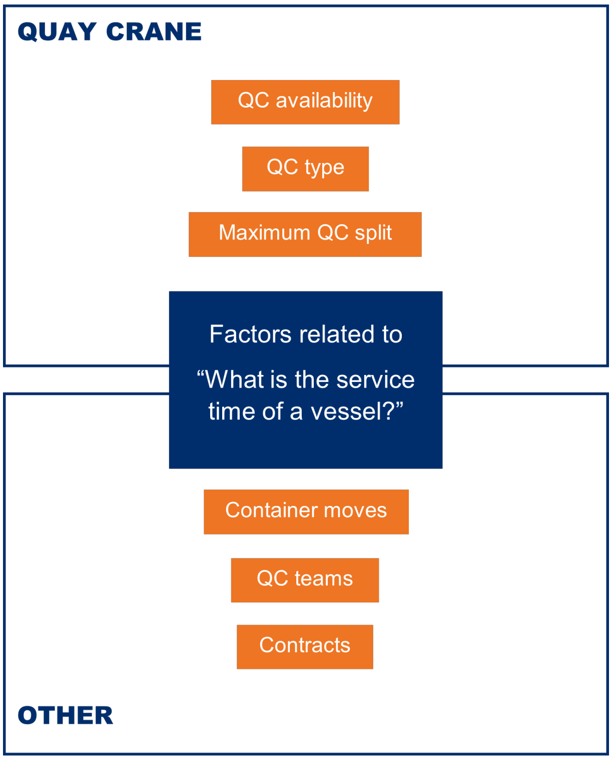


FIGURE 2.6: Factors related to 'service time'

2.2.4 Objective

The objective of the planners is formed by three components, as shown in Figure 2.7. For the customer, good service is important. Good service includes minimization of waiting time until mooring, a low port stay, on-time departure and a reliable plan with few changes, which relate to the factors currently taken into account by the planners. For Company X it is important to provide the service efficiently, minimizing the usage of costly resources such as QC teams and AGV kilometres for example. The last component is the total volume processed, a higher volume means more revenue. In the remainder of this section, we explain these components in more detail and formulate an objective function.

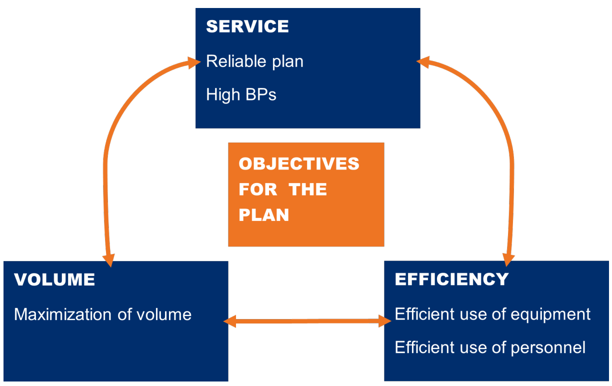


FIGURE 2.7: Objectives for the plan

Service

For a container shipping company, the ideal process is mooring immediately after arrival in the port, a service with a BP that is at least the contractually agreed value and a departure at the preferred time of departure. However, this ideal process does not take place often. If there is no place at the terminal, vessels have to wait at the anchor point before they can moor. In case this is known a few days in advance then vessels can change their scheme and sail slower to arrive later. A late arrival has as a consequence that the port stay shortens, as the preferred time of departure should still be met. To shorten the port stay, the BP should be increased. In case this is not possible, the vessel will depart with a delay. The delay is the most important measure of quality, if a late arrival can be compensated with faster service then the vessel can depart on time which means that the schedule of the vessel is not impacted. In case a vessel arrives with a significant delay, it is important that the delay does not increase. For all vessels that sail in a service and arrive in their pro forma window, penalties for caused delays are higher compared to vessels that arrive out window or have no pro forma window.

Volume

As Company X is paid per handled container, one of the objectives is to maximize the volume handled. However, Company X can only partially determine which vessels visit the terminal. Company X cannot reject vessels that visit the terminal based on the pro forma schedule. Furthermore, as the terminal is a multi-user terminal, Company X has a relationship with multiple customers. If the customers are not satisfied and terminate the collaboration, Company X becomes too dependent on the other customer(s). To keep a good reputation, Company X rarely refuses a vessel.

Efficiency

Company X provides the resources to service a vessel; to save expenses these resources should be used as efficient as possible. The quickest way to service a vessel is by allocating as many resources as possible. However, that is not the most efficient approach as some resources might become idle for certain periods. The resources are the QC teams, QCs and AGVs. By equalizing the workload peaks, the number of QC teams needed can be reduced. Furthermore, by mooring vessels closer to the containers, the AGVs drive fewer kilometres. By minimizing the number of QC changes, less time is wasted on moving the QCs. From an efficiency perspective, no more than the resources needed to meet the objective should be allocated.

Quantification

Quantification of the objectives enables a comparison of plans. Therefore, we set up an objective function for a plan. To represent the service level, a penalty is added for each hour of delay, this links to the factor preferred time of departure. The penalty is higher for vessels that arrived in window, linking to the factors preferred time of departure, pro forma schedules and contractual agreements.

To represent the volume, a penalty is included for every vessel that is deferred to outside the scope of seven days. This option is preferred over a bonus per handled container as that results in an undesired preference for deep-sea vessels, as the number of container moves is generally higher compared to feeder vessels.

The efficiency objective is represented by three parts. By including the cost of each QC setup and QC team allocation, the usage of resources is balanced with other objectives. The third component is the kilometres driven by the AGVs, which incorporates the soft constraint resulting from the factor yard range. This component is also known as the housekeeping cost.

2.3 Summary

With approximately [redacted] calls of deep-sea and feeder vessels at the terminal per week, there are many trade-offs to make in the planning process. The current planning process has several phases, where the availability and certainty of the needed information increases in every phase. The complexity of the planning process also increases in the phases closer to the current moment. All these processes are performed by the OPC.

The OPC is also in charge of balancing the interests of all stakeholders. The external stakeholder is the customer, the internal stakeholders are the general management, the maintenance department, the execution department and the sales department. The interests of the customer and the general management are partly conflicting, for the customer speed and reliability are most important, while for the general management efficient use of resources is a priority. The sales department is most interested in a satisfied customer, while the execution department desires a workable plan. The maintenance department needs sufficient time to perform maintenance.

The current logging of data is limited, which makes it challenging to get insight into the performance and trade-offs that planners make currently. The data analysis as discussed in Appendix B shows that the input for the plan is subject to many changes. The STA plan changes 12 times on average, while the allocated mooring position changes approximately 9 times. The call size is updated 3 times on average. In more than half of the cases, the BPs are not met and the port stay is often longer than contractually agreed. As there is no clear objective defined at this moment, it is difficult to quantify the quality of the plan to see if the planners made an adequate trade-off between all inputs and interests.

The objective consists of three components, service, volume and efficiency. We quantified these components into an objective function, where each component is translated into a value based on the related cost. This enables a balanced comparison of plans on all company interests. In total there are 29 factors that a planner takes into account when making a plan.

The most important factors that can be translated to hard constraints are the physical dimension constraints and the constraints related to arrival and departure time. Furthermore, the QC ranges and availability of QC teams are of major importance. We can simplify the problem by omitting the constraints related to maintenance, yard fill rate and relations between vessels, e.g. rotations, and connections. Furthermore, uncertain factors such as the weather and tide can be omitted, as well as situations that are that occur infrequently, such as ShoreTension.

The quay layout used on the terminal is continuous. The quay is divided into small sections using the bollards and a vessel is allocated a space between a range of bollards. However, planners try to maintain structure in the berth plan and keep vessels of the same type in the same positions.

Chapter 3

Literature review

The main goal of the literature review is to answer the third research question: *'Which solution methods are suitable for the case of Company X?'*. To answer this question we study the available literature. The literature review discusses all objectives and constraints as discussed in recent works that (partially) overlap with the problem as defined in this research. The exact problem formulation and the contributions of this research to the body of knowledge are discussed in Chapter 4. However, Section 3.2 discusses the most important features of the problem and the components of the objective.

Section 3.1 gives a helicopter view of the first developments of the BAP and discusses two classifications developed by well-known authors in the field of the berth allocation problem. Section 3.2 discusses all features that are used commonly and are relevant for the case of the terminal. Section 3.3 contains an overview and discussion of recent works. It discusses both the set of features and the solution methods. Several components can be used in an objective function, Section 3.4 discusses this. Finally, Section 3.5 summarises the literate review and sums up the identified gaps, such that we can indicate the contribution to the scientific body of knowledge.

3.1 First developments BAP and classifications

On a container terminal, several logistical processes come together. By using operations research techniques, processes can be improved, enabling performance improvements. Examples of operations that can be improved by operations research techniques are container stowage, berth and QC allocation, and scheduling of SCs and AGVs (Bierwirth and Meisel, 2010; Meersmans and Dekker, 2001). The planning of the quay and allocations of QCs are the focus of this review.

The challenge of allocating vessels to the available berths is known as the Berth Allocation Problem (BAP) (Bierwirth and Meisel, 2010). One of the first studies of the BAP is Lai and Shih (1992). They test several allocation strategies and evaluate these strategies for three objectives. A slightly different problem is analysed by Gerald, Lawphongpanich, and Katie (1994), who study changing berths within one harbour for naval purposes. Imai, Nishimura, and Papadimitriou (2001) is the first to tackle the BAP with dynamic vessel arrival times (DBAP) after the BAP with static arrival times (SBAP) was analysed in 1997 (Imai, Nagaiwa, and Tat, 1997). The SBAP assumes that all vessels to be scheduled are present in the port, while in the DBAP vessels also arrive during the scheduling period.

The DBAP is a more realistic approach compared to the SBAP, as vessel arrival and departure is a continuous process, so vessels can arrive during the planning horizon. Imai, Nishimura, and Papadimitriou (2001) tackle the DBAP using a heuristic based on the Lagrangian relaxation and successfully perform calculations with problem sizes of 10 berths with 50 ships. Their objective is to minimize the sum of waiting and handling time of all vessels (Imai, Nishimura, and Papadimitriou, 2001). A different approach is taken by Kim and Moon (2003), they use Simulated Annealing to optimize the berthing locations and minimization of delays. These papers assume that handling times are either fixed or depend on the allocated berth.

The problem of allocating available QCs to scheduled vessels is called the Quay Crane Allocation Problem (QCAP) (Bierwirth and Meisel, 2010). Park and Kim (2003) are the first to come up with a solution for the combined BAP and QCAP. Their approach is not a joint optimization, but a sequential optimization. The berth allocation is optimized using a subgradient optimization procedure followed by a QC assignment using dynamic programming. The solution has a run time of approximately ten minutes, for a problem with 40 vessels and nine QCs. All these solutions take into account only a limited number of features.

In the following years, numerous papers on both the BAP alone and the combination of the BAP and QCAP were published, including an increasingly diverse and complete set of features. To create an overview of all available literature and to provide structure for modelling problem characteristics, Bierwirth and Meisel (2010) surveyed berth allocation and quay crane scheduling problems. In 2015 they published a follow-up of the survey that includes the newest trends in the field (Bierwirth and Meisel, 2015).

The classification scheme of Bierwirth and Meisel classifies papers into four categories; spatial attribute; temporal attribute; handling time attribute and performance measure (Bierwirth and Meisel, 2010; Bierwirth and Meisel, 2015). The spatial attribute describes the quay layout and water depth restrictions. The temporal attribute describes constraints for the service process. The way that handling times are considered is described by the handling time attribute and the objective of the optimization problem is given by the performance measure (Bierwirth and Meisel, 2010; Bierwirth and Meisel, 2015).

Another way to classify solution methods is by the planning level that is considered. Iris, Lalla-Ruiz, et al. (2018) define the strategic, tactical and operational levels. The strategic level concerns the time horizon from one year to several years and includes decisions such as contractual agreements and investment in resources. An example of the tactical level is the pro forma schedule, where weekly visits are planned. Most research focuses on the operation level, which includes daily planning (Iris, Lalla-Ruiz, et al., 2018).

3.2 Objectives and Features

For each problem, there is an objective to fulfil. In many cases the objective is to minimize the total cost, however, there are many variants. Next to the objective, a solution method includes multiple features. Including more features makes the problem more realistic and complete, but often also more complex. This section discusses the objectives and features that are common in recent literature. Furthermore, it discusses the most important objectives and features in the problem as formulated in this research to find comparable problem settings.

3.2.1 Objectives

Table 3.1 enumerates four classes of components present in objective functions. The group of time components consists of the total service time, tardiness or other objectives related to arrival and or departure time. The second group is based on resource usage, for example, the total number of QCs allocated or the total personnel cost. The third category is penalties for unprocessed workloads, such as the number of vessels that are not planned. The last category is the elements for the deviations from the best mooring position.

The objective of this study is to minimize the total cost of several elements, Section 4.2 discusses the objective in detail. The first element is the cost of departure delays. The second element is in the same category and adds cost for all vessels that are deferred outside the time horizon of the problem. The third element includes the cost for the usage of resources (QCs and QC teams) and AGV KMs, which is in the category of deviations from the best mooring position.

3.2.2 Features

In the past years, both the variety and number of included features have increased. In this literature study, we make an overview of the features that are present in our problem and are discussed in recent research.

The BAP in this study has a continuous quay layout where a vessel is assigned a space between two bollards. This should include the length needed for mooring. The depth along the quay should be sufficient for the vessel draft. Each vessel has a preferred mooring position that is optimal in relation to the containers that it (un)loads. The vessel should be placed along the quay such that sufficient QCs can reach the vessel to service it. For the QCAP, each QC has a range on the quay that it can reach and they can be moved during service. There is no minimum number of QCs that should service a vessel simultaneously, but there is a maximum due to practical and safety constraints. For each vessel, it is known what the ETA and desired departure time are. There are no hard constraints on time windows.

Several features are part of the actual problem but not desired in the solution method developed in this research to keep the scope reasonable. Connections between vessels are not taken into account in this problem. In addition, QC availability is ignored and all QCs are assumed to be of the same type. However, the features are included in the overview for future research.

Table 3.1 explains all these features that appeared in recent studies. The table includes features that occurred in at least one of the discussed studies and overlap with this research. We divide the features into five categories, the first one contains information on the layout of the quay. The second and third categories are the vessel and call details, and the fourth category contains the times of the call. The last category concerns the QC details. For the objective function, four components are identified.

3.3 Comparable problem settings

To find a solution method for the case of the terminal, it is useful to look at other works. For similar sets of features, similar solution methods might be useful. The objective function is generally less important, as incorporating extra components is a minor task. Table 3.2 provides an overview of several recent works. It gives an overview of which problems are solved, which features are included and which components the authors use in the objective function.

The table includes papers that discuss the operational BAP and a form of QC allocation and have an (partial) overlap with features present in our problem. Several authors combine the BAP and QCAP with the QC scheduling or Yard planning (Ma et al., 2019; Meisel and Bierwirth, 2013; Türkoğulları et al., 2016). Further integration of problems often increases the efficiency, however, for this study it is outside the scope. The studies are included as the solution methods could also be used for the BAP and QCAP itself by omitting the elements for the QC scheduling or Yard planning.

As Table 3.1 depicts, most recent papers focus on a continuous quay layout, and only a minority of the authors use a discrete set up of the quay or a combination (X.-l. Han, Lu, and Xi, 2010; Liang, Huang, and Y. Yang, 2009; Türkoğulları et al., 2014; Xiang, C. Liu, and Miao, 2018). In the case of the terminal, a vessel can be moored at every bollard, so the quay layout can be seen as continuous. However, recent studies that have a discrete quay layout with features that overlap with our problem are included in the table.

TABLE 3.1: Overview of features and objectives discussed in this literature study

Features	Quay Layout	Continous	The quay is divided into sections and a vessel can moor at any section or the vessel can moor at any position
		Discrete	The quay is divided into multiple berths
		Hybrid	The quay is divided into multiple berths, but a single berth can be shared by multiple vessels
		Discontinuous	The quay is not one stretch but has a bend or other form of separation
	Vessel	Length	The length of the vessel
	Call	Draft	The draft of the vessel at arrival/during service/at departure
		Best mooring position	The preferred place for mooring, where the vessel is closest to the containers in the yard
		Connections	Containers that are unloaded from one vessel and loaded on another vessel
		Number of container moves	The number of discharged/loaded/restowed containers
	Times	Desired departure	The desired departure time of a vessel
		ETA	The expected time of arrival of a vessel
	QC	QC Reach	The reach of a QC along the quay
		Changeable QC allocation	A QC can start or stop service on a vessel, even if the service is not completed yet
		Unchangeable QC allocation	A QC cannot stop service on a vessel if the service is not completed yet
		Variable QC availability	The number of available QCs varies during each time interval
		QC types	The available QCs are heterogeneous and have different characteristics
		Minimum QCs	The minimum number of QCs that has to work on a vessel simultaneously
		Maximum QCs	The maximum number of QCs that can work on a vessel simultaneously
Objectives	Time/service		The service time, tardiness or other time-related values
	Resources		Use of resources, such as QCs
	Unprocessed workload		Containers that are not (un)loaded
	Deviation best mooring		Extra efforts for moving the containers to the vessel

3.3.1 Genetic Algorithms

The solution method that is represented the most in the selected literature is Genetic Algorithms (Chang et al., 2010; Juan Francisco Correcher and Alvarez-Valdes, 2017; X.-l. Han, Lu, and Xi, 2010; Lalla-Ruiz, González-Velarde, et al., 2014; Liang, Huang, and Y. Yang, 2009; C. Yang, X. Wang, and Li, 2012). Liang, Huang, and Y. Yang (2009) combine a GA with another heuristic as, according to them, a GA is useful for finding promising regions, but has difficulty finding the optima. They use a four-step procedure to solve the combined BAP and QCAP, with two operators for the GA: crossover and mutation. X.-l. Han, Lu, and Xi (2010) use GA to solve a problem with stochasticity incorporated, their chromosome is divided into two parts, one for the berth assignment and service sequence and one half for the assigned QC amount. If the GA process finds a better solution, then a local search heuristic is used to identify potential improvements in the same searching direction (X.-l. Han, Lu, and Xi, 2010).

To solve the BAP and QCAP sequentially, but with a feedback loop, C. Yang, X. Wang, and Li (2012) use an approach with two inner loops for solving the BAP and QCAP separately and an outer loop for the feedback loop. For both the BAP and QCAP, they use a GA, with chromosomes consisting of the service order and mooring positions for the BAP and the number of QCs appointed for the QCAP. In a comparison with Park and Kim (2003), C. Yang, X. Wang, and Li (2012) improve the BAP by 9.27% on average and the QCAP by 23.95%. The solution of Juan Francisco Correcher and Alvarez-Valdes (2017) also uses GA in combination with local search procedures. Their solution can provide good solutions for problems of up to 100 vessels, in line with realistic cases.

Lalla-Ruiz, González-Velarde, et al. (2014) also use Genetich Algorithms to solve the Tactical Berth Allocation Problem. Their method, the biased random key genetic algorithm (BRKGA), favor better solutions in the crossover process. Their genes consists of two parts, the first half determines the vessel berth links, while the second half determines the QC profiles. The QC profiles are also used in Giallombardo et al. (2010). Lalla-Ruiz, González-Velarde, et al. (2014) compare their performance with Giallombardo et al. (2010) and Vacca, Salani, and Bierlaire (2013) and are able to improve the outcomes with the BRKGA.

Overall, the discussed studies show that GA can successfully be applied to the BAP and QCAP, with a variety of features. GAs are often combined with local search heuristics. The studied implementations can solve cases of realistic sizes in reasonable time. However, none of the discussed papers has a similar set of features as the terminal case. Nonetheless, the studied implementations show that variation in the set of incorporated features is possible.

3.3.2 Other solution methods

In addition to GAs, other solution methods are regularly used. However, several of the works with other solution methods do not incorporate all features incorporated in the problem of the terminal. Park and Kim (2003) for example do not include the draft and QC reach and several other features. To solve their problem they use subgradient optimization for the BAP and dynamic programming for the QCAP. Meisel and Bierwirth (2009a)(2009b; 2013) also do not include these features, they use a collection of heuristics such as squeaky wheel optimization and tabu search to solve the BAP and QCAP.

Rodriguez-Molins, Salido, and Barber (2014) use a greedy randomized adaptive search for a problem set with a limited set of incorporated features. Raa, Dullaert, and Schaeren (2011) solve the same problem with the best mooring position as an added feature. They use a standard solver to find a solution for a specific period, based on the rolling horizon model that they use. Iris, Pacino, et al. (2015) use a generalized set-partitioning model to solve an extended model based on Meisel and Bierwirth (2009a). They support two versions of the QCAP, one where QCs can be moved during service and a version where this is not possible.

Hu (2015) and Karam and Eltawil (2016) solve the same problem, but only for the option where QCs are movable, they both use a set of heuristics. Hu (2015) uses a rolling-horizon heuristic and a neighbourhood search heuristic to solve the problem, with a focus on efficient QC utilization. Karam and Eltawil (2016) come up with a functional integration, where the BAP and QCAP are solved consecutively. However, the (possibly invalid) solution of the first problem is given back to the next problem and solved again. This back and forth between the two problems is repeated in a loop until a stable and valid state is found. The BAP and QCAP problems are solved using a CPLEX solver.

Juan F. Correcher, Alvarez-Valdes, and Tamarit (2019) and Türkoğulları et al. (2014) solve the BAP and QACP for similar sets of features, which only partially overlap with the terminal case. Agra and Oliveira (2018) incorporate a different set of features, they include the QC reach and heterogenous QCs, but there are no limits on the number of QCs used and the desired departure time of vessels is not included. All of these three studies use exact approaches, based on a Branch and Cut algorithm (Agra and Oliveira, 2018; Juan F. Correcher, Alvarez-Valdes, and Tamarit, 2019; Türkoğulları et al., 2014).

3.3.3 Similar features

X. Han, Gong, and Jo (2015), Ma et al. (2019), Türkoğulları et al. (2016), Xiang, C. Liu, and Miao (2018), and Zhang et al. (2010) incorporate a set of features in their approach that come closest to the case of the terminal. All of them include the Best Mooring Position, they have a changeable QC allocation and except for X. Han, Gong, and Jo (2015) they all include the desired departure time. Xiang, C. Liu, and Miao (2018) is the only work of these five that uses a discrete quay layout. Ma et al. (2019) and Türkoğulları et al. (2016) use an exact approach to solve the problem, while the other three use heuristics.

X. Han, Gong, and Jo (2015) do not include the desired departure, but they do take into account the QC reach and the variability in QC availability. Their approach has two phases, in the first phase the BAP is solved and the number of allocated QCs is determined, this is done using particle swarm optimization. In the second phase, specific QCs are assigned to the vessels. The solution method takes into account several objectives, namely the minimization of the service time of vessels and the cost of deviating from the preferred berth, balanced use of QCs in each shift and minimization of movement of QCs (X. Han, Gong, and Jo, 2015).

Ma et al. (2019) is the only paper of the studied papers that includes connections as a feature. Their focus is on discontinuous quays, instead of one quay, they split up the quay into multiple sections. The methodology that they use has six steps, of which the first two focus on the BAP and QCAP. This is then combined with yard planning, after which local refinement is applied. This process is repeated for every segment, after which a guided neighbourhood search is applied. The run times of the solution are significant, varying between 10 and 200 minutes.

Türkoğulları et al. (2016) solve both the BAP and QACP as well as the QCSP. They can solve this problem to optimality, but only for small instances. Therefore they decompose the problem into a relaxed master problem. The problem initially consists of all constraints for the BAP and QCAP, after which constraints for the QCSP are added using the cutting-plane method. The QCSP is outside the scope of this research, but the model for the BAP and QCAP is valuable, as it includes many relevant features.

Zhang et al. (2010) are one of the few to include QC reach as a feature. Their approach is a Lagrangian relaxation algorithm. Xiang, C. Liu, and Miao (2018) also include QC reach and many other features. Their problem setting is very similar to the case of the terminal. Their focus is on incorporating uncertainty, based on a baseline schedule they develop a reactive strategy that reacts to changes while minimizing the recovery cost. The features Variable QC availability is incorporated in this model, as one of the disruptions is a QC breakdown.

Xiang, C. Liu, and Miao (2018) call their solution method a rolling horizon optimization algorithm (RHOA). The algorithms divide the entire time horizon into sum problems, which are then solved to find optimal solutions. These sum problems are combined again to form a complete solution. RHOA can provide solutions for which a solver cannot find a solution in a reasonable time. Compared to the solution method of Türkoğulları et al. (2016) both objective values and run times are significantly reduced (Xiang, C. Liu, and Miao, 2018).

3.4 Objective function

The objective function is only part of the problem context. Adding extra (cost) components to the objective function is a minor task if the associated features are present in the problem.

To provide an overview of possible components in an objective function, this section discusses several objective functions that are used in studies for the BAP and/or the QCAP.

Two performance measures that are pursued frequently are the waiting time and handling time of vessels, also referred to as the service time (Cordeau et al., 2005; Imai, Nishimura, and Papadimitriou, 2001; Imai, Nishimura, and Papadimitriou, 2008; Lalla-Ruiz, Melián-Batista, and Moreno-Vega, 2012; Nishi et al., 2020; Nishimura et al., 2001; C. Yang, X. Wang, and Li, 2012). Some authors, for example Rodriguez-Molins, Salido, and Barber (2014), only look at the waiting time, while others only include the completion time (Agra and Oliveira, 2018). Many authors choose to use the sum of waiting and handling time of all vessels, such that a trade-off is made between the berth with the quickest service (handling time) and the time that is needed to wait until that berth is available (waiting time). A short port stay (waiting + handling time) is desired by container shipping companies. Several authors add weights to the objective function, such that priorities of certain vessels can be incorporated (Cordeau et al., 2005; Lalla-Ruiz, Melián-Batista, and Moreno-Vega, 2012; Nishi et al., 2020).

The waiting time and/or handling time performance measures are often combined with other measures to optimize for a more complete trade-off between performance measures. A frequently occurring combination includes tardiness, such that delayed departures are restrained (X.-l. Han, Lu, and Xi, 2010; Liang, Huang, and Y. Yang, 2009). Tardiness is undesired as vessels will arrive late at the next port, or need to speed up, leading to extra fuel costs. Several papers also include these speed up costs in the objective function (Hu, 2015; Iris, Pacino, et al., 2015; Ma et al., 2019; Meisel and Bierwirth, 2009a; Meisel and Bierwirth, 2013; Park and Kim, 2003). This is a realistic assumption for single user terminals, as speeding up might result in more efficient planning, improving the situation for all vessels. However, in a multi-user terminal, it is unlikely that a container shipping company will make extra fuel costs to help another container shipping company.

The position cost, which can cover preferred berths because of available resources or the movement of containers over the quay, for example, are also used as a performance measure frequently (Juan F. Correcher, Alvarez-Valdes, and Tamarit, 2019; Juan Francisco Correcher and Alvarez-Valdes, 2017; Giallombardo et al., 2010; X. Han, Gong, and Jo, 2015; Karam and Eltawil, 2016; Lalla-Ruiz, González-Velarde, et al., 2014; M. Liu et al., 2016; Raa, Dullaert, and Schaeren, 2011; Türkoğulları et al., 2014; Türkoğulları et al., 2016; Xiang, C. Liu, and Miao, 2018; Zhang et al., 2010; Zhen, Lee, and Chew, 2011). Most authors do not take into account the cost of using resources, as they assume that a substantial part of the cost is already invested and does not depend on usage. If resource usage costs are incorporated, it concerns the prevention of unused QC hours (Chang et al., 2010; Giallombardo et al., 2010; Lalla-Ruiz, González-Velarde, et al., 2014; Liang, Huang, and Y. Yang, 2009; Meisel and Bierwirth, 2006; Meisel and Bierwirth, 2009a; Meisel and Bierwirth, 2009b; Meisel and Bierwirth, 2013; Raa, Dullaert, and Schaeren, 2011).

The vast majority of objective functions focus on the minimization of the total cost. The disadvantage of this approach is that one vessel may be significantly impacted to improve the situation for many other vessels. To counteract this, a minimization of the maximum value of a performance measure is chosen. J. Liu, Wan, and L. Wang (2006) use the maximum tardiness as an objective value. By taking this approach the pain is divided overall vehicles more equally.

3.5 Summary

The main goal of the literature review was to answer the research question: "Which solution methods are suitable for the case of Company X?" and sub-questions. To answer these questions, Section 3.1 discussed the first developments of the BAP and two classifications for the BAP and QCAP. Section 3.2 showed which features appear in the BAP and QCAP literature.

TABLE 3.2: Overview of comparable works

			This Problem	(Park and Kim, 2003)	(Meisel and Bierwirth, 2009a)	(Meisel and Bierwirth, 2009b)	(Liang, Huang, and Y. Yang, 2009)	(X.-l. Han, Lu, and Xi, 2010)	(Zhang et al., 2010)	(Chang et al., 2010)	(Raa, Dullaert, and Schaeren, 2011)	(C. Yang, X. Wang, and Li, 2012)	(Meisel and Bierwirth, 2013)	(Rodriguez-Molins, Salido, and Barber, 2014)	(Türkoğulları et al., 2014)	(Iris, Pacino, et al., 2015)	(X. Han, Gong, and Jo, 2015)	(Hu, 2015)	(Karam and Eltawil, 2016)	(Türkoğulları et al., 2016)	(Juan Francisco Correcher and Alvarez-Valdes, 2017)	(Xiang, C. Liu, and Miao, 2018)	(Agra and Oliveira, 2018)	(Juan F. Correcher, Alvarez-Valdes, and Tamarit, 2019)	(Ma et al., 2019)
Problem	BAP		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	QCAP		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	QCSP												x							x					
	Yard Planning																								x
Features	Quay Layout	Continous	x	x	x	x			x	x	x	x	x	x		x	x	x	x	x	x		x	x	x
		Discrete					x	x														x			
		Hybrid													x										
		Discontinuous																							x
	Vessel Call	Length	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Draft	x					x														x			
		Best mooring position	x	x	x				x	x	x				x	x	x	x	x	x	x	x		x	x
		Connections	x																						x
		Number of container moves	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Times	Desired departure	x	x	x	x	x	x	x	x			x		x	x		x	x	x	x	x		x	x
		ETA	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	QC	QC Reach	x						x								x				x	x	x		
		Changeable QC allocation	x	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x		x	x		x
		Unchangeable QC allocation					x								x	x					x			x	
		Variable QC availability	x														x					x			x
		QC types	x																			x	x		
		Minimum QCs		x	x	x			x			x	x		x	x		x	x	x	x	x		x	x
		Maximum QCs	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x	x
Objective	Time/service		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Resources		x		x					x	x	x	x			x	x	x		x		x			
	Unprocessed workload					x																			
	Deviation best mooring		x	x					x	x	x				x		x		x	x	x	x		x	x

The features were divided into several categories. There is a large variety of features that can be incorporated. For the objective function four components were identified.

The overview in Table 3.2 showed which features appeared in which studies. The analysis showed that many features appear in at least one study. We discussed these studies in Section 3.3. X. Han, Gong, and Jo (2015), Ma et al. (2019), Türkoğulları et al. (2016), Xiang, C. Liu, and Miao (2018), and Zhang et al. (2010) incorporate a set of features in their approaches that comes close to the case of the terminal. However, none of the studied papers provides a set of features that is identical to the case of the terminal.

To solve the combined problem, a variety of solution methods is used. The method that is used most often is the genetic algorithm. Furthermore, there are several heuristics, such as tabu search, squeaky wheel optimization, greedy randomized adaptive search and generalized set-partitioning models, that are applied to the BAP and or QCAP. Other methods are heuristics specifically designed for the BAP or QCAP. In addition to the heuristics, there are exact solutions, using solvers or a branch and cut algorithm. Many authors constructed linear programming models to solve the BAP and/or QCAP on a small scale.

Two of the most similar feature sets use an exact solution method (Ma et al., 2019; Türkoğulları et al., 2016). The exact method is an improvement compared to the work of Zhang et al. (2010) as they use a Lagrangian relaxation. Another heuristic used in a problem set that has similarities with the terminal case is a particle swarm optimization by X. Han, Gong, and Jo (2015).

The research that has the most similarities with the case of the terminal uses the rolling horizon optimization algorithm (RHOA) (Xiang, C. Liu, and Miao, 2018). This solution method offers outcomes that are (close to) optimal in a reasonable run time. We discuss differences between our problem and the existing literature in Section 4.5.

Section 3.4 discussed several objective function components in recent works. It shows that a variety of objectives can be included, as long as the related features are present. Most authors optimize for low handling and waiting times. Furthermore, the objective function often includes a component for tardiness and cost for deviations from the preferred mooring position, also known as housekeeping cost. A component that is used less often is the cost of the usage of resources. With all the available components, it shows that it is possible to optimize for many objectives. The objective for Company X can also be realised with the discussed components.

Chapter 4

Problem formulation

As discussed in the literature review, there are many forms of the BAP and QCAP. To clarify the exact problem discussed in this research and the contributions to existing literature, we give a formal problem definition and introduce all notation in this chapter. Section 4.1 provides this problem definition and discusses the decisions to be made. The objective of the problem is formulated in Section 4.2. Section 4.3 discusses simplifications that are made compared to the problem in reality while Section 4.4 discusses the constraints that remain. In Section 4.5 we discuss the difference between problem formulations in existing literature and our problem formulation. Section 4.6 summarizes the chapter.

4.1 Problem description

A plan is always made at a single point in time using the data that is available at the moment that the plan is made. The planning process starts with all vessels $v \in V$ that want to visit the terminal in the next seven days. For each vessel, the container shipping company provides the estimated time of arrival in the port (ETA_v), preferred time of departure (PTD_v), maximum draft during the stay of the vessel ($draft_v$) and the workload ($workload_v$), which is the number of container moves. In case the vessel arrival is in window, the preferred time of departure is the end time calculated using the contractual agreements. Otherwise the preferred time of departure is the time given by the container shipping company, with a minimum port stay of the time needed to handle the number of container moves given the corresponding BP.

Other characteristics that are specific to the vessel, such as the length of the vessel in meters $length_v$, the maximum number of QCs that can work on the vessel simultaneously $max/_qc_v$ and type, $type_v \in \{deep\text{-}sea, feeder\}$, are stored in the planning system. The type of the vessel provides information on the exchange time ex_v and the length needed for mooring the vessel mo_v. Furthermore, for every vessel it is known if the arrival at the port is according to the pro forma window, $window_v \in \{in\ window, out\ window\}$.

The quay is split up into sections $q \in Q$ of 25 meters, which is the space between two consecutive bollards. This discretization is done only for practical reasons, there cannot be two vessels in the space between two consecutive bollards because of the securing lines. We use a continuous quay layout as a vessel can moor at any quay section and uses multiple consecutive quay sections. Each section of the quay has a depth $depth_q$. On the quay, all $qc \in QC$ are mounted on rails. Each QC has a reach of quay sections that it can cover $[r\_start_{qc}, r\_end_{qc}]$.

For each vessel, the containers to load are stored in the yard. Using the yard storage software, the weighted centre position of all these containers is calculated. Based on this point and the vessel characteristics, the software determines in which quay section the front the vessel should be to minimize the total housekeeping cost. This quay section is known as $pref\_moor_v$.

The time horizon of one week is split up into time sections $t \in T$ of one hour. The time sections are divided over shifts $s \in S$, each shift consists of $shift\_len$ time sections, in the case of Company X this is eight. For each shift s, the number of QC teams available $team\_avail_s$ is known.

The two main decisions to make are when and where a vessel is moored and which QC(s) service(s) the vessel at which moment.

4.1.1 BAP Decisions

In the BAP, a range of quay sections and time sections are allocated to a vessel. Figure 4.1 shows an example of such an allocation of quay and time sections for a single vessel. The left-most quay section that the vessel uses is referred to as $vessel\_start_v$ and the rightmost quay section used by the vessel is $vessel\_end_v$. In addition to this range, extra space is needed for securing the vessel. The left-most quay section used for securing the vessel is referred to as $reserved\_start_v$, the right-most section is $reserved\_end_v$. The ranges $[reserved\_start_v, vessel\_start_v)$ and $(vessel\_end_v, reserved\_end_v]$ are the ranges reserved for securing the vessel, the vessel itself is not present along these quay sections, but the securing lines are.

The first time section during which the vessel is serviced is referred to as $start\_time_v$, the last time section during which the vessel is serviced is $completion\_time_v$. In the period $[start\_time_v, completion\_time_v]$ the vessel is serviced and QCs can be allocated to the vessel. In addition to this period, the vessel needs time to arrive and depart, this time is denoted as exchange time. The first time-section allocated to the vessel is $arrival\_time_v$, the last time section is $departure\_time_v$. In the period $[arrival\_time_v, departure\_time_v]$, the vessel is denoted as 'present'.

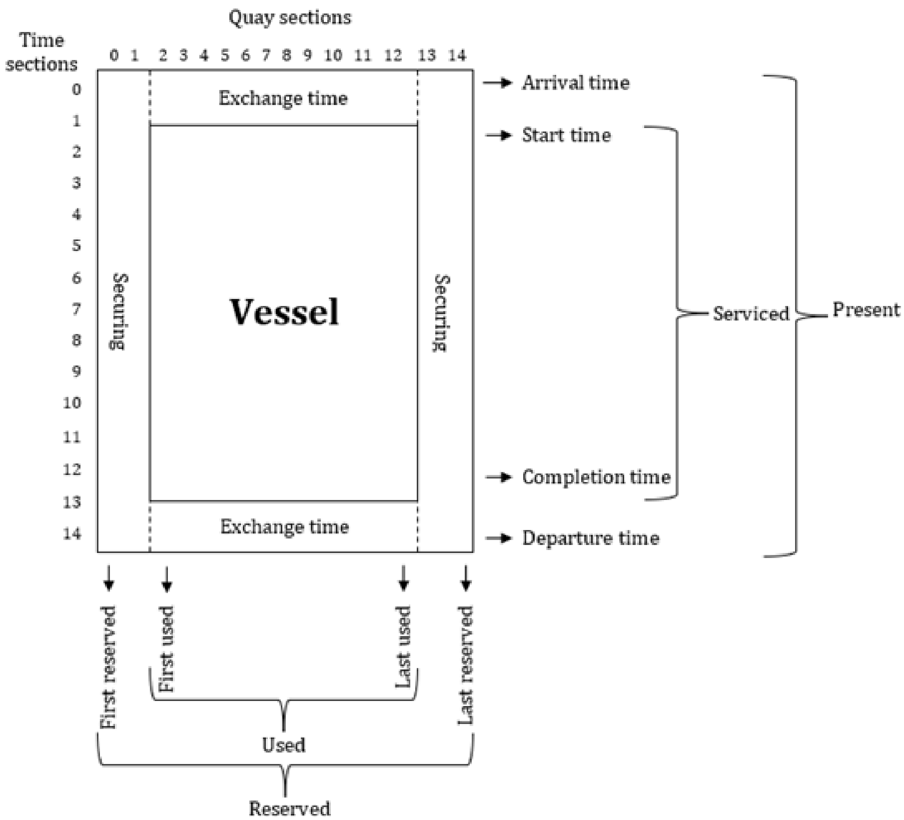


FIGURE 4.1: Example of the placement of a vessel in the BAP with a continuous quay layout

For a discrete quay layout, berths $b \in B$ can be used. The vessel (including securing lines) should then fit in a berth and the allocated mooring position no longer consists of quay sections but of a single berth. This also means that the quay is no longer partitioned in sections of 25 meters, but in full berths. The exchange time does not change and is still needed. QCs no longer cover a range of quay sections, but cover berths.

4.1.2 QCAP Decisions

The second decision concerns the allocation of one or multiple $qc \in QC$ to service the vessels, which is done in the QCAP. An allocation is referred to as a QC allocation, consisting of an assignment of a QC to a vessel for a set period $[start_{v,qc}, end_{v,qc})]$. Every start of a QC allocation is denoted as a QC set up $W_{v,qc,t}$. Based on the total allocations per time section, the number of allocated QC teams (T_s) per shift is known. Figure 4.2 provides an example of the QC allocations to a vessel. In this figure the length of a shift is four time sections.

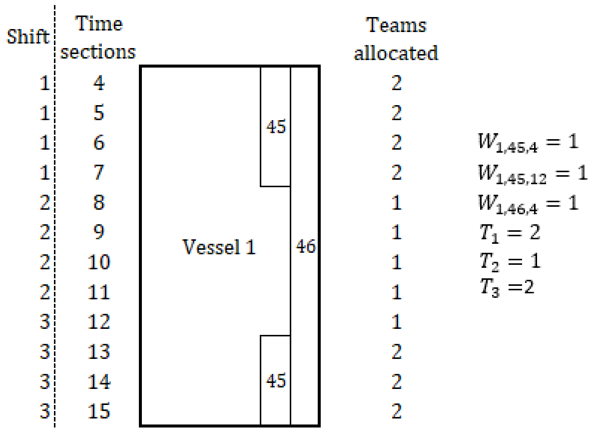


FIGURE 4.2: Example of QC allocations to a vessel

4.2 Objective

Section 2.2 discussed the objectives for the berth and crane plan for Company X. Quantification of the objectives enables a comparison of plans. Therefore, we set up an objective function to objectively evaluate the value of a plan. Listing 4.1 shows the components of the objective function, the sum of these three elements forms the objective function.

Objective function:

1. $\sum_{window} \sum_{v}^{V} c\_delay_{type,window} * delay_v$
2. $c\_deferred * numberofdeferredvessels$
3. $c\_qc\_setup * \sum_{v}^{V} \sum_{qc}^{Q} \sum_{t}^{T} W_{v,qc,t} + \sum_{s}^{S} c\_team\_allocation * T_s$
   $+ \sum_{v}^{V} c\_moor\_dev * moor\_dev_v$

LISTING 4.1: Objective function elements

To represent the service level, a penalty is added for each time section of departure delay. For each vessel the delay $delay_v$ of is defined as $max(0, departure\_time_v + 1 - PTD_v)$. However, the cost for these delays are not the same for each vessel. The penalty cost $c\_delay_{type,window}$ are higher for vessels that arrived in their window and also depend on the type of the vessel, to incorporate the pro forma schedules and contractual agreements.

The PTD is provided by the container shipping company. If the vessel is behind on its schedule, the container shipping company prefers that the vessel is serviced as quickly as possible. However, there is always a minimum port stay corresponding to the number of container moves and BP. These target BPs are applicable to all vessels that are not in window, Table 4.1 provides the target BPs for all classes. In other cases the vessel has some slack in its schedule and the PTD is set at a later moment in time.

To represent the volume, a penalty $c\_deferred$ is included for every vessel that is not scheduled in the period of seven days. A vessel can be deferred to outside the time horizon of seven

TABLE 4.1: Target BPs for vessels not in window

Type	Number of container moves	Target BP
Deep-sea	>3000	115
	2001 - 3000	100
	1001 - 2000	80
	0 - 1000	60
Feeder	>500	35
	0 - 500	20

days in case insufficient resources are available to service all vessels. The vessel is not cancelled, but delayed to a later moment after the next seven days. In the next run of forming a plan all vessels are included again. The option of using cost per deferred vessel is preferred over a bonus per handled container as that results in an undesired preference for deep-sea vessels, as the number of container moves is generally higher compared to feeder vessels.

The efficiency objective is represented by three parts. By including the cost c_qc_setup of each QC set up and $c\_team\_allocation$ for QC team allocation, the usage of resources is balanced with other objectives. The third component is penalty cost c_berth_dev, which penalizes the kilometres driven by the AGVs to move the containers from the yard to the vessel. The deviation in mooring position, $moor\_dev_v$ itself is defined as $abs(pref\_moor_v - vessel\_start_v)$. As the inflow of containers in the yard is not linear, we use the estimates for the portion of containers present as presented in Table 4.2.

TABLE 4.2: Portion of containers present for each vessel type on each day

	Deep-sea	Feeder
<24 hours	1	1
24-48 hours	0.96	0.96
48-72 hours	0.88	0.90
72-96 hours	0.79	0.84
96-120 hours	0.68	0.76
120-144 hours	0.56	0.68
144-168 hours	0.46	0.61
> 168 hours	0.37	0.54

4.3 Model simplifications

The actual problem is very complex, dealing with all features significantly increases the complexity of the problem. Therefore, we simplify the problem by omitting features or making them less strict. Several of these simplifications deviate from other works in literature, as the priority of features also differs per problem. In the following subsections we describe our simplifications in general, for the BAP and for the QCAP.

It is important to note that the problem consists of the data at a specific moment. The input data for the solution consists of the current status. We assume there is no stochasticity in the problem. Predictions of future events, changes in the data, or a rolling horizon are outside the scope of this problem.

4.3.1 General

- There is no influence of tide or weather.
- Maintenance for equipment (quay/QC/AGVs) is not scheduled and omitted in the problem.
- The costs of delays are equal for each container shipping company and do not depend on individual contractual agreements.
- Connections and rotations are not included but reflected in the ETA and PTD.
- Based on the ETA in the port of the vessel it is determined if the vessel is in window.
- The yard capacity is omitted in the problem, there is no maximum inflow or outflow of (reefer) containers.
- The quay layout is continuous as every vessel can be placed everywhere along the quay. The mooring lines are connected to the adjacent bollards. As the bollard are equally spaced along the quay, we use a continuous quay layout with partitioning of 25 meters.

4.3.2 BAP

- The exchange time of a vessel is deterministic and does not depend on other traffic, the selected mooring position or the availability of tugs for example.
- The length needed for mooring is deterministic and does not depend on the weather conditions.
- Vessels of the same type require the same length for securing and exchange.
- There is a maximum length of a vessel for each type.
- The draft of the vessel is the maximum draft during the whole process, including arrival, (un)loading and departure.
- The inflow of containers in the yard is not linear but follows the percentages as given in Table 4.2.
- The housekeeping cost are equal for every container.

4.3.3 QCAP

- The production of QCs scales linearly.
- The production rate of a QC team on a QC is deterministic and the same for each type of vessel. The production rate includes time for QC set up, breaks, movements and other short interruptions.
- There is no set up or movement time for a QC, this is incorporated into the production rate.
- All feeder and deep-sea vessels fit under all QCs and each QC can service the full width of a vessel, every QC can serve every vessel.
- A QC can only serve a vessel if the QC can cover the full length of the vessel.

- The number of QC teams available in a shift does not change, scheduling of QC teams is only done in full shifts.
- The QC split only depends on the length of the vessel.
- QCs are mounted on rails and cannot pass each other. Because of the QC split there is always sufficient space along a vessel for the allocated QCs.
- It is always possible to make a bay plan with the allocated QCs. The QCSP is outside the scope of this research and it is assumed that the QCSP can always be solved.
- There is no advantage if vessels of the same shipping company or alliance are placed after each other.

4.4 Constraints

For a plan to be valid, it needs to comply with a set of constraints. In this section, we enumerate these constraints for the BAP and the QCAP.

4.4.1 BAP

- Each quay section can only be used by one vessel at a time.
- A vessel cannot be split up into sections, so the full length including the length needed for securing needs to be available along the quay.
- The depth along the quay at the mooring position should be sufficient for the vessel to moor.
- The scheduled arrival time of a vessel cannot be before the estimated arrival time of a vessel.
- The time between two vessels should be sufficient according to the exchange time.
- The mooring lines of two vessels cannot overlap.
- Vessels that are already present at the starting point of the planning horizon cannot be moved and stay at their current position.

4.4.2 QCAP

- The time planned to service a vessel should be sufficient to unload and load all containers.
- The service of a vessel can be interrupted, but a vessel cannot be moved during its stay.
- To fully service a vessel, enough QC hours should be allocated to the vessel.
- A QC can only be planned on one vessel at a time.
- As the QCs are mounted on rails they cannot pass each other, the order of the QCs along the quay should always be the same.
- Each QC can only be allocated to a vessel that fully lies in the range that the QC can cover.
- A QC can only be used if a QC team is available to service the vessel.

- The total number of QCs allocated per time section cannot exceed the number of available QC teams.
- QC teams work in shifts and are allocated for a full shift, consisting of multiple time sections. Therefore, the maximum number of QC teams allocated at all time sections in a shift determines how many QC teams are allocated in that shift. It is not possible to calculate the cost of a QC team allocation per time section.
- The QC split determines how many QCs can service a vessel simultaneously.

4.5 Differences existing literature

In general, the literature review shows that many features of the BAP and QCAP applicable to the case of Company X are already present in existing literature. However, there are no works that combine all features present in the problem of the terminal. Combining all features would also make the problem formulation too complex. Therefore, we removed a number of features, as discussed in Section 3.2.2, and discuss the remaining features and subsequent constraints in this chapter. This combination of constraints and objective has not been discussed before.

One of the unique things about the case of the problem discussed in this research is that the QCs have a certain range along the quay that they can reach. In many problems only the total number of QCs is used as a constraint and not their reach. Furthermore, this problem takes into account draft constraints for each vessel. The studies that include vessel draft all have discrete quay layouts while this study has a continuous quay layout.

This study also makes use of two categories of vessels that have their own characteristics. For each type of vessel the exchange time and distance needed for the mooring lines are specified. None of the discussed studies takes into account these factors explicitly, the studies that include (one of the two) factors only add extra time or space. However, during the exchange time a vessel cannot be serviced and the space needed for securing cannot be used to (un)load a vessel.

The objective function used in this study is a unique combination of elements used in earlier works. It includes cost for delays, housekeeping cost and usage of resources. Part of these cost are also personnel cost, which are calculated based on shifts and not time sections unlike other studies that include costs for personnel.

4.6 Summary

In this chapter, we formally described the problem discussed in this research. Based on the actual situation and the available literature, we constructed a formal definition of the problem applicable to the case of the terminal. The problem contains two important decisions, which are the scheduling of the vessels and the allocation of the QCs. The objective, which is discussed in Section 4.2, is to minimize total cost, which consist of the cost for delays, deviations from the preferred mooring position and cost for the usage of resources (QC set ups and QC team usage).

All constrains applicable to the problem are discussed in Section 4.4. The constraints include constraints for the vessel length and draft, the reach of QCs and the usage of QC teams. Section 4.2 and Section 4.4 answered the sub question *'Which objectives and constraints should the solution method include?'* of research question 4. The literature review in Chapter 3 showed that many of these constraints are already incorporated in existing solution methods. In Chapter 5 we form a solution method for this specific case.

To ensure that the problem is practically solvable, we made several simplifications and assumptions. We discussed these simplifications and assumptions in Section 4.3. These assumptions are mainly focused on removing the components that bring uncertainty. Furthermore, they make generalizations such that fewer exceptions need to be handled. This answered the sub question *'Which simplification and assumptions do we need to make to make the problem solvable?'* of research question 4.

In Section 4.5 we answered the sub question *'What are the gaps and similarities between the Company X case and cases in literature?'* of research question 3.

Chapter 5

Solution design

In this chapter, we discuss the solution methods that we design for the problem as formulated in Chapter 4. We answer research question four: *'What does a solution method for Company X look like?'*. The preferred method would be to use an exact solution method, however, the literature review in Chapter 3 showed that the computation time for problem instances of a realistic size is too long for practical usage. Therefore, we design a solution method that uses several heuristics. To evaluate the performance of the heuristics and to test with exact solutions we also formulate an LP model.

In Section 5.1, we discuss the LP model for an exact solution. The LP model uses a continuous quay layout and is used to assess the performance of the heuristics, based on small problem instances. We introduce a second LP model based on the same problem formulation that has the same objective and constraints but uses a discrete quay layout. This LP model is not part of the solution itself, but is used to provide insight into the efficiency loss when a discrete quay layout is used.

Figure 5.1 presents all steps in the solution design for problem instances of a realistic size. We discuss two heuristic methods that we formulate for the BAP in Section 5.2, Section 5.2.2 discusses tabu search and Section 5.2.3 discusses the priority rules heuristic. These two methods result in a berth plan that is valid, but based on the target BPs. Depending on the available resources, the berth plan could still change.

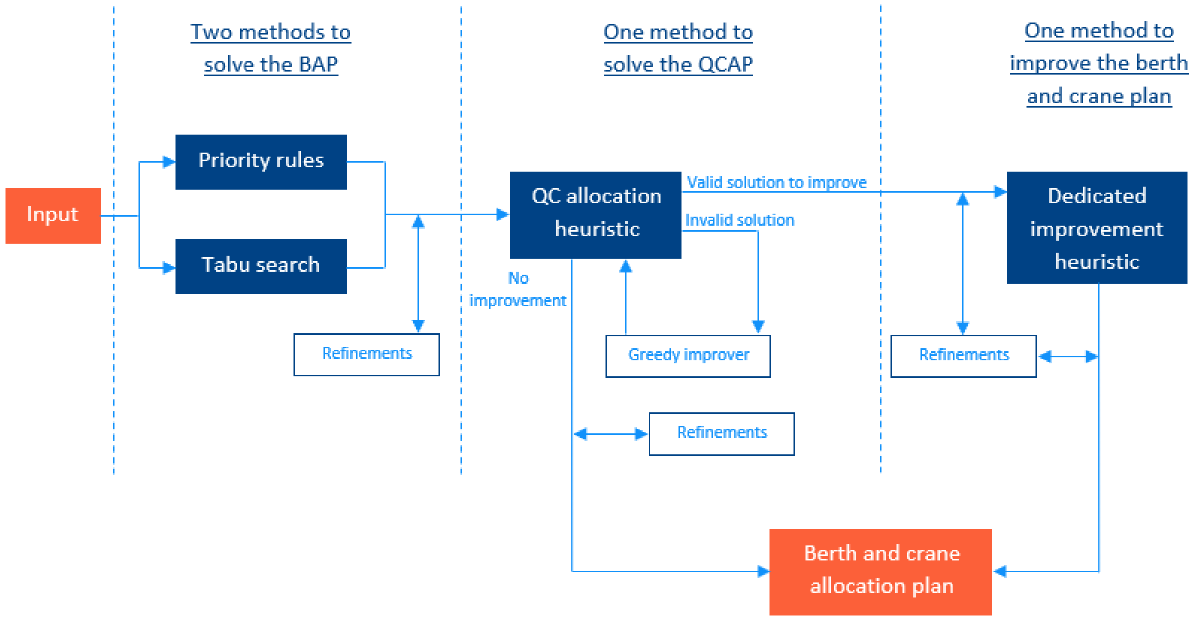


FIGURE 5.1: Overview of methods in the solution design

Using the berth plan, available QCs and QC teams as input, the QCAP is solved using a QC allocation heuristic that is discussed in Section 5.2.4. If it was not possible to service each vessel in the scheduled time from the berth plan, the berth plan is changed using the greedy improver. This improver is repeated until a valid berth and crane plan are formed.

Before a crane plan is formed based on the berth plan, some small refinements can be applied to the berth plan. Furthermore, the refinements can be applied to the combination of the berth and crane plan to further optimize the outcome. We discuss these refinements in Section 5.2.5. The valid berth and crane plan can be further improved using a dedicated improvement heuristic. Section 5.3 discusses the improvement heuristic. Section 5.4 summarizes the chapter.

5.1 LP Models

This section presents two models to solve the BAP and QCAP simultaneously to optimality. The models can generate a basic schedule that adheres to all applicable constraints and simultaneously has the lowest total cost. Both models follow the constraints discussed in Section 4.4, the difference between the two models is the usage of the quay. In the model discussed in Section 5.1.1, the quay layout is continuous while the model in Section 5.1.2 assumes a discrete quay layout, where the quay is divided into berths of a specific length.

Our literature study revealed that ILP models are often used for benchmarking. As the computation time rapidly increases with the scale of a problem, ILP models are often not usable for realistic problems. However, as the outcome is always optimal they serve as a benchmark for heuristics on small problem instances.

5.1.1 Continuous quay layout

The model for a continuous quay layout extends the model of Xiang, C. Liu, and Miao (2018) and X. Han, Gong, and Jo (2015). Contradictory to the model of Xiang, C. Liu, and Miao (2018), this model is based on a continuous quay layout. However, it uses sections of a pre-defined size, not a fully continuous quay layout as used in X. Han, Gong, and Jo (2015). A notable difference with many other models is the inclusion of exchange time and mooring length, these concepts are not considered in Xiang, C. Liu, and Miao (2018) and X. Han, Gong, and Jo (2015).

Compared to the model of Xiang, C. Liu, and Miao (2018), the model is extended with the allocation of QC teams. Furthermore, multiple types of vessels can be included and the model supports windows. The objective function is changed slightly to include these features. Compared to the model of X. Han, Gong, and Jo (2015) there are more substantial changes. Several features are added, such as the draft of a vessel and allocation of specific QCs. X. Han, Gong, and Jo (2015) include the availability of QCs but connect that to QC team allocation in shifts.

The complete model with all notation, variables and constraints is provided in Appendix A. In this section, we discuss the most relevant elements of the model. The following notation is used to formulate the model:

Sets & Indices

v	Index of vessels, $v = 1, ..., V$
q	Index of quay sections, $q = 1, ..., Q$
t	Index of time sections, $t = 0, ..., T$
qc	Index of quay cranes, $qc = 1, ..., QC$
s	Index of shift, $s = 0, ..., S$
typ	Index of Types set, $typ = F, D$
win	Index of Windows set, $win = inwindow, outwindow$

Parameters

<u>Vessel related</u>

ETA_v	The expected arrival time of vessel v
PTD_v	The preferred time of departure of v
l_v	The length of vessel v in quay sections
w_v	The workload of vessel v in time sections for one QC
ma_v	The maximum number of QCs that can be allocated to vessel v simultaneously
d_v	The maximum draft of vessel v during its stay
$type_{v,typ}$	Type indication of the vessel, 1 if vessel v is of type typ, 0 otherwise
$window_{v,win}$	Indication for arrival, 1 if vessel v arrives according to win, 0 otherwise
b_v	The preferred quay section for the front of vessel v
ex_v	Number of time sections needed for exchanging vessel v per arrival/departure
mo_v	Number of quay sections needed for mooring vessel v per side

<u>Shift related</u>

$aShift_s$	Number of available teams in shift s
ts	Length of a shift in time sections

<u>Time related</u>

a_t	Number of available teams in time section t, $a_t = aShift_{t-(tmodts))/ts}$

<u>Quay related</u>

$depth_q$	Depth of quay section q

<u>QC related</u>

$r_{qc,q}$	Reach per QC, 1 if QC qc has quay section q in reach, 0 otherwise

<u>Cost related</u>

$c1$	Cost per team deployed in a shift
$c2$	Cost per set up of a QC
$c3_{typ,win}$	Cost of delay per time section for a vessel of type typ and arrival according to win
$c4$	Cost per quay section deviation from the preferred mooring position based on the number of containers and period till ETA

The decisions to be made by the model are represented by the following decision variables:

$U_{v,q,t}$	1 if quay section q is occupied by vessel v at time section t, 0 otherwise
$Z_{v,qc,t}$	1 if QC qc services vessel v at time section t, 0 otherwise

Variables that are derived from these decision variables are:

$W_{v,qc,t}$	1 if $Z_{v,qc,t} - Z_{v,qc,t-1} \geq 1$; 0 otherwise, this denotes that QC qc is set up for vessel v at time section t
T_s	Number of teams allocated in shift s
$Delay_v$	Departure delay of vessel v
$Deviation_v$	Deviation from preferred quay section for vessel v

We define the objective function as:
$min f = \sum_{v=1}^{V}(c4 * Deviation_v + \sum_{type \in Types} \sum_{win \in Windows} c3_{typ,win} * typ_{v,typ} * window_{v,win} * Delay_v + \sum_{tqc=1}^{QC} \sum_{t=0}^{T} c2 * W_{v,qc,t}) + \sum_{s=0}^{S} c1 * T_s$

The objective function consists of four parts. For every vessel, it incorporates the cost for a delayed departure and the deviation between the preferred mooring location and the actual location. The third part is related to the usage of QCs and includes the set up cost for the QCs. The fourth part incorporates the cost for the QC teams that are used. The objective is to minimize the total of these four costs.

5.1.2 Discrete quay layout

The model for a discrete quay layout also extends the model of Xiang, C. Liu, and Miao (2018) and X. Han, Gong, and Jo (2015) and is largely similar to the model for a continuous quay layout. In contrast to the model for a continuous quay layout, it allocates vessels to berths, similar to the model of Xiang, C. Liu, and Miao (2018). This reduces the complexity of the problem, as the number of potential locations is reduced. However, it also reduces flexibility, as a small vessel allocated to a large berth results in lost capacity for example.

The model mostly uses the same sets, parameters and variables as the model presented in Section 5.1.1. We discuss the essential changes next, the complete model is provided in Appendix A. Instead of a set of quay sections, the model has a set of berths. The preferred mooring position b_v is converted into a preferred berth. In the model, QCs no longer have a range of quay sections that they can cover, but are coupled to one or more berths.

The length needed for securing the vessel becomes redundant, as for each berth the maximum length of a vessel is specified. The length needed for securing the vessel is included in the total berth length. The depth is now specified per berth instead of per quay section. The smallest depth is the bound for the depth of a berth. Using the length and depth of each berth, we make a set $suit\_berth_v$, that contains all berths suitable for handling the vessel.

The decision variable for quay section usage changes to berth usage. The objective does not change, although the calculation of deviation in mooring position $Deviation_v$ does change. For each berth b, we can calculate the middle quay section mid_b and subsequently, calculate $Deviation_v$ as $abs(mid_b - (b_v + \lceil l_v / length\_quay\_section/2 \rceil)$.

Sets & Indices	
b	Index of berths, $b = 1, ..., B$
$suit\_berth_v$	Set of suitable berths for vessel v
Parameters	
b_v	The preferred berth for vessel v
mo_v	*Redundant*
$depth_b$	Depth of berth b
$r_{qc,b}$	Reach per QC, 1 if QC qc can service a vessel in berth b, 0 otherwise
(Decision) Variables	
$U_{v,q,t}$	1 if berth b is occupied by vessel v at time section t, 0 otherwise

5.2 BAP and QCAP heuristics

Our literature study shows that to solve problem instances of a larger size, authors use various heuristic methods. Similar to Cordeau et al. (2005), we use tabu search (Glover, Taillard, and Taillard, 1993) for solving the BAP. In addition to tabu search, we also design a constructive heuristic based on priority rules for the BAP. For both methods, we use the concept of berth lines, which we discuss in Section 5.2.1. Using this concept we explain our implementation of tabu search in Section 5.2.2 and the heuristic based on priority rules in Section 5.2.3. These two methods result in a valid berth plan, where the service times are based on the target BPs.

To solve the QCAP, we propose a heuristic that determines for each time section how the available QC teams are divided over the vessels. The division is based on the portion of time of the stay that has passed and the QC time that is still to be allocated. In case it is not possible to make a valid crane plan with the berth plan and available resources, a greedy heuristic delays and/or extends vessels, based on the ratio between cost increase and solution improvement. This process of forming the crane plan is explained in Section 5.2.4.

Given a complete berth and crane plan, we can attune the plans to each other and further refine them. We discuss these refinements in Section 5.2.5.

5.2.1 Berth lines

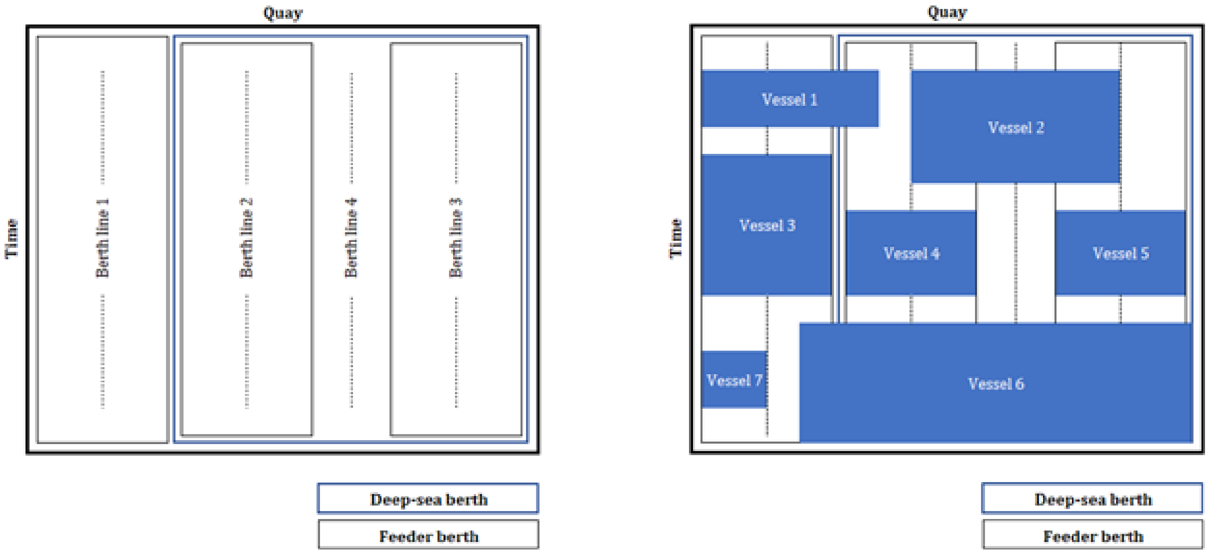
In the priority rules and tabu search heuristic, vessels are allocated to berth lines in a specific order. Once all vessels are allocated to a berth line, it is possible to form a berth plan from this allocation. The berth line is an intermediate step in the process that we use to reduce the initial solution space. Instead of testing every vessel at every quay section, we can now test every vessel at every berth line. However, when forming a berth plan based on berth lines we still have the flexibility to move vessels one or more quay sections. In this way we do not lose the continuous quay layout but do simplify the exploration of the solution space.

A berth line can be seen as a soft discretization of the quay, the berth line is the middle of an imaginary berth. The basis is a continuous layout, where vessels can berth at any position. To have structure in the quay usage, we use the imaginary berths. However, vessels are not necessarily in the middle of the berth and they can also be too long for a berth and use part of another berth if it does not overlap with other vessels. In other words, it is a continuous quay layout with extra structure. Figure 5.2a shows an example of the placement of berth lines along a quay.

For each berth line, we determine which types of vessels can use the berth line and what the depth along the quay is. However, these are not hard constraints, once a vessel is placed in the berth plan it is checked for every vessel if the depth is sufficient. There is also no hard constraint on length. Each vessel is allocated to a berth line and based on the selected berth line the rough position of the vessel is known. The allocation to the berth line is ordered, based on the order on the list.

Figure 5.2b shows an example of seven vessels placed on the berth lines. Vessel 2 and 6 are placed on berth line 4, for deep-sea vessels. Vessel 4 is placed on berth line 4 and vessel 5 is placed on berth line 3, they share a deep-sea berth, similar to a hybrid form of quay layout. Vessels 1, 3 and 7 are placed on berth line 1. Vessel 1 would be too large for the berth if it was fully discrete, however, because Vessel 2 does not use the complete deep-sea berth, Vessel 1 can use that space. The same occurs with Vessels 6 and 7 because Vessel 6 goes outside the limits, and Vessel 7 is pushed to the left.

The usage of berth lines results in a plan that has the vessels in roughly the same berthing positions. This means that QCs also can largely stay in the same place. Nonetheless, it does not remove flexibility, as a large vessel that is larger than the imaginary berth will fit next to a small vessel that is significantly smaller than the imaginary berth. In the case of a fully discrete berth, this would not be possible, as the large vessel would not fit in the berth. In case two large vessels are placed next to each other, they can both be moved away from their berth line a few quay sections such that they fit next to each other.



(A) Division of quay (B) Berth lines in use

FIGURE 5.2: Visualization of berth lines

Forming a berth plan

When we form a berth plan from berth lines, we prioritize the most constrained vessels. As in Figure 5.2, the deep-sea vessels, which are most constrained, are to the right of the quay, the berth lines are planned from right to left. Figure 5.3 shows an example of a berth line solution and the resulting berth plan. The first vessel of the rightmost berth line, vessel 104, is added to the berth plan first. Its estimated time of arrival is used as the start time and the vessel's middle is placed on the berth line middle. The stay time is based on the number of container moves and standard production rates.

Vessels to plan:

ID	Length	Container moves	Type
101	330	2500	D
102	174	775	F
103	152	425	F
104	130	520	F
105	142	235	F

Berth line solution:

1 (F): [102, 105]

2 (F): [103]

3 (F): [104]

4 (D): [101]

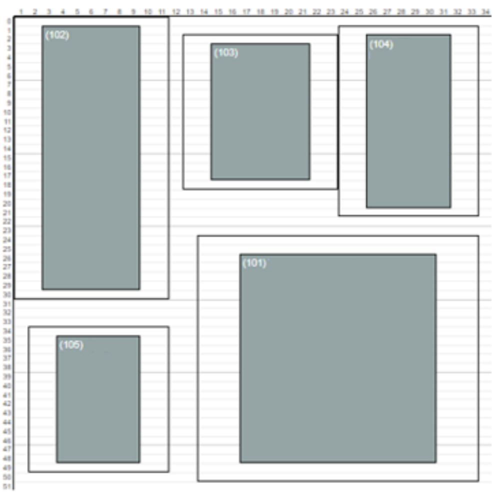


FIGURE 5.3: Example of berth lines and resulting berth plan

Once a vessel is planned in the berth plan, it is removed from the berth line list. The next vessel in the same berth line is then allocated to the berth plan. If the berth line is empty, the first vessel from the next berth line is planned. If a vessel is planned behind another vessel the start time is the estimated time of arrival of the vessel, or the first time section after the previous vessel has left, in case the estimated time of arrival is before the end of service of the previous vessel. This sequence is repeated for all berth lines until all vessels are planned.

In case the desired position results in overlap with an adjacent vessel, the vessel to be planned can be moved away from the vessel that is already planned. The maximum shift away from the berth line is configurable. In case there is still overlap if the maximum shift is reached, the vessel is placed after the vessel that conflicts with the vessel to be planned.

In problem instances where several vessels are already present, we first add the vessels that are present to the berth plan. The other vessels are then planned around the present vessels following the method explained.

5.2.2 Tabu search

Tabu search is a metaheuristic local search method used for mathematical optimization. By altering the solution, the solution space is discovered and better solutions can be found. In general, local search methods tend to get stuck in suboptimal regions and are unable to escape from these regions. In tabu search, solutions or changes are made tabu, making it unable to visit the solution again for a certain time. This method prevents circling between sub-optimal solutions and forces the algorithm to accept worse solutions and escape from local optima. Glover, Taillard, and Taillard (1993) made a user's guide to tabu search that contains more information.

Cordeau et al. (2005) and Lalla-Ruiz, Melián-Batista, and Moreno-Vega (2012) use tabu search to solve the berth allocation problem. Cordeau et al. (2005) discuss various applications of tabu search to solve the BAP with both discrete and continuous quay layouts. Lalla-Ruiz, Melián-Batista, and Moreno-Vega (2012) also apply tabu search but improve the algorithm with path relinking. In this section, we discuss our implementation. Algorithm 1 displays the pseudo-code of the tabu search algorithm applied in this research. The input for the algorithm is an initial solution that the algorithm can alter. Each solution has a fitness that is calculated based on the objective function. The solution is changed using the operators: switch and move.

The algorithm runs a pre-set number of iterations. In each iteration, all neighbours of the current solution are constructed and their fitness is calculated. A neighbour is a solution that can be formed from the current solution with the selected operator applied. Each operation is encoded as a key. If all neighbours are checked, the neighbour with the lowest value of which the operation is not on the tabu list is selected. An exception to this rule is the aspiration criterium, if the solution is better than the current overall best solution, the solution is still accepted, although it is tabu.

Once all neighbours are checked and the best neighbour is found, the solution is saved as the current solution. It is important to note that this solution is not necessarily better, worse solutions have to be accepted to escape from local optima. The best neighbour that was found is compared with the current best overall solution. In case the best neighbour is better, it is saved as the current overall best. The operation to form the neighbour is placed on the tabu list, using the key. Another option for the tabu search is to make a complete solution tabu, however, this is more memory intensive. In case the tabu list has reached the maximum length, the oldest value on the list is removed.

Next, we discuss each of the important elements of our implementation in more detail.

Initial solution

For forming the initial solution, each vessel is placed on the berth line that is closest to the desired position. The type and draft constraints are taken into account in the selection of the

Algorithm 1 Outline of the tabu search algorithm

```
s0: initial solution
sCurrent = s0
sBest = s0
iteration = 0
tabuList = []

while iteration < numberOfIterations do
    iteration += 1
    randomNumber = random()
    if randomNumber <= swapProbability then
        neighborhoodSwap = getNeighborsSwap(sCurrent)
        bestCandidate = None
        for neighborSwap in neighborhoodSwap do
            candidate = executeSwap(sCurrent, neighborSwap)
            if (neighborSwap not in tabuList or fitness(candidate) < fitness(sBest)) and
                    fitness(candidate) < fitness(bestCandidate) then        ▷ Aspiration criterion
                bestCandidate = candidate
            end if
        end for
    else
        neighborhoodMove = getNeighborsMove(sCurrent)
        bestCandidate = None
        for neighborMove in neighborhoodMove do
            candidate = executeMove(sCurrent, neighborMove)
            if (neighborMove not in tabuList or fitness(candidate) < fitness(sBest)) and
                    fitness(candidate) < fitness(bestCandidate) then        ▷ Aspiration criterion
                bestCandidate = candidate
            end if
        end for
        sCurrent = bestCandidate
    end if
    if fitness(sCurrent) < fitness(sBest) then
        sBest = sCurrent
    end if
    tabuList.append(getKey(bestCandidate))
    if length(tabuList) > tabuListLength then
        tabuList.remove(0)
    end if
end while
```

berth line. The vessels allocated to each berth line are ordered based on their PTD. In case vessels are already present, they are prioritized.

Evaluation

We construct a valuation function, that calculates the value of a berth plan. Using the provided berth line allocation, the vessels are planned as discussed in Section 5.2.1. This berth plan is then evaluated using the valuation function, making the quality of the berth plan measurable. The evaluation function takes only the delays and deviation in mooring position into account, as there is no crane plan yet. It also punishes vessels that are deferred.

To decrease running time, a dictionary of the evaluated solutions and their fitness is kept. As there is no randomness in forming a berth plan from berth line allocations, the same berth line allocations result in the same berth plan. Therefore, each berth line allocation is hashed once it is evaluated and the hash and fitness are stored in the dictionary. When calculating the fitness of a berth line allocation it is first checked if the fitness of the berth line allocation was already calculated.

Operators

We implemented the tabu search with two operators: move and swap. The move operator removes a vessel from the berth line plan and inserts it again at another place. This can mean a move to another berth line or a change of priority in the same berth line. The swap operator swaps the position in the berth line plan of two vessels. For both the move and swap operator, it holds that a change is not executed if the constraints concerning type and draft are not met. The ratio of usage of the two operators is a tuneable parameter in the tabu search algorithm.

Algorithm parameters

To execute the tabu search algorithm, we need to set the tabu list length and the stopping condition. The stopping condition that we use is the number of iterations, this results in a consistent run time each time we run the algorithm. The tuning of these parameters is part of our experiments. Furthermore, we use an aspiration criterium, if a solution is better than the best solution found so far it is accepted, even if the change is tabu. As storing complete solutions is very memory intensive, our tabu list stores the operations.

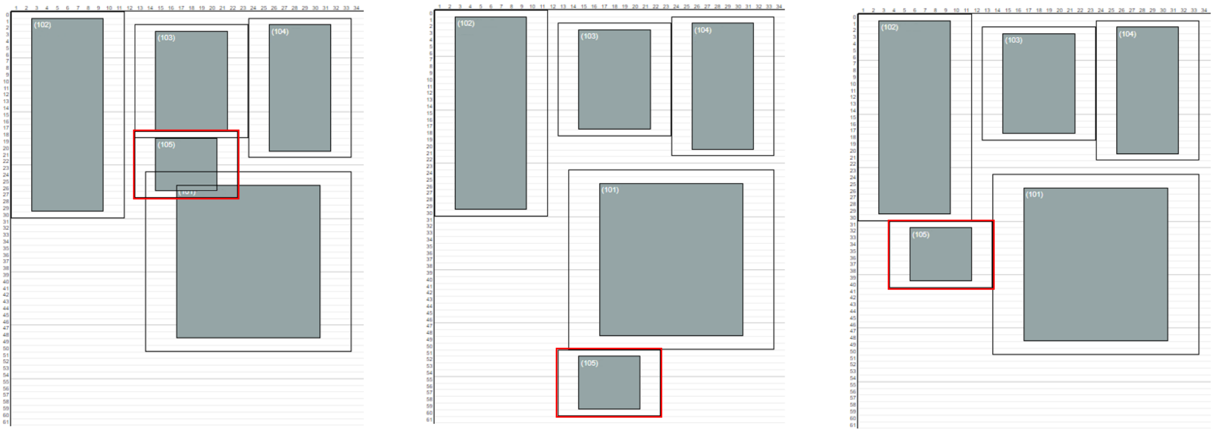
5.2.3 Priority rules

Next to the tabu search algorithm, we use a heuristic based on priority rules to form an initial berth plan. This heuristic first sorts the list of vessels using a list of characteristics and priorities. Next, these vessels are planned one by one, based on the order of the list.

Determining order

The priority rules determine in which order the vessels are planned. A priority rule sorts the vessel based on predefined criteria related to the vessel properties. An example of a priority rule is: first sorting all vessels on ETA, then preferred mooring position, then draft and then, if applicable, present vessels. This results in a prioritized list for planning the vessels. We determine the rules and priorities in one of our experiments.

The list of vessels is first sorted on the characteristic that is least prioritized. Next, the list is sorted on the one but least prioritized characteristics. This continues until all characteristics are handled. Characteristics that we can use for determining the order of vessels are: ETA, PTD, preferred mooring position, draft, type, in window and mooring position if already present.



(A) Vessel in conflict (B) Delaying the vessel (C) Moving the vessel

FIGURE 5.4: Example of two candidate positions for a vessel in conflict

Ordering the vessels is not necessarily based on the exact value of a characteristics, the values can also be divided in classes.

Draft and preferred mooring position are more suitable for division in classes. We form two classes for draft, as there are two depth levels along the quay. The berth lines can be used as classes for the preferred mooring position. Type and in window are binary values and form a classification already. In case vessels in the data set are present, these characteristics deserve most priority, as these vessels cannot move and need to be allocated to the spot in the plan that is in line with the spot in reality.

Planning vessels

The first vessel from the list is selected and directly placed in the berth plan, on the position of the berth line that is closest to the desired position and suitable for the draft and type of the vessel. In case there is no overlap, the next vessel is taken from the list and added to the berth plan in the same manner. In case there is overlap with other vessels, two methods are used to find a suitable place in the berth plan. Figure 5.4a gives an example of a vessel that is in conflict.

The first method is delaying the vessel to be planned. The arrival of the vessel is delayed by one time section until there is no overlap with other vessels, this is candidate position 1. Figure 5.4b shows an example of this position. The other method is to move the vessel along the quay. The vessel is moved away from the middle of the berth line by one quay section per try, first to the right then to the left. This is repeated until a location without overlap is found, or all suitable quay sections were tested. If no suitable location is found in the selected time section, the procedure is repeated for the next time section, until a suitable location is found. This is candidate position 2, which Figure 5.4c shows.

Now candidate position 1 is the first available place in the desired position and candidate position 2 is the first available place along the whole quay. The costs for delay and deviation in mooring position are evaluated for both options and the candidate position with the lowest cost is selected. The vessel is then added to the berth plan in this position. In case both candidate solutions do not provide a suitable location, the vessel is not planned. The procedure is repeated for all vessels in the list of vessels to be planned until the list is empty and a complete berth plan is formed. Algorithm 2 shows the pseudo code of this algorithm.

Algorithm 2 Outline of priority rules heuristic

```
vessels: sorted list of vessels to schedule
berth_plan: current berth plan, initially empty

for v in vessels do
    closest_berthline = find_closest_berthline(v)
    fastest_loc, fastest_t, found_fastest =
            findEarliestPosition(v,closest_berthline,berth_plan)        ▷ See Algorithm 3
    fastest_pref_loc,fastest_pref_t,found_fastest_pref =
            findEarliestPositionOnBerthLine(v,closest_berthline,berth_plan)

    if not found_fastest and not found_fastest_pref then
        deferred_vessel_count += 1
    else                                                    ▷ Check cost for both options
        if found_fastest then
            cost_fastest = calc_delay( v, fastest_t) + calc_moor_pos_dev( v, fastest_loc)
        else
            cost_fastest = infinite
        end if
        if found_fastest_pref then
            cost_fastest_pref = calc_delay(v, fastest_pref_t) +
                        calc_moor_pos_dev(v, fastest_pref_loc)
        else
            cost_fastest_pref = infinite
        end if
        if cost_fastest < cost_fastest_pref then            ▷ Select the cheapest option
            berth_plan = plan_vessel(berth_plan, fastest_loc, fastest_t)
        else
            berth_plan = plan_vessel(berth_plan, fastest_pref_loc, fastest_pref_t)
        end if
    end if
end for
```

Algorithm 3 Finding earliest available vessel position

```
for t in range(v.ETA, TIME_SECTIONS) do          ▷ t = start time, q = mid. pos. of vessel
    for i in range(0, QUAY_SECTIONS) do
        for j in range(0,2) do
            if j == 0 then
                q = closest_berthline + i
            else
                q = closest_berthline - i
            end if
            if no_overlap(berth_plan, v, q, t) and depth_sufficient(v, q) then
                fastest_location = q
                fastest_time = t
                vessel_planned_fastest = TRUE
            end if
        end for
        if vessel_planned_fastest then
            break
        end if
    end for
    if vessel_planned_fastest then
        break
    end if
end for
```

5.2.4 QC allocation

The QC allocation heuristic takes a berth plan as input. Furthermore, it requires the QC data and data on the availability of QC teams per time section. We first form an initial solution which determines how many QC teams are allocated to a vessel at each time section. The next step is to link actual QCs to the vessel, the final step is to complete the crane plan by adding locations and information for visualization.

Initial QC team allocation

For each vessel we determine how many QC teams are needed, assuming that the same number of QC teams is allocated constantly. The number of QCs desired depends on the number of container moves and the type of vessel and follows company standards. In case the vessel requires more QCs to meet the planned stay time, the number of QC teams is increased. In both cases, the constraint on the maximum number of QCs for a vessel is taken into account. We assume that the QCs are distributed evenly along the quay and that there are sufficient QCs on average to service the vessels. Therefore the crane planning method takes the number of available QC teams as the starting point for making the solution as this is most often the restricting factor.

Algorithm 4 provides the outline of the QC allocation algorithm. The total planning horizon is divided into batches of time sections of equal size. By allocating QC teams in batches of time sections we prevent allocations that are shorter than the minimum QC allocation time. The size of the batches is configurable, a logical value is (a multiple of) the shift length or the minimum QC allocation time. For each time section in the batch, we assume that the same number of QC teams is available, this is the minimum of QC teams available for each individual time section.

Algorithm 4 Outline of QC allocation algorithm

```
vessels: sorted list of vessels to schedule
berth_plan: current berth plan
teams_available: list of available teams per time period
initialize vessel_status    ▷ Status: QC hours needed, QC hours allocated, ratio fulfilled, time
ratio passed

for tp in time_period_set do
    vessels_present = FindPresentVessels(berth_plan, tp)
    qcs_needed = CalculateQCNeed(vessels_present)
    qcs_available = teams_available[tp]
    if qcs_available < qcs_needed then                                  ▷ Too few QCs
        remaining_qc = qcs_available
        if len(vessels_present) <= qcs_available then
            for v in vessels_present do                         ▷ A QC for every vessel
                AllocateOneQC(v, tp)
                UpdateStatus(v)
                qcs_available -= 1
            end for
        end if
        while remaining_qc > 0 do                              ▷ Divide remaining QCs
            v_lowest_fillrate = DetermineVesselLowestFillrate(vessel_status)
            AllocateOneQC(v_lowest_fillrate, tp)
            UpdateStatus(v_lowest_fillrate)
            remaining_qc -= 1
        end while
    else if qcs_available == qcs_needed then                   ▷ Exactly enough QCs
        for v in vessels_present do
            AllocateGoalQCs(v, tp)
            UpdateStatus(v)
        end for
    else if qcs_available > qcs_needed then                              ▷ Extra QCs
        remaining_qc = qcs_available
        for v in vessels_present do                          ▷ Desired QCs for every v
            AllocateGoalQCs(v, tp)
            UpdateStatus(v)
            qcs_available -= v.QCGoal
        end for
        while ( doremaining_qc > 0)                            ▷ Divide remaining QCs
            v_largest_shortage = DetermineVesselLargestShortage(vessel_status)
            AllocateOneQC(v_largest_shortage, tp)
            UpdateStatus(v_largest_shortage)
            remaining_qc -= 1
        end while
    end if
end for
```

Based on the berth plan, we determine which vessels are present in each batch of time sections. A vessel is said to be present if it is present in the period of the batch for at least the minimum QC allocation time. The total number of QC teams required per time section is the sum of QC teams needed for each vessel that is present.

Based on the number of QC teams needed and the number of QC teams available in the batch of time sections, there are three options. Either there are too few QC teams, exactly enough QC teams or too many QC teams. In case there are too few QC teams available, we first try to allocate one QC team to each vessel. If QC teams are remaining, or if we were not able to allocate a QC team to each vessel, we divide the remaining QC teams. To do this we use the 'fill rate', which is the number of QC teams allocated already in this batch of time sections divided by the number of QC teams needed in this batch of time sections. In each iteration, we determine which vessel has the lowest fill rate and allocate a QC team to this vessel. This is repeated until no QC teams are remaining.

In case we have exactly enough QC teams, we allocate the desired number of QC teams to each vessel. For every QC team that we allocate we update the progress information per vessel. We store how many QC teams are allocated so far, how many QC teams are needed in total, what the ratio fulfilled is and what the stay time passed ratio is.

In case we have too many QC teams in a batch of time sections, we allocate the desired number of QC teams to each vessel. We then determine if there are vessels with a shortage, where the time passed ratio is higher than the fulfilled ratio. We allocate a QC team to the vessel with the largest shortage that does not yet have the maximum number of QC teams allocated. This process is repeated until there are no QC teams left, or the maximum number of QC teams is allocated to each vessel.

The procedure is repeated for each batch of time sections until the full horizon is processed. This results in a plan that has for each vessel the number of QC teams allocated per time section.

QC allocation refinement

After the initial QC team allocation is formed, there are two methods to improve the solution. The first method removes QC team allocations that are superfluous. Because QC teams are allocated per batch of time sections, in multiples, it can happen that the number of QC teams allocated exceeds the required number. The method checks for each vessel if there are too many QC teams allocated and removes the excess allocations at the best place, preventing forming allocations that are shorter than the minimum QC allocation time.

Because the initial QC team allocation method only works from start to end and does not anticipate the future, there can be shortages at the end of a vessel, while there is an excess of QC teams at the start of the vessel. To solve this we identify the shortage for each vessel and sort these by decreasing size. Then for vessels with a shortage, we check for each time section that the vessel is present: if any QC teams are remaining; if the maximum QC team allocation is not yet met at that time section; and if it does not cause an allocation shorter than the minimum time. In case these three constraints are met, we allocate an extra QC team to the vessel at the current time section. This process is repeated until there are no shortages left, or it is not possible to allocate extra QC teams anymore.

Linking QCs

The current plan only tells how many QC teams are allocated to each vessel at each time section. The next step is to link actual QCs to these allocations. We allocate QCs to vessels from early to late and from left to right, as vessels with many allocations are on the right. For vessels with many allocations, there is more room to compensate for shortages, therefore we prioritize vessels with few allocations. Based on the QC team allocation, we form periods of one QC team allocation that are as long as possible, such that we minimize QC set ups and movements. Figure 5.5 provides an example of forming the periods, on the left the QC team allocation is provided and on the right the resulting periods are shown. Using the allocated QC teams the minimum number of periods is five.

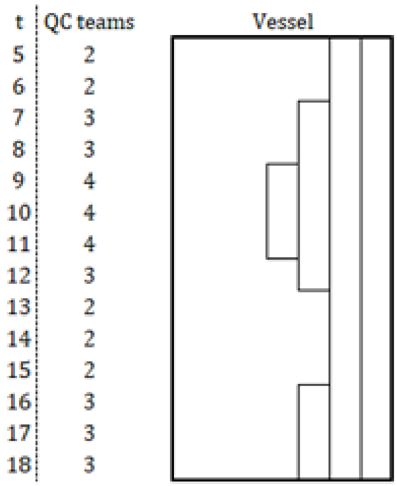


FIGURE 5.5: QC allocation periods on a vessel with QC team usage

Next, a selection of suitable QCs for the vessel is made, taking into account the constraint on the QC range. The vessel position should fully overlap with the QC reach. Then for each period, the left-most QC of the suitable QCs is selected and it is checked if the QC is available for the complete period. If the QC is not available, the next QC in the selection is checked, otherwise, the QC is coupled to the vessel, forming a QC allocation. The left-most QC is preferred, to leave as many QCs as possible for the remaining vessels. In case there is no QC available for the period, the period is skipped and no QC is allocated. This also means that the QC teams are available again.

The list of crane allocations is then formalized in a crane plan by determining a location for each QC and adding the information needed for visualization. It is important to note that the crane plan might be invalid and not have enough QC hours scheduled for each vessel. If this is the case the berth plan needs to be changed to make it possible to construct a valid crane plan.

Making a plan valid

In case it was not possible to create a valid crane plan based on the stay times in the berth plan, the berth plan should be adapted. There are two options for changing the allocation of a vessel in the berth plan. By delaying a vessel, the stay time is kept equal, but the arrival and departure are later. By extending a vessel the stay time increases as the departure is delayed.

The method to make a plan valid operates in a greedy way. If the crane plan is not valid, it tries to extend and delay each vessel in the berth plan for two time sections one by one. For each of these operations, it tries to make a new crane plan and then checks what the new QC shortage and objective value of the solution are. After all possible operations are checked, the operation with the lowest cost increase per QC allocation shortage reduction is executed. This procedure is repeated until all shortages are removed. In case this is not possible, a vessel is removed from the berth plan.

5.2.5 Refinements

To change to berth plan such that a better crane plan can be formed and to better align the berth and crane plan we introduce four refinements:

- Remove unused time
- Extend vessels
- Cut to deadline
- Reduce deviations from preferred mooring position

The refinements can be used at several moments in the solution method. The refinement only changes the berth plan, but also impact the crane plan, as it could become invalid with a changed berth plan. To better understand the refinements, we explain each of them in more detail.

As the crane plan is constructed after the berth plan, the berth plan is not fully adapted to the crane plan. Therefore there may be time sections where there is no QC allocated to the vessel while the vessel is present. Using the assumption that service times are deterministic, we can remove this excess time, possibly reducing delays. This also provides space for other vessels. This refinement is called 'remove unused time'.

Free space in the berth plan can be used to extend vessels within the period between the estimated arrival and preferred departure. For each vessel, we check if we can extend the stay of the vessel, without creating overlap or extra cost. By increasing the stay time of vessels we offer more flexibility to the crane planning method to create a good crane plan. This refinement is called 'extend vessels'.

We can further adapt the berth plan to force the crane planning method to give more priority to delayed vessels. If we cut all vessels to their deadline, while keeping a minimum of 80% of the required service time, we force the crane planning method to give a higher priority to these vessels. As the stay time is shorter, the ratio of time passed increases faster and in case of excess QC teams, these will be allocated to the delayed vessels. If the crane plan is not valid after construction because there are shortages, we can use the crane plan improvement method. This refinement is called 'cut to deadline'.

Since we use the concept of berth lines for creating the berth plan, vessels are not always placed in their desired position, but to the middle of a berth line. In a complete and valid berth plan, there is often space between vessels. This space can be used for decreasing the deviation from the preferred position for each vessel. We can move each vessel in the direction of its desired position until the desired position is reached, or if there is another vessel in the way. This refinement is called 'reduce deviations from preferred mooring position'.

5.3 Improvement heuristic

Juan Francisco Correcher and Alvarez-Valdes (2017) use a ruin-and-recreate heuristic that removes several vessels and subsequently adds them again based on a pre-defined order. We also implement this concept in a slightly different manner. For each vessel, we calculate the total cost of the individual vessel. Next, we randomly select a number of vessels, where we use the cost as a weight. Vessels with a higher cost have a higher chance of being selected. In case a vessel is selected multiple times, we do not pick a new vessel. Each of the selected vessels is removed from the berth and crane plan.

Once all of the selected vessels are removed we add them again to the berth plans. The method for adding vessels to the berth plan operates greedily and adds the vessels to the cheapest positions. To find the cheapest position, it loops over all suitable places and calculates the cost of adding the vessel to that position. Once the cheapest position is found the vessel is placed there and vessels that overlap are delayed to construct a valid plan. The vessels are added again one by one in the same order as they were removed.

With the completed berth plan we can form the crane plan using the same methods as discussed in Section 5.2.4. With the complete and valid berth and crane plan we calculate the total cost and compare the solution with the initial solution. In case the new solution is better we save the solution as our new best. The outcomes of the current iteration are the input for the next iteration. This procedure is repeated for a predefined number of iterations. Once all iterations are performed the best solution is returned, possibly providing an improvement to the existing solution.

5.4 Summary

In this chapter, we developed several solution methods for the problem formulation from Chapter 4. We formulated two LP models to form exact solutions for small problem instances that consist of both the BAP and QCAP. One model is focused on a continuous quay layout, while the other model uses predefined berths. To solve problems of realistic size, e.g., a full week, we propose two heuristics to solve the BAP. The first heuristic is based on a Priority rule and plans vessels based on predefined rules. The second constructive heuristic uses Tabu search to come up with solutions.

Both heuristics use the concept of berth lines to provide more structure while using a continuous quay layout. As solving the BAP is only half of the problem, we constructed a QC allocation algorithm that allocates QCs to the vessels to meet the scheduled service times. In case of shortages, we alter the plan until it is valid. We construct several refinements that can be used between or during forming the BAP and QCAP.

We designed a dedicated improvement heuristic to further improve the berth and crane plane once we have a valid solution. The improvement heuristic remove part of the solution and subsequently adds the vessels to the berth plan again. With the complete berth plan, a crane plan is formed. By repeating this procedure various times, new and possibly better solutions are found.

Chapter 6

Experiments and results

In this chapter, we introduce the experiments performed and discuss their results to answer the fifth research question *'What performance can be expected from the proposed solution method?'*. During the experimentation phase, we tune our solution methods for the problem instances. Furthermore, we seek insights into the performance of the proposed solutions. In Section 6.1, we discuss how we translated company data to problem instances. In Section 6.2, we discuss which experiments we run and how they relate to each other. These experiments and their results are discussed in Sections 6.3 till 6.9. In Section 6.10 we summarize our findings.

6.1 Problem instances

Company X has a database in which it stores all operational information. We use this information to create realistic problem instances for tuning and testing the various solutions. For the LP models we adapt the problem instances and make them smaller.

Based on tests that we performed, we found that the exact solutions can handle problems with up to seven vessels with a time horizon of sixty time-sections and a quay length of twenty sections in a timeframe of fifteen minutes, which we deem the maximum. Therefore, the problem instances that we use for testing exact solutions consist of six or seven vessels. The problem instances for testing the exact solutions use adapted data from several weeks from 2021. The quay is divided into one feeder and one deep-sea berth and vessel lengths are adapted such that each vessel fits in the berth of its type. Appendix C provides the problem instance data for the small problems.

To adapt the actual situation and data to this study, we make the following assumptions and simplifications:

- By blocking three berths full-time, sufficient space is reserved for barges
- The quay is divided into sections of 25 meters
- The time horizon of one week is divided into time sections of one hour
- Exchange time for feeder vessels is 2 hours (one before, one after)
- Exchange time for deep-sea vessels is 4 hours (two before, two after)
- Mooring length for feeder vessels is two quay sections on each side
- Mooring length for deep-sea vessels is three quay sections on each side
- There are no special arrangements with customers, all customers are treated equally
- The weighted centre of all containers to load for a vessel is known
- QC teams work in shifts of eight hours

- The minimum crane allocation length is 3 time-sections
- We provide the determination of cost factors in Appendix D

The realistic problem instances for tuning and testing the heuristics are based on several weeks in 2021. Table 6.1 provides some statistics of each problem instance. The problem instances include the actual vessel visits, movements and QC team availability for one week. Furthermore, we use the quay and QC data of the current situation at the terminal. In total a week consists of 168 time sections of one hour and a quay has 127 quay sections of which 25 are blocked for barges. On the quay there are 21 QCs to service the deep-sea and feeder vessels. We use different problem instances for tuning and testing, to prevent unrealistic outcomes due to overfitting. If the same problem instances are used for tuning and testing, the method is biased and performs better on the test instances, as it was also configured to perform good in these instances.

	Problem instance	**Deep-sea** Vessels	**Deep-sea** Containers	**Deep-sea** In window	**Feeder** Vessels	**Feeder** Containers	**Teams available**
Tuning	1	12	27.454	1	34	7.674	276
	2	10	25.329	2	35	6.353	238
	3	11	33.858	2	37	6.792	295
Testing	1	12	24.798	0	37	7.412	278
	2	12	34.729	0	41	7.938	312
	3	14	27.379	0	37	6.521	300
	4	12	23.896	2	40	7.098	301
	5	13	27.239	1	38	6.093	260
	6	10	25.301	1	36	6.446	245
	7	10	26.036	1	35	7.450	252
	8	14	29.801	1	36	6.271	265
	9	10	25.599	1	39	6.949	249
	10	9	22.692	1	32	5.727	250

TABLE 6.1: Overview of problem instance characteristics

6.2 Experimental design

This section describes the experimental design, we discuss the experiments and their goals. Table 6.2 provides an overview and description of all experiments. Part of the experiments focuses on configuring the solution methods while other experiments focus on comparing methods.

We evaluate each solution on the total cost, in addition, we compare the solutions on deviations from the preferred mooring position, delays, QC setups and QC team usage. For solutions that make use of random numbers, we run three replications and present the average outcomes as well as the standard deviation in brackets. Selected Orders and Cases are highlighted in gray. The '% diff' is defined as $(ValueB - ValueA)/ValueA * 100$. All experiments are run on a Windows machine equipped with an Intel Quad-Core 2.6GHz processor and 16GB of RAM. Run times are reported in seconds.

Our first experiment concerns the quay layout. Using two LP models with the same constraints and objective, except for the constraints related to quay usage, we identify what the difference is between a continuous and discrete quay layout. Using this outcome, we show the importance of using a continuous quay layout.

Section	Problem	Method	Goal	Explanation
6.3	BAP + QCAP	LP Cont. vs LP Dis.	Comparison	Find the efficiency loss when using a discrete quay layout
6.4	BAP + QCAP	LP Cont. vs PR vs TS	Comparison	Compare the performance of the heuristic with the exact solution method
6.5	BAP	PR	Tuning	Determine the best set of rules and priorities for problem instances of a realistic size
6.6	BAP	TS	Tuning	Find the tabu list length, swap probability and number of iterations
6.7	BAP + QCAP	PR, TS	Tuning	Determine the best order of refinements for both solution methods
6.8a	BAP	PR vs TS	Comparison	Compare the performance of the heuristic for the BAP for problem instances of a realistic size
6.8b	BAP + QCAP	PR vs TS	Comparison	Compare the performance of the heuristic for the BAP&QCAP for problem instances of a realistic size
6.9	BAP + QCAP	Improv.	Comparison	Compare the outcome of the improvement heuristic with the outcome from Priority rules and Tabu search

TABLE 6.2: Overview of experiments

The next experiment compares the performance of the exact methods with the heuristics to provide insight into the differences. Unfortunately, this can only be done on a small scale as run time rapidly increases for larger problems. The problem instances and solution methods are adapted to make the comparison as equal as possible.

One of the solution methods is based on priority rules. We form various rules and priorities that each result in different outcomes. In the next experiment, we test various combinations of rules and priorities to find the best combination for problem instances of realistic size.

Our next experiment includes the tuning of Tabu search. We test various settings for the Tabu search parameters to produce the best outcome for realistic problem instances. We run these experiments after the comparison between exact and heuristic solutions as the problem instances differ and different settings are required for the small problem instances.

As we formed multiple refinements that we can use at several steps in the problem-solving process, our next experiment covers these refinements. We test multiple combinations and orders of the refinements to find out which combination performs best.

Using the tuned methods, we compare Priority rules with Tabu search. To provide more insight into the performance, we compare both outcomes with a simple solution method for benchmarking to provide an upper bound. We provide more information on this method in Appendix E. The benchmarking method is a simplified version of the Priority rules heuristic, with a very simple rule and no refinements applied. We provide a lower bound based on simplifications, more information on this method is also provided in Appendix E. As we solve the BAP and QCAP sequentially, we also provide and compare the intermediate outcomes of the BAP.

The final experiment provides further insight into the performance of Priority rules and Tabu search. We apply two improvement heuristic to the solution to see if the solutions can be improved further.

6.3 Continuous vs discrete quay exact

To provide insight into the difference between a continuous and discrete quay we run ten problem instances. Each problem instance is solved using the LP model with a continuous quay layout and a discrete quay layout. All other parameters as well as the objective are equal. Both models solve the BAP as well as the QCAP. The calculation of deviation from the desired mooring position is adapted such that the comparison is fair.

Tables 6.3 and 6.4 depict the outcomes for each problem instance. In three cases the LP for the continuous quay was not able to finish in the time limit of 15 minutes. The maximum difference between the two quay layouts in these ten problem instances is 8,6% as shown in Table 6.5. The average cost increase with a discrete quay layout of these ten problem instances is 2,9%. Most of the cost increases are due to deviations from the preferred mooring position and larger delays. This is caused by the reduced flexibility of a discrete quay layout. In three problem instances the discrete quay layout has fewer QC setups than a continuous quay layout.

Problem	Continuous quay						
instance	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Gap	Run time
1	18	0	0	33	1.920,0	-	36,5
2	26	0	0	36	2.190,0	-	268,3
3	21	24	6	36	2.953,7	18,5%	900,0
4	16	0	0	36	2.040,0	-	819
5	16	0	0	32	1.840,0	-	112,8
6	15	1	0	33	1.900,0	-	332,7
7	19	5	0	37	2.260,0	2,6%	900,0
8	24	0	0	33	2.010,0	3,6%	900,0

TABLE 6.3: Outcomes experiment continuous quay LP model

Problem	Discrete quay					
instance	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Run time
1	15	3	1	33	2.071,5	48,1
2	23	3	1	36	2.341,5	128,0
3	17	26	1	36	2.969,5	82,2
4	16	2	1	36	2.216,0	160,3
5	16	0	1	32	1.879,0	43,3
6	15	1	0	33	1.900,0	75,5
7	19	5	0	37	2.260,0	135,5
8	24	0	0	33	2.010,0	129,4

TABLE 6.4: Outcomes experiment discrete quay LP model

The tested problem instances have a relative short quay, which makes it difficult to estimate the cost saving of a continuous quay layout for longer quays. Because the flexibility increases if the quay length increases it is likely that the difference in cost between a continuous and discrete quay layout increases. Unfortunately, with the current models and run time, it is not feasible to test this. However, with the insight that the cost increase for a discrete quay layout is up to 8,6%, we feel confident that using the concept of berth lines in a continuous quay layout is better than using a discrete quay layout.

Problem instance	Abs diff	% diff
1	151,5	7,9%
2	151,5	6,9%
3	15,8	0,5%
4	176,0	8,6%
5	39,0	2,1%
6	0,0	0,0%
7	0,0	0,0%
8	0,0	0,0%

TABLE 6.5: Comparison of outcomes experiment continuous vs discrete quay LP models

6.4 Exact vs heuristics

To provide insight into the performance of the heuristics we compare the solutions for several problem instances for which we solve the BAP and QCAP. The heuristic solutions are adapted such that they can also solve smaller problems and enable a fair comparison of the two methods. The tuning of Priority rules and Tabu search is done separately for these small problem instances. The tuning for problem instances of a realistic size is discussed in Sections 6.5 and 6.6.

Tables 6.6 and 6.7 depict the outcomes of this experiment with ten problem instances. The solution for Problem instance 9 is not complete, the solution method was not able to plan all vessels in the available time and one vessel is fully outside the time horizon.

Problem instance	Priority rules QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Run time	Exact vs. Priority rules Abs. diff	% diff
1	15	2	4	36	2.123,6	<5	203,6	10,6%
2	16	17	4	40	3.663,6	<5	1.473,6	67,3%
3	15	8	0	37	3.525,0	<5	571,3	19,3%
4	12	17	4	41	3.105,4	<5	1.065,4	52,2%
5	13	5	0	36	2.320,0	<5	480,0	26,1%
6	15	22	0	39	2.725,0	<5	825,0	43,4%
7	15	8	4	42	2.775,4	<5	515,4	22,8%
8	17	32	6	36	2.950,4	<5	940,4	46,8%
9	15	40	4	34	6.940,6	<5	4.770,6	219,8%
10	8	1	0	26	1.445,0	<5	345,0	31,4%

TABLE 6.6: Outcomes and comparison of priority rules with exact solution

In all problem instances the outcome of the heuristics is worse than the outcome of the exact model; the heuristics never reach the same outcome as the exact model. The average increase in the cost of the priority rules heuristic compared to the exact solution over these ten problem instances is 54,0%. If the outlier of problem instance 9 is not included, the average is 35,5%. Tabu search performs slightly better with an average cost increase of 32,8% in these ten problem instances.

The reduction in cost due to fewer QC setups of the heuristics is negated by the increase in QC team usage. Although the heuristics allocate more QC teams, the delays and quay deviations are larger compared to the exact solution. The heuristics are unable to efficiently use the

Problem instance	Tabu search QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Run time	Exact vs. Tabu search Abs. diff	% diff
1	14 (0)	4 (0)	4 (0)	37 (0)	2.209 (0)	<5	289,0	15,1%
2	15 (0)	11 (0)	9,7 (5,2)	36 (0)	3.380 (80,9)	<5	1.190,0	54,3%
3	15 (0)	8 (0)	0 (0)	37 (0)	3.525 (0)	<5	571,3	19,3%
4	13,3 (0,5)	8 (1,4)	18 (1,4)	40,3 (2,4)	3.140 (48,4)	<5	1.100,0	53,9%
5	13 (0)	5 (0)	0 (0)	36 (0)	2.320 (0)	<5	480,0	26,1%
6	16 (0)	2 (0)	6 (0)	36 (0)	2.177 (0)	<5	277,0	14,6%
7	14 (0)	9 (0)	10 (0)	42 (0)	2.826 (0)	<5	566,0	25,0%
8	17 (0)	23,3 (5,2)	7,7 (2,4)	36,3 (0,5)	2.802 (33,6)	<5	792,0	39,4%
9	15 (0)	6 (0)	6 (0)	41 (0)	3.223 (0)	<5	1.053,0	48,5%
10	8 (0)	1 (0)	0 (0)	26 (0)	1.445 (0)	<5	345,0	31,4%

TABLE 6.7: Outcomes and comparison of Tabu search with exact solution

QC teams and QC teams are allocated fewer time sections per shift than in the exact solutions.

Figure 6.1 shows the three solutions constructed by each method for problem instance 1. The aforementioned difference is visible in these plans, the exact solution has more and shorter QC allocations. The heuristics prefer longer sessions and fewer setups. However, this results in a less efficient usage of QC teams, as the exact QC allocations are based on QC team availability while the heuristic QC allocations are focussed on length. The difference between the solution formed by Priority rules and Tabu search lies mainly in vessels 105 and 106, which are planned later in the Tabu search solution.

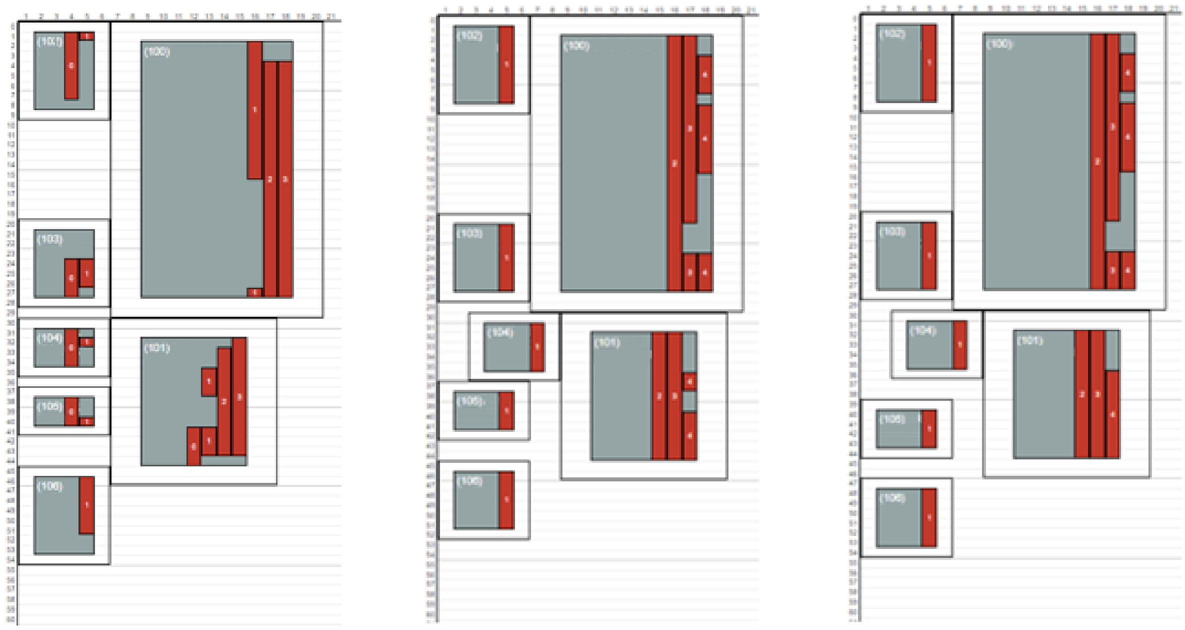
Although the performance of the heuristic methods is worse than the exact solution, the heuristics do provide an advantage. Solving the problem instances in this experiment only took a few seconds for the heuristic methods, while the exact method took 7,5 minutes on average.

6.5 Determining rules and priorities

For the priority rules heuristic, various characteristics of a call can be used for rules. Furthermore, the priorities of these characteristics can change. These two factors determine the order in which vessels are planned and have a large influence on the initial outcome of the BAP. In this experiment, we test various combinations and orders of characteristics. We test the combinations as depicted in Table 6.8.

Order 1	Present vessels
Order 2	ETA → Present vessels
Order 3	PTD → Present vessels
Order 4	ETA → Preferred position → Present vessels
Order 5	PTD → Preferred position → Present vessels
Order 6	ETA → Draft → Present vessels
Order 7	PTD → Draft → Present vessels
Order 8	ETA → Draft → Preferred position → Present vessels
Order 9	PTD → Draft → Preferred position → Present vessels
Order 10	ETA → Preferred position → Draft → Present vessels

TABLE 6.8: Tested combinations of rules and priorities



(A) Exact (B) Priority rules (C) Tabu search

FIGURE 6.1: Overview of plans for problem instance 1

We sort the ETA from early to late, the preferred positions are classified in the berth lines. The draft is classified into two categories, one category only fits along the deepest part of the quay and gets priority. The present vessels are prioritized from right to left along the quay.

	Order 1	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
Problem instance 1	95.497,7	124.755,1	158.862,0	115.829,3	121.665,6	124.755,1
Problem instance 2	27.147,0	47.789,3	138.436,2	50.368,5	104.566,7	47.789,3
Problem instance 3	203.172,3	114.207,1	307.127,8	109.562,5	276.915,6	90.494,5
Average	*108.605,7*	*95.583,8*	*201475,3*	*91.920,1*	*167.716,0*	*87.679,6*

	Order 7	**Order 8**	**Order 9**	**Order 10**	**Order 11**
Problem instance 1	158.862,0	115.829,3	121.665,5	115.829,3	121.665,6
Problem instance 2	138.436,2	50.368,5	104.566,7	50.368,5	104.566,7
Problem instance 3	126.011,6	109.562,5	110.574,1	109.562,5	110.574,1
Average	*141.103,3*	*91.920,1*	*112.268,8*	*91.920,1*	*112.268,8*

TABLE 6.9: Total cost for each problem instance for each combination of rules and priorities

Based on the experiment outcomes in Tables 6.9, 6.10 and 6.11, we can see that using the ETA as a rule always performs better than using the PTD as a rule. Although Order 3 and Order 7 perform best on deviation in mooring position in all cases, their total cost are the highest of all orders. Giving priority to the present vessels only (Order 1) performs best in two of the three cases, in Problem instance 3 Order 6 performs better.

Overall, the outcomes of Order 1 are percentually better than the outcomes of Order 6, however, the total cost of Order 6 are lower than the total cost of Order 1. This is due to the enormous cost of Order 1 for Problem instance 3. As Order 6 is always in the top 4 best solutions

	Order 1	Order 2	Order 3	Order 4	Order 5	Order 6
Problem instance 1	290	265	336	332	371	265
Problem instance 2	76	97	224	106	250	97
Problem instance 3	203	259	357	261	308	247
Average	*190*	*207*	*306*	*233*	*310*	*203*

	Order 7	Order 8	Order 9	Order 10	Order 11
Problem instance 1	336	332	371	332	371
Problem instance 2	224	106	250	106	250
Problem instance 3	279	261	259	261	259
Average	*280*	*233*	*293*	*233*	*293*

TABLE 6.10: Total delays for each problem instance for each combination of rules and priorities

	Order 1	Order 2	Order 3	Order 4	Order 5	Order 6
Problem instance 1	602	464	523	919	1.066	464
Problem instance 2	356	460	357	485	487	460
Problem instance 3	467	452	384	430	877	399
Average	*475*	*459*	*421*	*611*	*810*	*441*

	Order 7	Order 8	Order 9	Order 10	Order 11
Problem instance 1	523	919	1.066	919	1.066
Problem instance 2	357	485	487	485	487
Problem instance 3	377	430	446	430	446
Average	*419*	*611*	*666*	*611*	*666*

TABLE 6.11: Total deviations in mooring position for each problem instance for each combination of rules and priorities

and Order 1 has an outlier for Problem instance 3, we choose to apply Order 6 as our priority rule.

6.6 Tuning Tabu search

The quality of solutions formed by Tabu search heavily depend on the tuning of the algorithm (Glover, Taillard, and Taillard, 1993). There is a trade-off between iterations and running time, more iterations offer longer exploration and deeper exploitation but increase the running time. A short tabu list often results in cycling, while a long tabu list reduces the number of neighbours significantly (Glover, Taillard, and Taillard, 1993). The probability of using the swap operator versus using the move operator is a problem specific tuneable parameter. To optimize the performance of Tabu search, we test several parameter settings.

After some initial testing, we found that the values in the range as provided in Table 6.12 offer the best outcomes.

Therefore, we test the following sets of settings, on three different problem instances, with three replications per problem instance. Each problem instance consists of a set of vessels with

	Minimum	Maximum
Tabu list length	50	100
Swap probability	0.5	0.7
Number of iterations	500	1.000

TABLE 6.12: Tested ranges for Tabu search

randomized arrival times and preferred mooring positions. As we use the Tabu search only for the BAP, the QCAP is not included in our tests. Table 6.13 provides the value of each problem instances with the tested configuration. Table 6.14 provides the run times for the experiments.

Based on these outcomes, we select the parameters of Case 6 as Table 6.15 depicts. These parameter settings offer the best outcome in most cases. Unfortunately, Case 6 also has the highest average run time, exceeding the maximum run time of 15 minutes with a factor of 8 in one problem instance. However, all Cases exceed the maximum run time. As it is likely that the algorithm still contains inefficiencies and that the experiments are run on an older machine, we assume that the run time can be reduced once applied to actual problems. Therefore, we choose to prioritize performance over run time and choose the best performing case, which is Case 6.

6.7 Application of refinements

After the BAP is solved, the QCAP is solved. However, in between these steps, we can already alter the berth plan. This can reduce the costs of the berth plan and make it easier to allocate QCs. The refinements can also be used once the QCs are allocated to further optimize the solution.

We discussed four methods to alter the berth plan: remove unused time, reduce deviations from preferred mooring positions, cut vessels to deadline and extend vessels. These methods can be used at two moments, in between the BAP and QCAP and after the QCAP. The refinement 'remove unused time' is always applied after the QCAP, as this might reduce delays and does not have other consequences. We test the combinations as shown in Table 6.16.

We use the same problem instances as we used for determining the Priority rules and tuning Tabu search. We test the orders for both solution methods, as the best usage of refinements may depend on the solution method.

The outcomes of our experiments for each order of refinements for the Priority rules heuristic are shown in Table 6.17, we provide the detailed outcomes in Appendix F. All orders with the reduction in mooring deviation after the QCAP performed worse than all other orders. The four best performing orders are the orders in which only one refinement is applied: Order 1, 2, 4 and 5. Of these four orders, Order 1 has the best score, it is most capable to align the berth and crane plan.

The outcomes of our experiments for each order of refinements for the Priority Rules heuristic are shown in Table 6.18, we provide the detailed outcomes in Appendix F. For Tabu search Order 1 has a good score, however, Order 6 has a better score. By shortening the port stay of delayed vessels and increasing the port stay of vessels where possible, the QC allocation method is better able to make a good crane plan.

In the next experiments we therefore apply Order 1 to the Priority rules heuristic and Order 6 to Tabu search.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Tabu list length	50	50	50	100	100	100
Swap probability	0,7	0,7	0,7	0,7	0,7	0,7
Number of iterations	500	750	1.000	500	750	1.000
Problem instance 1 seed 1	32.100	31.600	31.600	31.200	31.200	31.200
Problem instance 1 seed 2	32.234	28.434	25.900	26.900	26.900	26.900
Problem instance 1 seed 3	43.726	43.726	43.726	42.600	33.256	32.323
Average	*36.020*	*34.587*	*33.742*	*33.567*	*30.452*	*30.141*
Problem instance 2 seed 1	10.805	10.805	10.805	8.105	8.105	8.105
Problem instance 2 seed 2	13.505	13.505	13.505	9.005	9.005	8.805
Problem instance 2 seed 3	10.805	10.805	10.805	8.805	8.805	8.805
Average	*11.705*	*11.705*	*11.705*	*8.638*	*8.638*	*8.571*
Problem instance 3 seed 1	36.309	35.809	35.809	36.921	36.909	35.755
Problem instance 3 seed 2	40.421	40.409	40.409	36.421	36.421	34.309
Problem instance 3 seed 3	40.309	40.309	40.309	39.809	36.509	33.909
Average	*39.013*	*38.842*	*38.842*	*37.717*	*36.613*	*34.657*
	Case 7	**Case 8**	**Case 9**	**Case 10**	**Case 11**	**Case 12**
Tabu list length	50	50	50	100	100	100
Swap probability	0,5	0,5	0,5	0,5	0,5	0,5
Number of iterations	500	750	1.000	500	750	1.000
Problem instance 1 seed 1	30.600	30.600	30.600	32.134	32.134	32.134
Problem instance 1 seed 2	32.700	32.700	25.500	28.026	28.026	28.026
Problem instance 1 seed 3	32.800	31.500	31.400	36.700	36.700	26.408
Average	*32.033*	*31.600*	*29.167*	*32.287*	*32.287*	*28.856*
Problem instance 2 seed 1	8.805	8.805	8.805	8.805	8.805	8.805
Problem instance 2 seed 2	9.005	8.805	8.805	9.605	9.605	9.605
Problem instance 2 seed 3	8.805	8.805	8.805	8.305	8.305	8.305
Average	*8.871*	*8.805*	*8.805*	*8.905*	*8.905*	*8.905*
Problem instance 3 seed 1	35.509	35.509	33.809	37.051	37.051	37.051
Problem instance 3 seed 2	36.809	36.809	36.609	35.509	35.509	35.509
Problem instance 3 seed 3	40.509	36.909	36.909	41.124	41.124	41.124
Average	*37.609*	*36.409*	*35.775*	*37.894*	*37.894*	*37.894*

TABLE 6.13: Experiment outcomes value Tabu search tuning

6.8 Priority rules vs Tabu search

With the insight into the performance of the heuristics on small problems, we can now apply the heuristics to problems of realistic size. Due to the size of the problem instances, it is not possible to solve them to optimality with an LP model. Therefore, we use a simple heuristic to provide a baseline for benchmarking. We apply the tuning and refinements to the solution methods as we found in the previous experiments. We first experiment with only the BAP in Section 6.8.1, in Section 6.8.2 we test the BAP and QCAP.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Tabu list length	50	50	50	100	100	100
Swap probability	0,7	0,7	0,7	0,7	0,7	0,7
Number of iterations	500	750	1.000	500	750	1.000
Problem instance 1 seed 1	1.231	1.829	2.389	1.436	2.172	2.828
Problem instance 1 seed 2	1.294	1.906	2.490	1.627	2.464	3.310
Problem instance 1 seed 3	1.482	1.959	2.455	1.543	2.253	2.906
Average	*1.336*	*1.898*	*2.445*	*1.535*	*2.296*	*3.015*
Problem instance 2 seed 1	1.353	2.080	2.809	1.593	2.347	3.112
Problem instance 2 seed 2	1.611	2.364	3.162	1.874	2.592	3.334
Problem instance 2 seed 3	1.620	2.359	3.071	1.523	2.420	3.322
Average	*1.528*	*2.268*	*3.014*	*1.663*	*2.453*	*3.256*
Problem instance 3 seed 1	1.658	2.472	3.295	1.870	2.689	3.496
Problem instance 3 seed 2	1.676	2.448	3.202	5.391	7.760	10.326
Problem instance 3 seed 3	1.782	2.594	3.357	4.869	7.055	9.217
Average	*1.705*	*2.505*	*3.284*	*4.043*	*5.835*	*7.679*
	Case 7	**Case 8**	**Case 9**	**Case 10**	**Case 11**	**Case 12**
Tabu list length	50	50	50	100	100	100
Swap probability	0,5	0,5	0,5	0,5	0,5	0,5
Number of iterations	500	750	1.000	500	750	1.000
Problem instance 1 seed 1	1.023	1.503	1.961	1.661	2.626	3.714
Problem instance 1 seed 2	2.977	3.994	5.135	1.952	3.016	4.386
Problem instance 1 seed 3	2.561	3.475	4.450	2.015	2.878	3.789
Average	*2.187*	*2.991*	*3.848*	*1.876*	*2.840*	*3.963*
Problem instance 2 seed 1	1.091	1.692	2.212	2.275	3.752	4.962
Problem instance 2 seed 2	1.112	1.639	2.149	2.091	3.365	4.965
Problem instance 2 seed 3	1.185	1.761	2.317	1.770	2.773	4.153
Average	*1.129*	*1.697*	*2.226*	*2.046*	*3.296*	*4.693*
Problem instance 3 seed 1	1.266	1.858	2.435	2.085	3.002	3.890
Problem instance 3 seed 2	1.224	1.781	2.368	1.606	2.421	3.226
Problem instance 3 seed 3	2.396	3.412	4.356	1.848	2.911	3.744
Average	*1.629*	*2.350*	*3.053*	*1.846*	*2.778*	*3.620*

TABLE 6.14: Experiment outcomes run time Tabu search tuning

Tabu list length	100
Swap probability	0.7
Number of iterations	1.000

TABLE 6.15: Final values Tabu search tuning

Order 1	BAP → QCAP
Order 2	BAP → Reduce deviations from preferred mooring position→ QCAP
Order 3	BAP → QCAP → Reduce deviations from preferred mooring position → QCAP
Order 4	BAP → Extend vessels → QCAP
Order 5	BAP → Cut to deadline → QCAP
Order 6	BAP → Cut to deadline → Extend vessels → QCAP
Order 7	BAP → Extend vessels → Cut to deadline → QCAP
Order 8	BAP → Reduce deviations from preferred mooring position → Cut to deadline → Extend vessels → QCAP
Order 9	BAP → Reduce deviations from preferred mooring position → Extend vessels → Cut to deadline → QCAP
Order 10	BAP → Cut to deadline → Extend vessels → QCAP → Reduce deviations from preferred mooring position → QCAP
Order 11	BAP → Extend vessels → Cut to deadline → QCAP → Reduce deviations from preferred mooring position → QCAP

TABLE 6.16: Tested combinations and orders of refinements

	Order 1	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
Problem instance 1	252.304	251.736	272.476	252.304	247.905	261.129
Problem instance 2	156.860	156.695	156.695	170.235	163.910	161.710
Problem instance 3	225.351	227.329	230.188	215.301	228.101	225.869
Average	*211.505*	*211.920*	*219.786*	*212.613*	*213.306*	*216.236*

	Order 7	**Order 8**	**Order 9**	**Order 10**	**Order 11**
Problem instance 1	247.905	260.561	247.338	275.626	271.638
Problem instance 2	177.610	161.545	177.445	161.745	186.170
Problem instance 3	237.144	227.372	238.297	223.632	241.426
Average	*220.886*	*216.493*	*221.026*	*220.334*	*233.078*

TABLE 6.17: Total cost after application of refinements in given order for Priority rules

6.8.1 BAP

We first analyse the solutions of the BAP; we compare three solution methods. Tables 6.19 and 6.20 show the detailed outcomes of each individual solution method, while Table 6.21 shows the comparison. On average the run time of TS was four times larger than the run time of PS.

The simple method for benchmarking has the best performance. PR performs better in problem instances 4, 6 and 10. Tabu search performs better in problem instances 6 and 10. problem instances 4, 6 and 10 are the problem instances with the fewest container moves, based on this it seems that the performance is better in problem instances with less pressure on the plan.

PR performs significantly better than TS, except for problem instances 2 and 6. The difference in PR and TS is mostly in the preference for delays or deviations from the preferred mooring position. PR has higher delays, but smaller deviations in mooring position. In most problem instances it appears to be better to focus on smaller deviations in mooring position as this results in lower cost.

	Order 1	Order 2	Order 3	Order 4	Order 5	Order 6
Problem instance 1	300.238	310.595	325.174	313.263	322.590	319.185
Problem instance 2	180.065	192.737	175.633	202.590	187.240	165.740
Problem instance 3	280.150	279.185	284.894	280.822	270.347	274.749
Average	*253.484*	*260.839*	*261.900*	*265.558*	*260.059*	*253.224*

	Order 7	Order 8	Order 9	Order 10	Order 11
Problem instance 1	330.738	338.713	313.995	321.492	337.062
Problem instance 2	184.190	173.012	172.837	163.865	181.267
Problem instance 3	271.247	274.749	280.831	279.712	272.318
Average	*262.058*	*262.158*	*255.888*	*255.023*	*263.549*

TABLE 6.18: Total cost after application of refinements in given order for Tabu search

Problem instance	Priority rules (PR) Delay	Moor. pos. dev.	Value
1	239	626	111.865,4
2	348	661	138.813,3
3	391	632	113.261,0
4	235	462	58.717,9
5	127	723	59.368,8
6	129	553	82.050,1
7	201	619	101.497,5
8	262	860	96.780,3
9	145	470	54.849,2
10	113	410	78.227,9

TABLE 6.19: Experiment outcomes for the BAP using Priority rules

Problem instance	Tabu search (TS) Delay	Moor. pos. dev.	Value
1	180,3 (36,4)	1.224,7 (37,6)	126.726,4 (15.504,1)
2	237,3 (16,0)	960,7 (38,7)	111.040,4 (4.992,7)
3	236,7 (16,0)	1.332,7 (67,3)	112.027,3 (10.097,1)
4	162,3 (10,4)	1.177,3 (99,1)	101.639,5 (8.194,6)
5	276,0 (277,9)	881,7 (515,6)	94.916,5 (22.732,7)
6	122,3 (3,3)	1.077,3 (41,7)	75.053,4 (5.457,0)
7	137,0 (20,8)	1.252,3 (113,5)	134.695,5 (27.706,5)
8	128,0 (8,3)	1.105,0 (38,8)	108.661,3 (2.121,7)
9	124,3 (3,8)	1.244,7 (120,3)	129.529,7 (14.788,9)
10	46,3 (1,9)	1.029,0 (19,8)	91.466,3 (5.140,3)

TABLE 6.20: Experiment outcomes for the BAP using Tabu search

Problem instance	High Benchmark (HB) Value	TS-PR Abs diff	TS-PR % diff	HB-PR Abs diff	HB-PR % diff	HB-TS Abs diff	HB-TS % diff
1	76.653,7	14.861,0	13,3%	-35.211,7	-31,5%	-50.072,7	-39,5%
2	68.604,9	-27.772,9	-20,0%	-70.208,4	-50,6%	-42.435,5	-38,2%
3	83.005,1	-1.233,7	-1,1%	-30.255,9	-26,7%	-29.022,2	-25,9%
4	66.661,4	42.921,6	73,1%	7.943,5	13,5%	-34.978,1	-34,4%
5	33.026,3	35.547,7	59,9%	-26.342,5	-44,4%	-61.890,2	-65,2%
6	93.475,6	-6.996,7	-8,5%	11.425,5	13,9%	18.422,2	24,5%
7	76.837,2	33.198,0	32,7%	-24.660,3	-24,3%	-57.858,3	-43,0%
8	60.317,1	11.881,0	12,3%	-36.463,2	-37,7%	-48.344,2	-44,5%
9	37.292,8	74.680,5	136,2%	-17.556,4	-32,0%	-92.236,9	-71,2%
10	108.222,9	13.238,4	16,9%	29.995,0	38,3%	16.756,6	18,3%

TABLE 6.21: Comparison of solution methods for realistic problem instances BAP

6.8.2 BAP and QCAP

Next, we analyse the outcome for the BAP and QCAP, again, we compare three solution methods. Tables 6.22 and 6.23 show the detailed outcomes of the experiments for each of the ten problem instances. The outcomes of the two benchmarking methods are provided in Table 6.24. Table 6.25 compares the outcomes of each solution method with each other. On average the run time of TS was four times larger than the run time of PS.

PR performs better than TS in all problem instances except for problem instances 2 and 10 where TS is slightly better. There are only minor differences in the number of QC set ups and QC team usage for both solution methods. However, while PR had higher delays in the berth plans, this gap is now closed. The delays that PR has are similar to the delays of TS, or better. PR still performs better on the deviations in mooring positions, these are smaller for all problem instances. This makes PR perform better in almost all problem instances.

Problem instance	Priority rules (PR) QC-setups	Delay	Moor. pos. dev.	Used teams	Value
1	96	438	626	231	215.740,4
2	114	661	661	291	275.320,8
3	108	550	632	254	205.992,6
4	98	471	462	228	182.267,9
5	105	586	723	232	245.316,1
6	99	414	553	219	258.550,0
7	94	424	619	228	206.823,8
8	114	661	860	245	275.335,0
9	98	599	470	224	275.216,1
10	78	631	410	203	335.679,0

TABLE 6.22: Experiment outcomes for the BAP and QCAP using Priority rules

The total costs of the ten problem instances are 14.5% higher for TS than for PR. The performance over all ten problem instances is better for PR than HB, the total costs of HB are 9,3% higher in the ten problem instances. None of the solutions is close to the LB, which can have two reasons. Either the performance of the heuristics is very poor, or the problem instances cannot be completed without delays and deviations in mooring positions. In the case of these

Problem instance	Tabu search (TS) QC-setups	Delay	Moor. pos. dev.	Used teams	Value
1	99,3 (1,7)	701,0 (70,1)	1.224,7 (37,6)	224,7 (4,0)	283.857,3 (12.593,0)
2	109,7 (1,9)	720,0 (61,0)	960,7 (38,7)	288,0 (3,6)	274.375,8 (7.469,6)
3	108,3 (2,5)	596,7 (93,0)	1.332,7 (67,3)	248,0 (0,8)	245.518,5 (20.494,1)
4	97,7 (1,2)	357,7 (23,0)	1.177,3 (99,1)	227,3 (1,2)	217.033,3 (9.922,5)
5	102,3 (5,0)	530,3 (101,9)	1.342,7 (144,5)	229,0 (5,9)	317.417,7 (41.067,9)
6	98,0 (2,2)	488,7 (40,1)	1.077,3 (41,7)	219,0 (1,6)	264.261,3 (10.736,6)
7	94,0 (4,3)	424,0 (31,8)	1.252,3 (113,5)	226,7 (1,9)	292.382,9 (49.862,2)
8	114,0 (5,0)	532,0 (21,1)	1.105,0 (38,8)	247,3 (3,3)	294.877,3 (8.397,6)
9	91,3 (2,6)	695,0 (19,5)	1.244,7 (120,3)	224,7 (4,2)	322.129,9 (22.692,9)
10	83,3 (1,7)	604,0 (52,3)	1.029,0 (19,8)	199,7 (2,9)	323.810,2 (11.998,9)

TABLE 6.23: Experiment outcomes for the BAP and QCAP using Tabu search

Problem instance	Low Benchmark (LB) Value	High Benchmark (HB) Value
1	52.275	194.186,4
2	67.950	289.142,3
3	54.975	213.180,1
4	50.925	225.531,1
5	54.450	253.676,3
6	51.075	285.070,1
7	53.700	273.828,5
8	58.500	273.649,8
9	52.350	364.338,9
10	45.675	334.514,0

TABLE 6.24: Benchmarking values BAP and QCAP

Problem	TS-PR		HB-PR		HB-TS	
instance	Abs diff	% diff	Abs diff	% diff	Abs diff	% diff
1	68.116,9	31,6%	-21.554,0	-10,0%	-89.670,9	-31,6%
2	-945,0	-0,3%	13.821,5	5,0%	14.766,5	5,4%
3	39.525,9	19,2%	7.187,5	3,5%	-32.338,4	-13,2%
4	34.765,4	19,1%	43.263,2	23,7%	8.497,8	3,9%
5	72.101,6	29,4%	8.360,2	3,4%	-63.741,4	-20,1%
6	5.711,3	2,2%	26.520,1	10,3%	20.808,8	7,9%
7	85.559,1	41,4%	67.004,7	32,4%	-18.554,4	-6,3%
8	19.542,3	7,1%	-1.685,2	-0,6%	-21.227,5	-7,2%
9	46.913,8	17,0%	89.122,8	32,4%	42.209,0	13,1%
10	-11.868,8	-3,5%	-1.165,0	-0,3%	10.703,8	3,3%

TABLE 6.25: Comparison of solution methods for realistic problem instances BAP

realistic problem instances, delays and deviations from the preferred mooring position are unavoidable.

All solutions made for the ten problem instances are valid, however, in several cases vessels are (partly) outside the scope of seven days as the solution methods are not always able to service all vessel is the available time. The exchange time and space for mooring lines are respected in each solution. Furthermore, sufficient QCs are allocated to service each vessel and enough QC teams are available to operate the QCs.

6.9 Improvement heuristics

After a complete and valid plan is formed using the BAP and the QCAP there can still be room for improvement. As the BAP and QCAP are solved sequentially, the outcome might be sub-optimal. Therefore, we experiment with an improvement heuristic. We test the improvement heuristic for five outcomes of the Priority rules solution method and five outcomes of the Tabu search solution method. We apply the method as discussed in Section 5.3.

Solution method	Problem instance	Original solution QC-setups	Delay	Moor. pos. dev.	Used teams	Value	
PR	1	96	438	626	231	215.740	
PR	2	114	661	661	291	275.321	
PR	3	108	550	632	254	205.993	
PR	4	98	471	462	228	182.268	
PR	5	105	586	723	232	245.316	
TS	1	97	800	1.178	228	295.637	
TS	2	111	642	991	285	264.471	
TS	3	105	728	1.407	249	273.746	
TS	4	96	361	1.316	227	215.223	
TS	5	97	674	1.297	221	370.406	
Solution method	**Problem instance**	**Improved solution QC-setups**	**Delay**	**Moor. pos. dev.**	**Used teams**	**Value**	**% change in value**
PR	1	96	438	626	231	215.740	0%
PR	2	114	661	661	291	275.321	0%
PR	3	108	550	632	254	205.993	0%
PR	4	98	471	462	228	182.268	0%
PR	5	105	586	723	232	245.316	0%
TS	1	97	800	1.178	228	295.637	0%
TS	2	111	642	991	285	264.471	0%
TS	3	105	728	1.407	249	273.746	0%
TS	4	96	361	1.316	227	215.223	0%
TS	5	90	1046	1.295	215	362.447	-2%

TABLE 6.26: Comparison of solutions with improved solutions

Table 6.26 provides the outcomes for the experiment. There is only one solution that is improved by the improvement heuristic. The improvement of TS 5 is 2%. While solutions initially improve when vessels are placed at different spots with smaller delays, the formation of the crane plan diminishes this effect. In the initial berth plan all vessel stays are adapted to the available QC teams. As this is often the most restricting factor, moving vessels only shifts delays from one vessel to another. In the improved problem instance the delays significantly increased, but fewer QC teams were used, lowering the total cost.

Another reason why it is difficult for the improvement heuristic to find improvements is that Tabu search in itself is already an improvement heuristic. If receives an initial solution and, in the case of the BAP, moves vessels around to find a better solution. The Priority rules heuristic also tries several positions for each vessel to find the best position. This already optimizes the berth plan, which reduces the possibilities for the dedicated improvement heuristic to find further improvements.

6.10 Conclusion

In Section 6.3 we compared a continuous quay layout with a discrete quay layout with an exact solution method for small problem instances. The performance of the discrete quay layout is always equal to or worse than the performance of the continuous quay layout, this strengthens the choice for a continuous quay layout. In Section 6.4 we compared the exact solution method with the heuristics proposed in this research. As we use an exact model, the comparison is based on small problem instances. The average increase in the cost of the Priority rules heuristic compared to the exact solution over these ten problem instances is 54,0%. Tabu search performs slightly better with an average cost increase of 32,8% in these ten problem instances.

In Section 6.5 we determined the Priority rule to construct a berth plan using the Priority rules heuristic. The selected priority rule is ETA $\rightarrow$ Draft $\rightarrow$ Present vessels. In Section 6.6 we run several tests to tune Tabu search. The configuration that performs best is a tabu list length of 100, with a swap probability of 0.7, using 1000 iterations. In Section 6.7 we test several combinations of refinements for both heuristics. For the Priority rules heuristic, it is best to apply no refinements. For Tabu search the selected order is BAP $\rightarrow$ Cut to deadline $\rightarrow$ Extend vessels $\rightarrow$ QCAP.

In Section 6.8 we compared the solution methods proposed in this research. To provide more insight we also give a minimum and maximum value using benchmarking methods. Both heuristics perform worse than the benchmarking method when making the berth plan. However, this gap is closed when the heuristics construct a berth and crane plan. Priority rules perform better than Tabu search and the benchmark. The performance of Tabu search is poor, it is outperformed by the benchmarking method. In our experiment for the dedicated improvement heuristic, only one minor improvement was realised in the solutions. Based on this minor improvement we conclude that the improvement heuristic is not sophisticated enough to identify improvements in the berth and crane plan. This is partly because the berth plan itself is already optimized by the Priority rules heuristic and Tabu search.

Chapter 7

Conclusion

In this chapter, Section 7.1 summarizes the main findings and answers the main research question. Subsequently, Section 7.2 provides more information for implementation and recommendations. Section 7.3 discusses the limitations of this research and provides direction for future research. Finally, Section 7.4 describes the contribution of this research to science.

7.1 Conclusion

In the current way of working, all scheduling at the container terminal of Company X is done manually. Planners construct the berth, crane and bay plans manually based on their own insights. This raises questions on the quality of the plans as it is not possible to evaluate multiple problem instances. Furthermore, it limits the ability to optimize the plan. In literature there exist many algorithms for the BAP and QCAP, which could improve the scheduling at the container terminal. Therefore, we formulate research questions in Chapter 1, with the main research question:

"How can berth planning and quay crane allocation for Company X be automated by an algorithm?"

We analyse the current way of working and determine all the features that are currently considered when making the berth and crane plans in Chapter 2. The objective function consists of three elements: service, volume, and efficiency. Many of the features are already present in literature as we discuss in Chapter 3, however, the combination of all features is unique. The combination of a continuous quay with quay depth and a coverage range for each QC are elements that are unique in this problem.

Based on the actual problem and the input from literature, we set the exact problem formulation in Chapter 4; several features are omitted to simplify the problem. Moreover, we remove all elements that bring uncertainty, such as the weather. In Chapter 5 we formulate a LP model that can solve small problem instances. For problem instances of a realistic size, we propose two solutions for the BAP, one based on Tabu Search, and one based on priority rules. Subsequently we propose a QC allocation heuristic for the QCAP. Furthermore, we introduce refinements that better align the berth and crane plan. To further improve the solution, we test a ruin and recreate heuristic.

We perform experiments in Chapter 6 to tune each method and subsequently compare the outcomes. In all tested small problem instances the heuristics performed worse compared to the exact solution, as Tables 6.6 and 6.4 show. The average increase in the cost of the priority rules heuristic compared to the exact solution over these ten problem instances is 54,0%. Tabu search performs better with an average cost increase of 32,8% in these ten problem instances.

All solutions methods are tuned to problem instances of a realistic size. For the priority rules heuristic, the priority rules that we use are first sorting on ETA, then draft, followed by present vessels. For Tabu Search we use 1000 iterations, with a swap probability of 0.7 and a tabu list length of 100. For priority rules we do not apply any refinements, while for Tabu Search we shorten stay time of delayed vessels and extend vessels where possible before making the crane plan.

We test these heuristics on ten problem instances based on actual company data from 2021. Overall, Priority Rules performs better than Tabu Search. Table 6.25 provides the difference between Tabu Search (TS), the priority rules heuristic (PR) and a benchmark (HB). The main difference is in the delays and deviations from the preferred mooring positions, Priority Rules performance better on both elements. With a ruin-and-recreate improvement heuristic we attempt to further improve the solution. The tested configuration of the improvement heuristic did not result in any significant improvements.

We conclude that the selected Priority rule performs better than Tabu search in the current configuration, but that the performance is only slightly better than the benchmark, the total cost for the ten problem instances is 9.3% higher using the benchmark method. The total costs of the ten problem instances are 14.5% higher for TS than for PR. As the improvement heuristic only improved one problem instance, we conclude that the complexity of the solutions is too high for the current improvement method. A more advanced improvement heuristic is needed to improve the solution.

7.2 Practical implementation and recommendations

This research is a first exploration of possibilities for solving the BAP and QCAP using an algorithm for the features and objective of the terminal. This development contributes to the fourth step of the strategy for changing the current way of working of Company X as mentioned in Section 1.1.1. In the literature study we discuss many methods for solving the BAP and QCAP. Based on this study we form a solution method for a simplified problem definition. The main reason to simplify the problem is to fit it in the available time. Furthermore, it decreases the demands for the solution method.

Although the performance of the solution method is not satisfactory, the process gives a good insight in the whole planning process. In Chapter 2, all factors that are considered by a planner when planning are discussed and worked out. Furthermore, we formulated a clear objective function, balancing the interests of the company, customers, and other stakeholders. We recommend considering this information when continuing with the automatic scheduling project.

We also recommend continuing with the exploration of solution methods, for three reasons. First, the performance of the solution method should be improved to justify the investment and show that automated scheduling is as good as or better than human performance. Second, different solution methods might be able to consider more features to make the plans also applicable to reality. Another option could be to extend the selected solution method and expand the current solution by including more features. Third, the solution method that we constructed in this research is not suitable for step two and three. The solution method needs modifications to let it provide feedback on manual planning.

Overall, the solution that we formed in this research is not directly applicable to reality as there are too many simplifications. However, the process offered a lot of insights and enables a continuation of exploration for solution methods. Furthermore, the current solution can serve as a benchmark for future solutions. As Tabu Search as implemented in this study offered good outcomes for the BAP, Company X could investigate if the heuristic can improve the long-term plan that does not include the QCAP. Many of the features that are not included in this study are also not applicable for the long-term plan, which makes the Tabu Search implementation usable in reality.

As a small part of this project a visualzation tool for the berth and crane plan was developed. On `https://0xlu0b.csb.app/` the *.txt* files which are produced by the solution method code can be uploaded to visualize the plans. This eases interpretation of the plans and analysis of the differences.

7.3 Limitations and future research

This section discusses the limitations of this research and provides directions for future research.

In this research we significantly limited the scope of the problem, we omitted many features that are present in reality. Including more of these features improves the usability of the solutions as fewer adaptations need to be made to use the plans in reality. The current solution methods make plans that are too simplified to use. Many of these features are not unique to the problem discussed in this research, which makes inclusion of these features advantageous for other problem definitions on the BAP and QCAP as well.

The literature study discusses many solution methods for the BAP and QCAP. In this research the focus is on sequentially solving the BAP and QCAP with Tabu Search and two newly constructed heuristics. As the performance is unsatisfactory it is worth to test other solutions method for the set of features and objective discussed in this study. Furthermore, the proposed solution methods can be improved by introducing new rules for the Priority Rules heuristic, or smarter use of memory for Tabu Search.

Another point for future research is that the solution method is made for a deterministic problem, while the input data is highly dynamic. Therefore, future research could focus on evaluating the performance of the model under stochastic circumstances. By using a simulation study, the robustness of the plans can be tested. This allows testing strategies to make the berth and crane plan more robust. More robustness can be achieved by increasing port stay of buffer time between vessels for example.

7.4 Scientific contribution

Many features of the BAP and QCAP included in this study are already present in existing literature. However, there are no works that combine all features present in this study into a solution method. One of the unique things about the case of the problem discussed in this research is that the QCs have a certain range along the quay that they can reach. Furthermore, this problem considers draft constraints for each vessel. This study contributes by including vessel draft as a feature for a continuous quay layout, in the LP model as well as in the heuristics.

This study also makes use of two categories of vessels that have their own characteristics. For each type of vessel, the exchange time and distance needed for the mooring lines are specified. Our research contributes by including exchange time and space for mooring lines, as none of the discussed studies considers these factors explicitly. The features are included in both the LP model and heuristics.

The usage of berth lines to simplify the application of Tabu Search is also new. The usage of berth lines makes the solutions space easier to explore. Cordeau et al. (2005) use a different concept to apply Tabu Search to a continuous quay layout, the application of berth lines is a new contribution to the field.

The QC allocation algorithm is a new heuristic for solving the QCAP. Although the performance of the complete solution method with the BAP heuristics and the QC allocation algorithm is poor, the heuristic is a new contribution. There are no studies that consider crew shifts and schedule QCs in time sections that are fractions of a crew shift. As the availability of QC teams is limited and a high portion of the cost, optimizing QC team usage can significantly improve the performance.

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Appendix A

LP Models

A.1 Continous quay model

This section presents a model to solve the BAP and QCAP simultaneously to optimality. The model can generate a basic schedule that adheres to all applicable constraints and simultaneously has the lowest total cost. The model extends the model of Xiang et al. (2018) and Han et al. (2015). Contradictory to the model of Xiang et al. (2018), this model is based on a continuous quay. However, it uses sections of a pre-defined size, not a fully continuous quay as used in Han et al. (2015). A notable difference with many other models is the inclusion of exchange time and mooring length, these concepts are not implanted in Xiang et al. (2018) and Han et al. (2015).

Compared to the model of Xiang et al. (2018) the model is extended with the allocation of teams. Furthermore, multiple types of vessels can be included and the model supports windows. The objective function is changed slightly to include these features. Compared to the model of Han et al. (2015) there are more substantial changes. Several features are added, such as the draft of a vessel and allocation of specific QCs. Han et al. (2015) do include the availability of QCs but do connect that to team allocation in shifts.

In the following sections we discuss the notation used to formulate the model.

Sets & Indices

v	index of vessels, $v = 1, ..., V$
q	index of quay sections, $q = 1, ..., Q$
t	index of time sections, $t = 0, ..., T$
qc	index of quay cranes, $qc = 1, ..., QC$
s	index of shift, $s = 0, ..., S$
typ	index of Types set, $typ = F, D$
win	index of Windows set, $win = inwindow, outwindow$

Parameters

Vessel related	
ETA_v	The expected arrival time of vessel v
PTD_v	The preferred time of departure of v
l_v	The length of vessel v in quay sections
w_v	The workload of vessel v in time sections for one QC
ma_v	The maximum number of QCs that can be allocated to vessel v simultaneously
d_v	The maximum draft of vessel v during its stay
$type_{v,typ}$	Type indication of the vessel, 1 if vessel v is of type typ, 0 otherwise
$window_{v,win}$	Indication for arrival, 1 if vessel v arrives according to win, 0 otherwise
b_v	The preferred quay section for the front of vessel v
ex_v	Number of time sections needed for exchanging vessel v per arrival/departure
mo_v	Number of quay sections needed for mooring vessel v per side
Shift related	
$aShift_s$	Number of available teams in shift s
ts	Length of a shift in time sections
Time related	
a_t	Number of available teams in time section t, $a_t = aShift_{t-(t mod ts))/ts}$
Quay related	
$depth_q$	Depth of quay section q
QC related	
$r_{qc,q}$	Reach per QC, 1 if QC qc has quay section q in reach, 0 otherwise
Cost related	
$c1$	Cost per team deployed in a shift
$c2$	Cost per set up of a QC
$c3_{typ,win}$	Cost of delay per time section for a vessel of type typ and arrival according to win
$c4$	Cost per quay section deviation from the preferred mooring position based on the number of containers and period till ETA

Decision variables

The decisions to be made by the model are represented by the following decision variables:

$U_{v,q,t}$	1 if quay section q is occupied by vessel v at time section t, 0 otherwise
$Z_{v,qc,t}$	1 if QC qc services vessel v at time section t, 0 otherwise

Auxiliary variables

The value of the following variables are determined based on the value of the decision variables and are used to check all constraints and calculate the objective function value:

$R_{v,q,t}$	1 if quay section q is reserved for vessel v at time section t, 0 otherwise
$W_{v,qc,t}$	1 if $Z_{v,qc,t} - Z_{v,qc,t-1} \geq 1$; 0 otherwise, this denotes that QC qc is set up for vessel v at time section t
$S_{v,t}$	1 if $\sum_{qc=1}^{QC} Z_{v,qc,t} \geq 1$; 0 otherwise, this denotes if vessel v is serviced at time section t
$SN_{v,t}$	1 if $S_{v,t} = 0$; 0 otherwise, this denotes if vessel v is not serviced at time section t
$P_{v,t}$	1 if $\sum_{q=1}^{Q} R_{v,q,t} \geq 1$; 0 otherwise, this denotes if vessel v is present at time section t
$PN_{v,t}$	1 if $PN_{v,t} = 0$; 0 otherwise, this denotes if vessel v is not present at time section t
$SB_{v,t}$	1 if the starting time of vessel v is at time section t, 0 otherwise
$CB_{v,t}$	1 if the completion time of vessel v is at time section t, 0 otherwise
$AB_{v,t}$	1 if the arrival time of vessel v is at time section t, 0 otherwise
AT_v	$AT_v = t$ if $AB_{v,t} = 1$; arrival time of vessel v
$DB_{v,t}$	1 if the departure time of vessel v is at time section t, 0 otherwise
DT_v	$DT_v = t$ if $DB_{v,t} = 1$; departure time of vessel v
$FU_{v,q,t}$	1 if quay section q is the left-most quay section used by vessel v at time section t, 0 otherwise
$LU_{v,q,t}$	1 if quay section q is the right-most quay section used by vessel v at time section t, 0 otherwise
$FR_{v,q,t}$	1 if quay section q is the left-most reserved quay section for vessel v at time section t, 0 otherwise
$LR_{v,q,t}$	1 if quay section q is the right-most reserved quay section for vessel v at time section t, 0 otherwise
$LQC_{v,qc,t}$	1 if QC qc is the left-most QC used by vessel v at time section t, 0 otherwise
$RQC_{v,qc,t}$	1 if QC qc is the right-most QC used by vessel v at time section t, 0 otherwise
T_s	Number of teams allocated in shift s
$Delay_v$	Departure delay of vessel v
$Deviation_v$	Deviation from preferred quay section for vessel v

Figure A.1 provides a visualization of the relationship between several variables.

Objective function

The objective for the model is composed as follows:

$minf = \sum_{v=1}^{V}(c4 * Deviation_v + \sum_{type \in Types} \sum_{win \in Windows} c3_{typ,win} * typ_{v,typ} * window_{v,win} * Delay_v + \sum_{tqc=1}^{QC} \sum_{t=0}^{T} c2 * W_{v,qc,t}) + \sum_{s=0}^{S} c1 * T_s$

The objective function consists of four parts. For every vessel, it incorporates the cost for a delayed departure and the deviation between the preferred mooring location and the actual location. The third part is related to the usage of QCs and includes the set up cost for the QCs. The fourth part incorporates the cost for the teams that are used. The objective is to minimize the total of these four costs.

Constraints

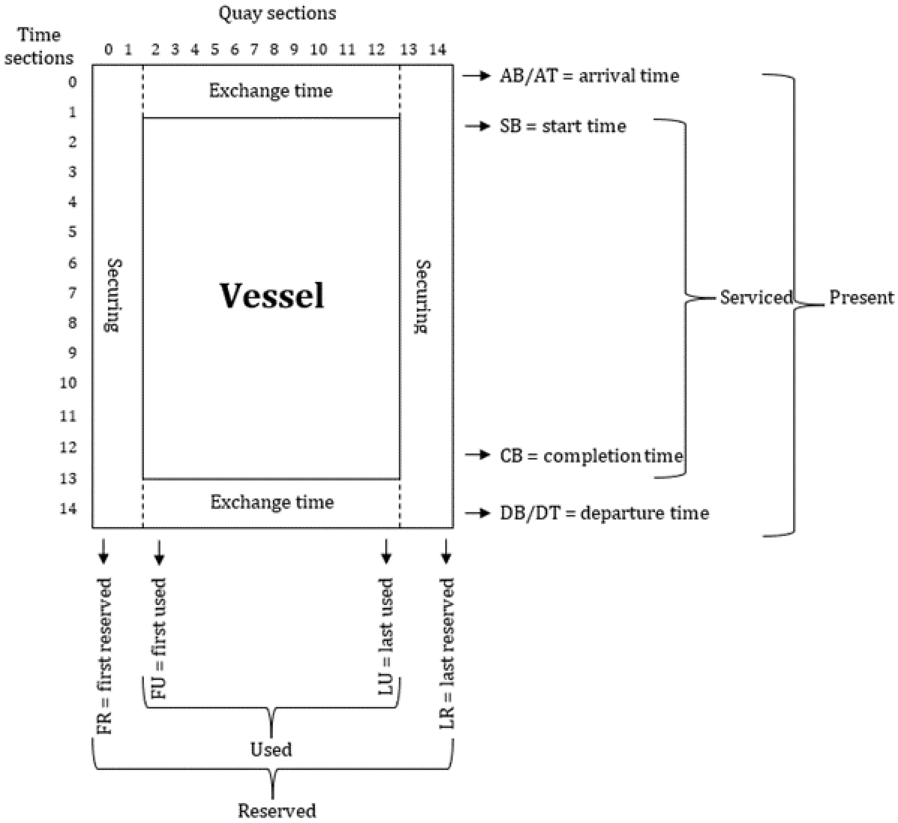

FIGURE A.1: Relation between variables LP model

<u>Service location related</u>

$$\sum_{q=1}^{Q} FU_{v,q,t} = S_{v,t}, \quad \forall v \in V, t \in T \tag{1}$$
$$\sum_{q=1}^{Q-l_v+1} FU_{v,q,t} = S_{v,t}, \quad \forall v \in V, t \in T \tag{2}$$
$$\sum_{q=1}^{Q} LU_{v,q,t} = S_{v,t}, \quad \forall v \in V, t \in T \tag{3}$$
$$\sum_{v=1}^{V} U_{v,q,t} \leq 1, \quad \forall t \in T, q \in Q \tag{4}$$
$$FU_{v,q,t} = LU_{v,q+l_v-1,t}, \quad \forall v \in V, t \in T, q = 1, ..., Q - l_v + 1 \tag{5}$$
$$FU_{v,0,t} - U_{v,0,t} = 0, \quad \forall v \in V, t \in T \tag{6}$$
$$LU_{v,Q,t} - U_{v,Q,t} = 0, \quad \forall v \in V, t \in T \tag{7}$$
$$U_{v,q,t} - U_{v,q-1,t} - FU_{v,q,t} \leq 0, \quad \forall v \in V, t \in T, q = 2, ..., Q \tag{8}$$
$$U_{v,q,t} - U_{v,q-1,t} - 2 * FU_{v,q,t} + 1 \geq 0, \quad \forall v \in V, t \in T, q = 2, ..., Q \tag{9}$$
$$U_{v,q,t} - U_{v,q+1,t} - LU_{v,q,t} \leq 0, \quad \forall v \in V, t \in T, q = 1, ..., Q - 1 \tag{10}$$
$$U_{v,q,t} - U_{v,q+1,t} - 2 * LU_{v,q,t} + 1 \geq 0, \quad \forall v \in V, t \in T, q = 1, ..., Q - 1 \tag{11}$$
$$FU_{v,q,t} - FU_{v,q,t-1} - (S_{v,t} + S_{v,t-1}) + 2 \geq 0, \quad \forall v \in V, t = 1, ..., T, q \in Q \tag{12}$$
$$FU_{v,q,t} - FU_{v,q,t-1} + (S_{v,t} + S_{v,t-1}) - 2 \leq 0, \quad \forall v \in V, t = 1, ..., T, q \in Q \tag{13}$$

Constraints (1)-(3) ensure that each vessel has one left-most position and one right-most position along the quay. Constraint (4) ensures that no more than one vessel is allocated per time and quay section. The right-most position along the quay of the vessel is set in constraint (5). Constraints (6)-(11) connect all used quay sections allocated to a vessel. As switching berthing position during service is not possible, constraints (12)-(13) make switching positions impossible.

<u>Time related</u>

$$AT_v \geq ETA_v, \quad \forall v \in V \tag{14}$$
$$SB_{v,0} = S_{v,0}, \quad \forall v \in V \tag{15}$$
$$S_{v,t} - S_{v,t-1} - SB_{v,t} \leq 0, \quad \forall v \in V, \text{t = 1, ...,T} \tag{16}$$
$$S_{v,t} - S_{v,t-1} - 2 * SB_{v,t} + 1 \geq 0, \quad \forall v \in V, \text{t = 1, ...,T} \tag{17}$$
$$\textstyle\sum_{t=0}^{T} SB_{v,t} = 1, \quad \forall v \in V \tag{18}$$
$$CB_{v,T} = S_{v,T}, \quad \forall v \in V \tag{19}$$
$$S_{v,t} - S_{v,t+1} - CB_{v,t} \leq 0, \quad \forall v \in V, \text{t = 0, ...,T-1} \tag{20}$$
$$S_{v,t} - S_{v,t+1} - 2 * CB_{v,t} + 1 \geq 0, \quad \forall v \in V, \text{t = 0, ...,T-1} \tag{21}$$
$$\textstyle\sum_{t=0}^{T} CB_{v,t} = 1, \quad \forall v \in V \tag{22}$$

Constraint (14) ensures that the vessel does not arrive before the earliest time that the vessel can arrive. Constraints (15)-(18) set the binary start of the service variable. The binary completion variable is set by constraints (19-22).

<u>Service related</u>

$$S_{v,t} * ma_v \geq \textstyle\sum_{qc=1}^{QC} Z_{v,qc,t}, \quad \forall v \in V, t \in T \tag{23}$$
$$S_{v,t} + SN_{v,t} = 1, \quad \forall v \in V, t \in T \tag{24}$$
$$SN_{v,t1+1} \leq SN_{v,t1} + SN_{v,t2}, \quad \forall v \in V, t1, t2 \in T, t2 \geq t1 + 2 \tag{25}$$

Constraint (23) links allocated QCs to the binary service variable. In constraint (24) the complement is set, which is used to ensure continuous service in constraint (25).

<u>QC related</u>

$$\textstyle\sum_{v=1}^{V} Z_{v,qc,t} \leq 1, \quad \forall t \in T, qc \in QC \tag{26}$$
$$\textstyle\sum_{t=0}^{T} \sum_{qc=1}^{QC} Z_{v,qc,t} \geq w_v, \quad \forall v \in V \tag{27}$$
$$\textstyle\sum_{qc=1}^{QC} Z_{v,qc,t} \leq ma_v, \quad \forall v \in V, t \in T \tag{28}$$
$$W_{v,qc,0} - Z_{v,qc,0} = 0, \quad \forall v \in V, qc \in QC \tag{29}$$
$$Z_{v,qc,t} - Z_{v,qc,t-1} - W_{v,qc,0} \leq 0, \quad \forall v \in V, t = 1, ..., T, qc \in QC \tag{30}$$
$$Z_{v,qc,t} - Z_{v,qc,t-1} - 2 * W_{v,qc,0} + 1 \geq 0, \quad \forall v \in V, t = 1, ..., T, qc \in QC \tag{31}$$
$$LQC_{v,0,t} - Z_{v,0,t} = 0, \quad \forall v \in V, t \in T \tag{32}$$
$$Z_{v,qc,t} - Z_{v,qc-1,t} - LQC_{v,qc,t} \leq 0, \quad \forall v \in V, t \in T, qc = 2, ..., QC \tag{33}$$
$$Z_{v,qc,t} - Z_{v,qc-1,t} - 2 * LQC_{v,qc,t} + 1 \geq 0, \quad \forall v \in V, t \in T, qc = 2, ..., QC \tag{34}$$
$$RQC_{v,QC,t} - Z_{v,QC,t} = 0, \quad \forall v \in V, t \in T \tag{35}$$
$$Z_{v,qc,t} - Z_{v,qc+1,t} - RQC_{v,qc,t} \leq 0, \quad \forall v \in V, t \in T, qc = 1, ..., QC - 1 \tag{36}$$
$$Z_{v,qc,t} - Z_{v,qc+1,t} - 2 * RQC_{v,qc,t} + 1 \geq 0, \quad \forall v \in V, t \in T, qc = 1, ..., QC - 1 \tag{37}$$
$$\textstyle\sum_{qc=1}^{QC} LQC_{v,qc,t} \leq 1, \quad \forall v \in V, t \in T \tag{38}$$
$$Z_{v,qc,t} * r_{qc,q} \geq Used_{v,q,t} - (1 - Z_{v,qc,t}), \quad \forall v \in V, t \in T, q \in Q, qc \in QC \tag{39}$$

Constraint (26) ensures that a QC is scheduled only once per time section. Constraint (27) makes sure that enough QC hours are allocated to process the complete workload. However, there is a maximum number of QCs that can service the vessel simultaneously, this is verified in constraint (28). Constraint (29)-(31) set the QC set up variable. The left-most QC and the right-most QC at each time segment are identified in constraints (32)-(34) and (35)-(37). Constraint (38) assigns all QCs between the let-most QC and right-most QC to the vessel. Constraint (39) ensures that all allocated QCs have the complete vessel in reach.

<u>Quay related</u>

$$d_v * Res_{v,q,t} \leq depth_q * Res_{v,q,t}, \quad \forall v \in V, t \in T, q \in Q \tag{40}$$

<u>Team related</u>

$$\textstyle\sum_{v=1}^{V} \sum_{qc=1}^{QC} Z_{v,qc,t} = a_t, \quad \forall t \in T \tag{41}$$
$$aShift_s \geq \textstyle\sum_{v=1}^{V} \sum_{qc=1}^{QC} Z_{v,qc,s*ts+i}, \quad \forall s \in S, i = 0, ..., ts - 1 \tag{42}$$

Constraint (40) checks for all reserved quay sections if the depth of the quay section is sufficient for the draft of the vessel. Constraint (41) ensures that the maximum number of teams available per time section is not exceeded. Constraint (42) set the maximum number of teams that are allocated per shift.

Exchange time

$\sum_{t=0}^{T} AB_{v,t} = 1, \quad \forall v \in V$ (43)

$\sum_{t=0}^{T-ex_v} AB_{v,t} = 1, \quad \forall v \in V$ (44)

$AB_{v,t} = SB_{v,t+ex_v}, \quad \forall v \in V, t = 0, ..., T - ex_v$ (45)

$\sum_{t=0}^{T} t * AB_{v,t} = AT_v, \quad \forall v \in V$ (46)

$\sum_{t=0}^{T} DB_{v,t} = 1, \quad \forall v \in V$ (47)

$DB_{v,t} = CB_{v,t-ex_v}, \quad \forall v \in V, t = ex_v, ..., T$ (48)

$\sum_{t=0}^{T} t * DB_{v,t} = DT_v, \quad \forall v \in V$ (49)

Constraints (43)-(45) set the binary arrival variable, which is used in constraint (46) to set the arrival time. The binary departure variable is set by constraints (47)-(48), which is used to set the departure time in constraint (49).

Moor length

$FR_{v,q,t} \geq FU_{v,q+mo_v,t}, \quad \forall v \in V, t \in T, q = 0, ..., Q - mo_v$ (50)

$LR_{v,q,t} \geq LU_{v,q-mo_v,t}, \quad \forall v \in V, t \in T, q = mo_v, ..., Q$ (51)

Reserved location related

$\sum_{q=1}^{Q} FR_{v,q,t} = P_{v,t}, \quad \forall v \in V, t \in T$ (52)

$\sum_{q=1}^{Q} LR_{v,q,t} = P_{v,t}, \quad \forall v \in V, t \in T$ (53)

$FR_{v,q,t} = LR_{v,q+l_v+2*mo_v,t}, \quad \forall v \in V, t \in T, q = 0, ..., Q - l_v - 2 * mo_v$ (54)

$R_{v,q,t} \geq U_{v,q,t}, \quad \forall v \in V, t \in T, q \in Q$ (55)

$\sum_{v=1}^{V} R_{v,q,t} \leq 1, \quad \forall t \in T, q \in Q$ (56)

$FR_{v,0,t} - R_{v,0,t} = 0, \quad \forall v \in V, t \in T$ (57)

$RU_{v,Q,t} - R_{v,Q,t} = 0, \quad \forall v \in V, t \in T$ (58)

$R_{v,q,t} - R_{v,q-1,t} - FR_{v,q,t} \leq 0, \quad \forall v \in V, t \in T, q = 2, ..., Q$ (59)

$R_{v,q,t} - R_{v,q-1,t} - 2 * FR_{v,q,t} + 1 \geq 0, \quad \forall v \in V, t \in T, q = 2, ..., Q$ (60)

$R_{v,q,t} - R_{v,q+1,t} - LR_{v,q,t} \leq 0, \quad \forall v \in V, t \in T, q = 1, ..., Q - 1$ (61)

$R_{v,q,t} - R_{v,q+1,t} - 2 * LR_{v,q,t} + 1 \geq 0, \quad \forall v \in V, t \in T, q = 1, ..., Q - 1$ (62)

$FR_{v,q,t} - FR_{v,q,t-1} - (P_{v,t} + P_{v,t-1}) + 2 \geq 0, \quad \forall v \in V, t = 1, ..., T, q \in Q$ (63)

$FR_{v,q,t} - FR_{v,q,t-1} + (P_{v,t} + P_{v,t-1}) - 2 \leq 0, \quad \forall v \in V, t = 1, ..., T, q \in Q$ (64)

Constraints (50) and (51) include the length for securing the vessel on each side. Constraints (52) and (53) ensure that there is only one left-most and one right-most reserved quay section. Constraint (54) connects these two. Constraint (55) ensures that all used quay sections are also reserved. Constraint (56) ensures that no more than one vessel is allocated per reserved time and quay section. Constraints (57)-(62) connect all reserved quay sections allocated to a vessel. As switching berthing position during service is not possible, constraints (63)-(64) make switching positions impossible.

Present related

$AB_{v,0} - P_{v,0} = 0, \quad \forall v \in V$ (65)

$P_{v,t} - P_{v,t-1} - AB_{v,t} \leq 0, \quad \forall v \in V, t = 1, ..., T$ (66)

$P_{v,t} - P_{v,t-1} - 2 * AB_{v,t} + 1 \geq 0, \quad \forall v \in V, t = 1, ..., T$ (67)

$DB_{v,t} - P_{v,t} = 0, \quad \forall v \in V$ (68)

$P_{v,t} - P_{v,t+1} - DB_{v,t} \leq 0, \quad \forall v \in V, t = 0, ..., T - 1$ (69)

$P_{v,t} - P_{v,t+1} - 2 * DB_{v,t} + 1 \geq 0, \quad \forall v \in V, t = 0, ..., T - 1$ (70)

$P_{v,t} \geq S_{v,t}, \quad \forall v \in V, t \in T$ (71)

$P_{v,t} + PN_{v,t} = 1, \quad \forall v \in V, t \in T$ (72)

$PN_{v,t1+1} \leq PN_{v,t1} + PN_{v,t2}, \quad \forall v \in V, t1, t2 \in T, t2 \geq t1 + 2$ (73)

Constraint (65)-(70) set the binary present variable using the binary arrival and departure variable. Constraint (71) ensures that if a vessel is serviced it is also present. In constraint (72) the complement of the present variable is set, which is used to ensure continuous service in constraint (73).

$$U_{v,q,t}, R_{v,q,t}, Z_{v,qc,t}, W_{v,qc,t}, S_{v,t}, SN_{v,t}, P_{v,t}, PN_{v,t}, SB_{v,t}, CB_{v,t}, AB_{v,t}, DB_{v,t}, FU_{v,q,t}, LU_{v,q,t}, FR_{v,q,t}, LR_{v,q,t}, LQC_{v,qc,t}, RQC_{v,qc,t} \in \{0,1\} \quad (74)$$

$$AT_v, DT_v, T_s, Delay_v, Deviation_v \in \mathbb{N} \quad (75)$$

Constraints (74) and (75) are the binary and integer variable constraints.

A.2 Discrete quay model

The model for a discrete quay layout is largely similar to the model for a continuous layout. Instead of a set of quay sections, the model has a set of berths. The preferred mooring position b_v is converted into a preferred berth. In the model, QCs no longer have a range of quay sections that they can cover, but are coupled to one or more berths.

The length needed for securing the vessel becomes redundant, as for each berth the maximum length of a vessel is specified. The length needed for securing the vessel is included in the total berth length. The depth is now specified per berth instead of per quay section. The smallest depth is the bound for the depth of a berth. Using the length and depth of each berth, we make a set $suit\_berth_v$, that contains all berths suitable for handling the vessel.

The decision variable for quay section usage changes to berth usage. The objective does not change, although the calculation of deviation in mooring position $Deviation_v$ does change. For each berth b, we can calculate the middle quay section mid_b and subsequently, calculate $Deviation_v$ as $abs(mid_b - (b_v + \lceil l_v / length\_quay\_section/2 \rceil)$.

In the following sections we discuss the notation used to formulate the model.

Sets & Indices

v	index of vessels, $v = 1, ..., V$
b	Index of berths, $b = 1, ..., B$
$suit\_berth_v$	Set of suitable berths for vessel v
t	index of time sections, $t = 0, ..., T$
qc	index of quay cranes, $qc = 1, ..., QC$
s	index of shift, $s = 0, ..., S$
typ	index of Types set, $typ = F, D$
win	index of Windows set, $win = inwindow, outwindow$

Parameters

Vessel related	
ETA_v	The expected arrival time of vessel v
PTD_v	The preferred time of departure of v
l_v	The length of vessel v in meters including length needed for mooring
w_v	The workload of vessel v in time sections for one QC
ma_v	The maximum number of QCs that can be allocated to vessel v simultaneously
d_v	The maximum draft of vessel v during its stay
$type_{v,typ}$	Type indication of the vessel, 1 if vessel v is of type typ, 0 otherwise
$window_{v,win}$	Indication for arrival, 1 if vessel v arrives according to win, 0 otherwise
b_v	The preferred berth for vessel v
ex_v	Number of time sections needed for exchanging vessel v per arrival/departure
Shift related	
$aShift_s$	Number of available teams in shift s
ts	Length of a shift in time sections
Time related	
a_t	Number of available teams in time section t, $a_t = aShift_{t-(tmodts))/ts}$
Berth related	
$depth_b$	Depth of berth b
len_b	Length of berth b in meters
QC related	
$r_{qc,b}$	Reach per QC, 1 if QC qc can service a vessel in berth b, 0 otherwise
Cost related	
$c1$	Cost per team deployed in a shift
$c2$	Cost per set up of a QC
$c3_{typ,win}$	Cost of delay per time section for a vessel of type typ and arrival according to win
$c4$	Cost per quay section deviation from the preferred mooring position based on the number of containers and period till ETA

Berth b is suitable for vessel v if $dept_b \geq d_v$ and $len_b \geq l_v$.

Decision variables

The decisions to be made by the model are represented by the following decision variables:

$U_{v,b,t}$	1 if berth b is occupied by vessel v at time section t, 0 otherwise
$Z_{v,qc,t}$	1 if QC qc services vessel v at time section t, 0 otherwise

Auxiliary variables

The value of the following variables are determined based on the value of the decision variables and are used to check all constraints and calculate the objective function value:

$X_{b,qc,v,t}$	1 if berth b is occupied by vessel v and serviced by QC qc at time section t, 0 otherwise
$R_{v,b,t}$	1 if berth b is reserved for vessel v at time section t, 0 otherwise
$W_{v,qc,t}$	1 if $Z_{v,qc,t} - Z_{v,qc,t-1} \geq 1$; 0 otherwise, this denotes that QC qc is set up for vessel v at time section t
$S_{v,t}$	1 if $\sum_{qc=1}^{QC} Z_{v,qc,t} \geq 1$; 0 otherwise, this denotes if vessel v is serviced at time section t
$P_{v,t}$	1 if $\sum_{b=1}^{B} R_{v,q,t} \geq 1$; 0 otherwise, this denotes if vessel v is present at time section t
$A_{v,b}$	1 if vessel v is assigned berth b; 0 otherwise
B_v	berth number assigned to vessel v
$SB_{v,t}$	1 if the starting time of vessel v is at time section t, 0 otherwise
$CB_{v,t}$	1 if the completion time of vessel v is at time section t, 0 otherwise
$AB_{v,t}$	1 if the arrival time of vessel v is at time section t, 0 otherwise
AT_v	$AT_v = t$ if $AB_{v,t} = 1$; arrival time of vessel v
$DB_{v,t}$	1 if the departure time of vessel v is at time section t, 0 otherwise
DT_v	$DT_v = t$ if $DB_{v,t} = 1$; departure time of vessel v
$LQC_{v,qc,t}$	1 if QC qc is the left-most QC used by vessel v at time section t, 0 otherwise
$RQC_{v,qc,t}$	1 if QC qc is the right-most QC used by vessel v at time section t, 0 otherwise
T_s	Number of teams allocated in shift s
$Delay_v$	Departure delay of vessel v
$Deviation_v$	Deviation from preferred berth for vessel v

Appendix B

Data study

The circumstances to form a plan are very dynamic, a plan depends on many inputs that are changed often. This section provides data that displays this variability. The analysed data concerns the period from 2019 week 1 till 2021 week 40.

There is a limitation in the data analysis due to the availability of data. The system used for berth planning does not support storing the ETA of a vessel in the database. The planners use a text field without a consequent format for storing the ETA of a vessel, which means that this data is not accessible. The system does store the STA, this value is the first time that there is a place in the plan for the vessel after the ETA of the vessel. This means that the STA represents two values, it is the maximum of the ETA and the first place in the planning. If possible, the STA is used as a replacement for the ETA.

The disadvantage of using the STA as a replacement of the ETA is that it is not known what the cause of a change is if the STA is changed. There are two options, either the vessel is delayed (the vessel changes its ETA) or something is changed in the plan and the vessel has to move (start time of the vessel changes). A delay of the vessel is often caused by the shipping company, a delay of the start time is often caused by Company X. Unfortunately, it is currently not possible to distinguish between these causes.

Another limitation is that the ATA of a vessel in the port is not stored in the database. The ATA in the berth is stored. If the ATA in the port is unknown, it impossible to compare the ETA with the ATA. This makes it impossible to analyse delays of vessels. Furthermore, it is not possible to analyse waiting times of vessels. A vessel might have arrived already and be waiting until the STA, but as the ATA in the port is not stored, the difference between the STA and ATA, which is the waiting time, is not known. This means that delays due to a full plan or delays due to prioritization of another vessel are not noticeable.

B.1 In window

The windows in the proforma schedule are the basis for the berth plan. Deviations from the window often result in overlapping visits, making the planning more complex. Arrival in window is defined as the start time of the window + or - four hours. A window is appointed if a vessel is first announced, however, the window is updated retrospectively. The definite window is the window that is closest to the ETA of the vessel two weeks before the actual visit. This reduces the number of extreme window delays and provides a more realistic view as major delays incurred on other continents do not influence the performance in Rotterdam.

Because of the limitation described earlier, the ATA in the berth is used instead of the ATA in the port. The ATA in the berth is compared with the start of the window to analyse the performance. The downside of this method is that if a vessel arrived early in the port and there is no berth available then the vessel is not seen as early, as an arrival in the berth is only possible if a berth is available. Furthermore, it is not possible to trace back if a vessel missed its window because it was too late, or because there was no berth available.

Of all visits with a window, 17.3% of all deep-sea visits arrived in window. A small portion of 9.0% arrived early and could be serviced earlier. The largest portion, 55.5% missed their window. 18.3% of the vessels do not sail in a specific service and therefore they do not have a window. Missing a window can have many causes, the two most important are that the vessel itself is late, or that there is no berth available.

There are several degrees of severity of missing a window. A vessel that is early can simply wait until a berth is available. Vessels that are late need to be serviced in between other vessels that are in window. The severity of the delay is of important for this. As services have a weekly frequency, a vessel that is seven days too late might arrive at the same time as the next vessel scheduled in the service. Having two vessels of the same service at the same time often puts a lot of pressure on operations, having two discharge calls present at the same time will quickly fill up the stack for example. Therefore, delays of more than seven days have more impact than delays of several days.

Figure B.1 provides a histogram of the deviations from the original window starts. It gives the difference between the planned start of the window and the actual arrival for every deep-sea call with a window in the analysed period. The graph shows that most delays are less than 48 hours. Delays of more than two days also occur regularly, however most delayed vessels arrive within seven days. Around 2% of the vessels with a window have a delay of seven days or more. Of all vessels with a window, less than 1% is serviced two days or more in advance.

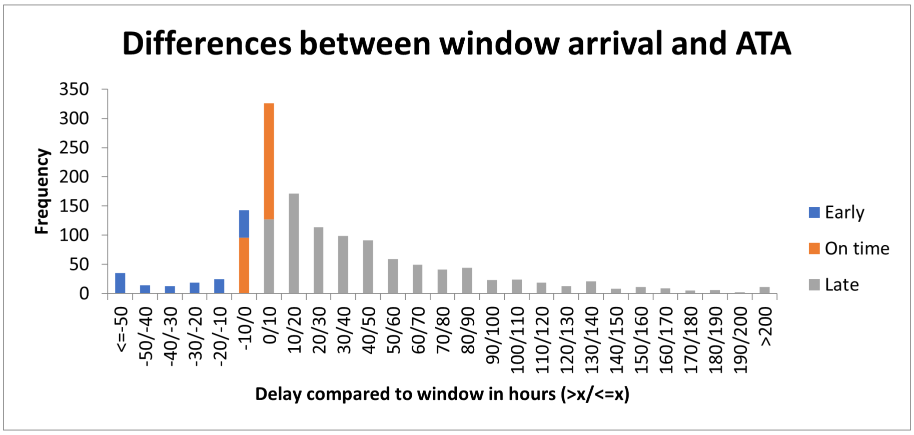

FIGURE B.1: Histogram of window arrival deviations

B.2 Deviations in First ETA, STA and ATA

As described in the current processes, the ETA of a vessel changes regularly. However, as this value is not stored, the STA is used as a replacement. In the following analysis, three timestamps are compared. The First ETA, the STA and the ATA. The First ETA is the ETA provided in the long term schedule in case of a deep-sea vessel and the estimated time of arrival provided if the vessel is announced in case of a feeder vessel. This value is stored once and not updated anymore.

The definition of STA is provided in the introduction of this section. This STA is only a few hours old in most cases, as the planned time of arrival is often updated in the system up to a few hours before the actual start of service. Therefore, it has small deviations compared to the ATA in most cases. The ATA is defined as the moment that the vessel is secured in the berth.

Figure B.2 and Figure B.3 provide the difference between the ATA and First ETA for all calls in the analysed period. A difference of zero means that the vessel arrived at the same moment as announced when it was first allocated. This is very rare, as there are many aspects that can influence the arrival time of a vessel. A smaller difference is better, as larger differences have a larger impact on the plan.

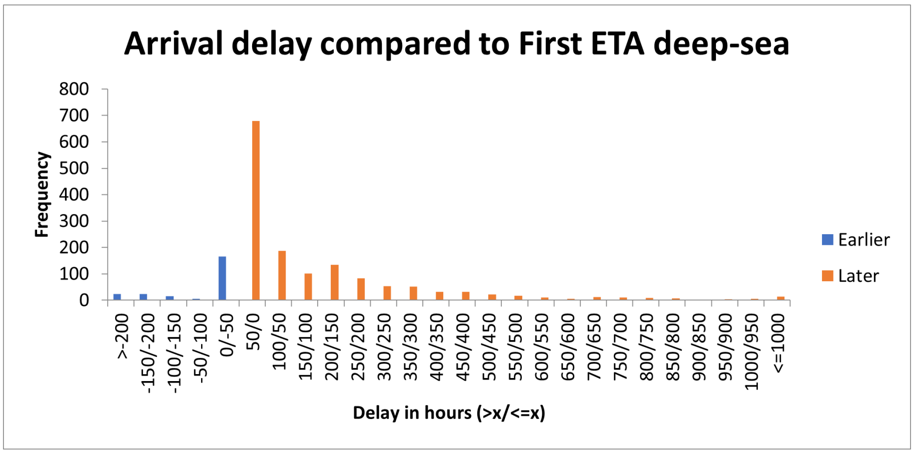

FIGURE B.2: Histogram of delays compared to First ETA deep-sea

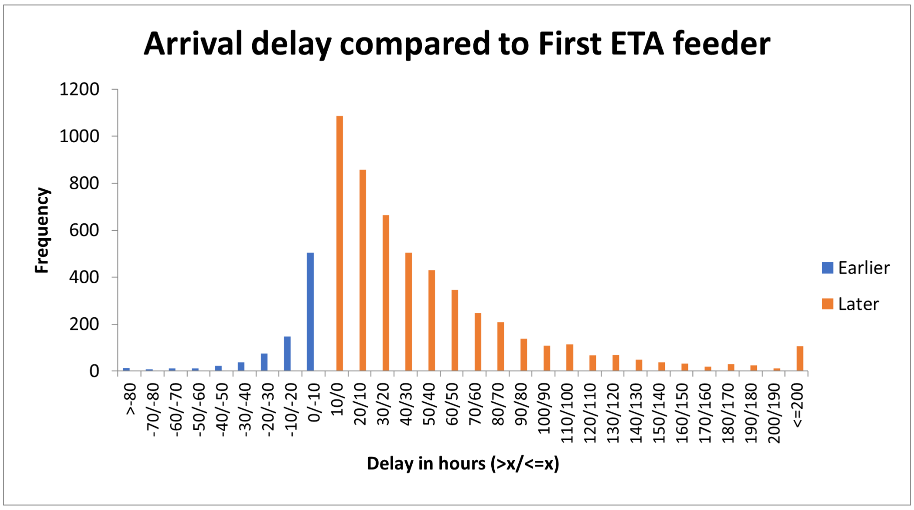

FIGURE B.3: Histogram of delays compared to First ETA feeder

The average difference between First ETA and ATA is approximately five days (119 hours) for deep-sea vessels. This means that on average a vessel arrives five days later than expected when the vessel was first entered in the planning system. However, Figure B.2 shows that most of the vessels have a deviation of approximately two days (-50/+50 hours), this is 49.4% of the vessels. 13.6% of the vessels arrive earlier than the First ETA, which means that the vessel arrived earlier than planned initially. Feeders are announced shorter in advance which makes it easier to estimate the time of arrival, the data also shows this. 81.3% of the feeders have a deviation within two days and there are fewer excessive delays. The percentage of vessels arriving early (13.9%) is similar to deep-sea vessels. Figure B.3 shows the distribution of the delays.

Figure B.4 and Figure B.5 show the difference between STA and ATA for the deep-sea and feeder vessels. A delay here means that the vessel got a delay in the last few hours before the arrival at the terminal. 87.5% of the deep-sea vessels arrive within one hour of the STA. For feeder vessels, this is 95.9%. The data shows that the STAs in this phase are relatively reliable, which is logical as they are often only a few hours old. In some cases the vessels have been waiting in the port or on the anchor point, reducing possible delays. Last moment delays are

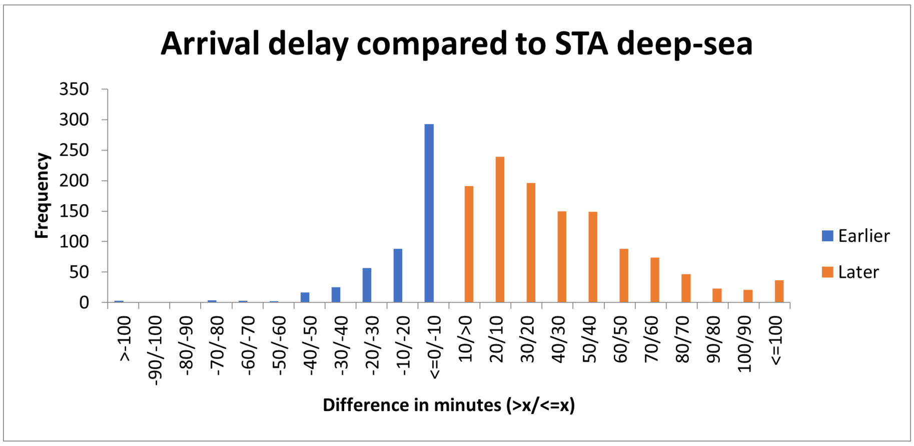

FIGURE B.4: Histogram of arrival delays compared to STA deep-sea

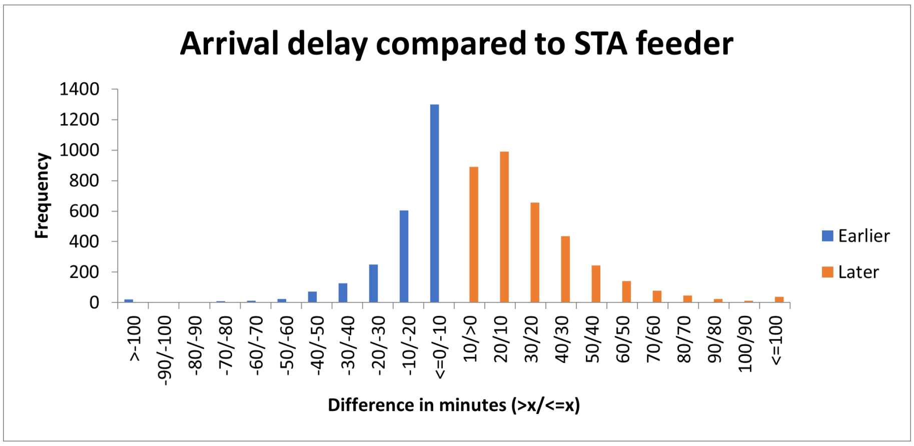

FIGURE B.5: Histogram of arrival delays compared to STA feeder

often caused by external factors, such as pilots or tugs that are not available. Feeders do not need a tug in most cases, which also explains why they are more reliable.

B.3 Changes in STA

The data shown so far shows the difference between the start and end situation. However, it does not show how often the situation changes in between. Figure B.6 provides insight on how often the STA of a vessel is changed. The displayed data show all changes that existed for fifteen minutes or more. Changes that existed less than fifteen minutes were filtered out, because in fifteen minutes the impact of a change can easily be reversed. A deep-sea vessel has on average 11.7 unique STAs as a result of 11.8 changes. Only 5.5% of the deep-sea STAs is never updated. About 48% of the deep-sea vessels see more than ten updates.

Feeder vessels receive 12.3 STAs on average, based on 12.2 changes. Compared to deep-sea vessels, there are fewer feeder vessels that do not receive any changes, only 3.8% does not receive a STA change. This shows that feeder vessels are more dynamic than deep-sea vessels, even tough the First ETA is provided only seven days in advance, it is still changed more often compared to deep-sea vessels. 58% of the feeder vessels see more than ten unique STAs.

The changes in STA vary between fifteen minutes and a couple of days, this can be backward as well as forward. The causes of these changes are not logged, therefore it cannot be determined if the changes are due to Company Xs decisions or external influences. Possible

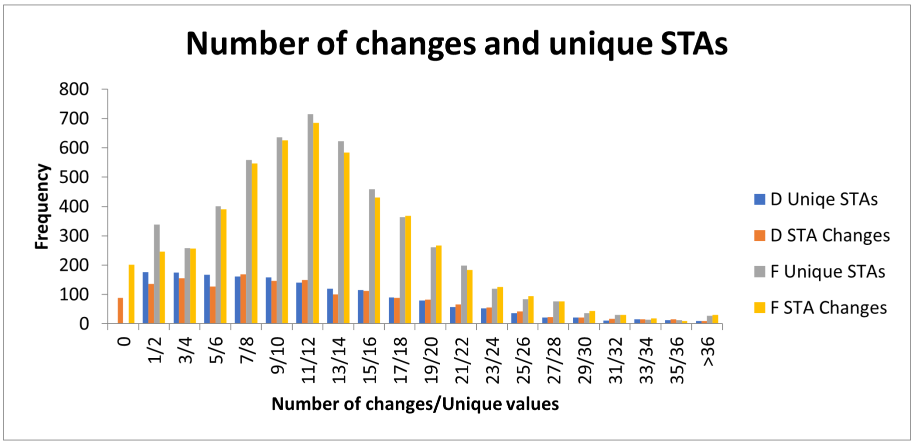

FIGURE B.6: Histogram of ETA change data

reasons are delays of vessels due to disruptions en route to the port or delays in other ports. Factors due to Company X are the unavailability of a berth due to for example maintenance, breakdowns of equipment or slowed service or delayed arrival of the previous vessel.

B.4 Changes in Moves

Together with the ETA, the number of moves is also provided in an announcement. The average call size for a deep-sea vessel is approximately 2.800 and for feeders 200. On average the Actual call size is equal to the Proforma call size. However, large deviations also occur. Approximately 33% of the deep-sea vessels have a deviation of more than 20% between the Actual and Proforma call size. Significantly larger or smaller call sizes often mean significant changes in service time as well. Especially if this happens shortly in advance. Approximately 83% of the Estimated call size is within a 5% bound of the Actual call size. Which indicates that the latest information is relatively reliable, this is also logical as the Estimated call size is the call size stored in the system a few hours before the arrival of a vessel.

For feeders, the average difference between First call size, the call size that is registered when a vessel is announced, and Actual call size is -7%. The Estimated and Actual call size differ -1% on average. For approximately 80% of the calls, the difference between the Estimated and Actual call size is less than 5%.

The data shows the difference between the start and end situation. However, it does not show how often the situation changes in the meantime. As explained in the current processes, there are three important moments for most calls. The initial estimated call size is provided in the announcement, which is later updated. This is also reflected in the data, as Figure B.7 shows. The data includes all changes that existed for fifteen minutes or more. Most calls see three or four unique call sizes. This is approximately 52% for deep-sea vessels and 46.4% for feeder vessels. This is a result of 2.9 changes in call size for deep-sea vessels and 2.8 changes for feeder vessels.

B.5 Change in Berths

A vessel is often moved from one berth to another to optimize the plan. However, this influences where the containers are stored in the stack and which QCs can be used. Therefore, it is interesting to analyse how often a vessel is moved in the plan. In this analysis, the fore-bollard is used as reference point for the berth along the quay. In some cases a vessel is only moved

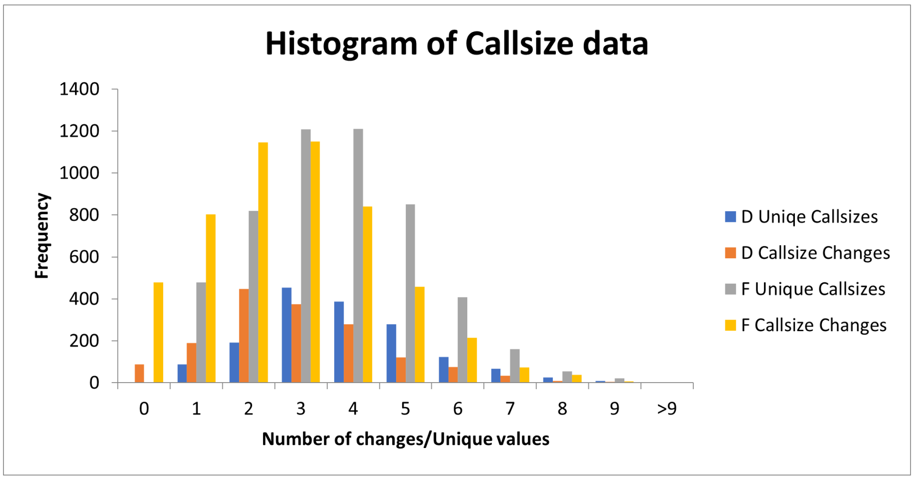

FIGURE B.7: Histogram of call size change data

one bollard, which is twenty metres, to make more space for a large vessel next to it for example. In other cases, a vessel is moved from one side of the quay to another, because service can start earlier in that berth for example. All changes that existed fifteen minutes or more are incorporated in the analysis.

Deep-sea vessels are placed in 7.7 unique places along the quay on average, for feeder vessels this value is 6.5. The fore-bollard is changed 9.4 times for deep-sea vessels and 7.8 times for feeder vessels on average. Figure B.8 shows a histogram of the number of changes and number of unique berths for both deep-sea and feeder vessels. The data shows that berth planners have many possibilities for placing vessels, as the quay is continuous and not split up in multiple berths, all vessels can be moved to several places, independent of the length of the vessel.

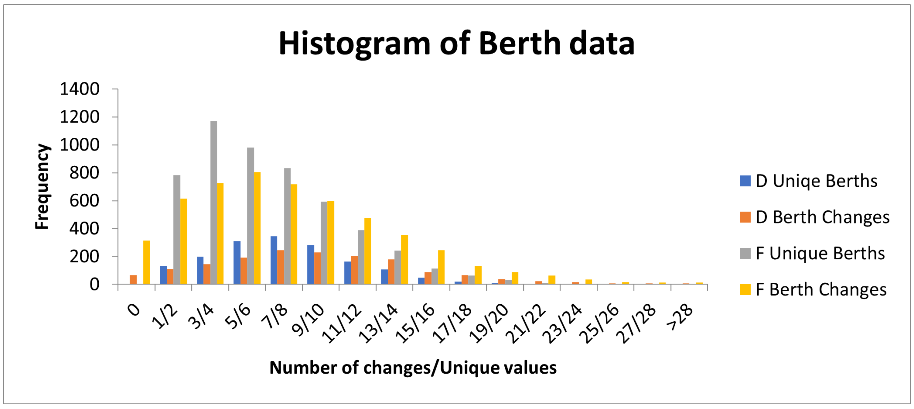

FIGURE B.8: Histogram of berth change data

B.6 Resource availability

Personnel is one of the resources that a berth planner uses in making decisions. The forecasts coming from the HR department are seen as reliable. Due to illness or other absences, deviations in the forecast sometimes occur. For employees that want to work overtime, it is possible to accept extra shifts if these are available. However, they often indicate this only a few shifts before the start of the actual shift. Furthermore, part of the personnel is hired from another company, this availability is only known a day in advance. These two factors make that the available personnel for a shift often changes.

Maintenance of QCs and other equipment is often planned in advance. It does not occur often that maintenance is scheduled only a day in advance. However, this is different for breakdowns, which are not planned. In most cases, the equipment can be repaired in a few hours and thus is outside the horizon of the plan. Yet in some cases, it does influence the plan, if the equipment has to stay out of service because parts are not available.

B.7 Performance

In the current situation, the performance is measured using several KPIs. Most of these KPIs are focused on production, such as BP, total moves and moves per manhour. However, these KPIs do not include all aspects. There is no dashboard that shows the delays caused by Company X for example. The logging of data to calculate these kinds of KPIs is still in development. This makes it hard to show the current performance in detail. Some aspects are logged and can be used to provide an insight into the performance.

B.7.1 Delayed departures

When a vessel is entered in the system, the end time of service is also estimated. The value that is used in this analysis is the STD that is registered in the system at the moment that the vessel arrives. Delays in service can have several causes, both internal and external. The causes for the delays are not elaborately logged, therefore it is difficult to determine if delays are caused by Company X, or external parties, or a combination. Common causes for delays are breakdowns of equipment, faulty containers or smoke emissions by vessels.

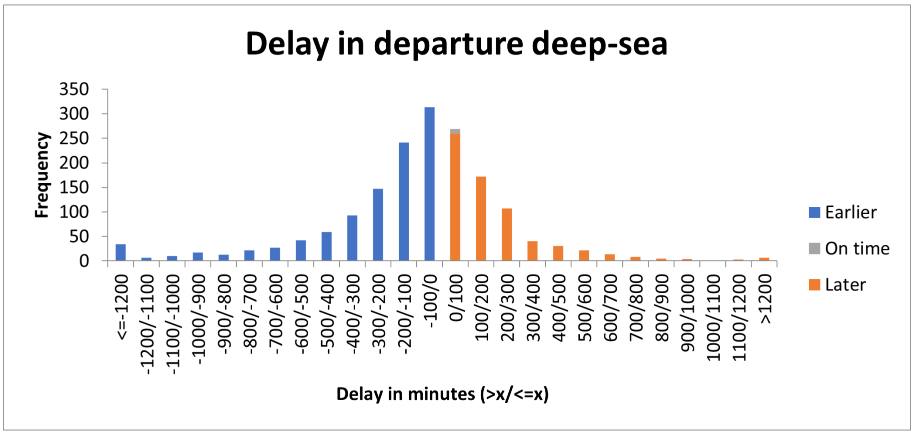

FIGURE B.9: Histogram of deep-sea departure deviations

Approximately 60% of all deep-sea vessels depart earlier than estimated. Figure B.9 shows the distribution of these differences. 92% of the deep-sea vessels have a maximum delay of five hours. This shows that berth planners are good at estimating how long service will take and/or can build in sufficient slack. Figure B.10 shows the distribution of differences for feeder vessels. 80% of the vessels have a maximum delay of 50 minutes. Even though the feeders are more dynamic, their smaller move counts reduce the probabilities of significant delays.

B.7.2 Productivity

The berth productivity (BP) is defined as the number of moves (including hatch covers) per hour. The average BP realized for deep-sea vessels is approximately 70, with an average crane

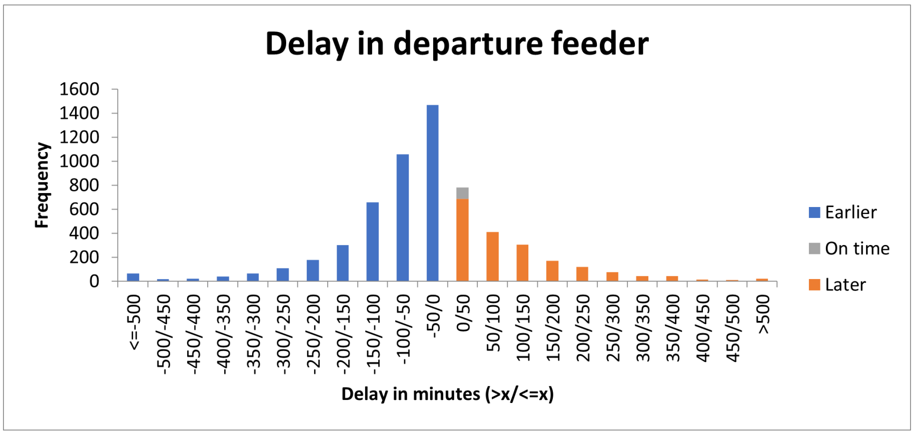

FIGURE B.10: Histogram of feeder departure deviations

split of 3.4. The crane split is the average number of QCs that worked on the vessel. For deep-sea vessels, the BP is fixed in the proforma schedules. If the BP is less than contractually agreed and the port stay is exceeded then shipping lines may file claims. In 63.4% of the deep-sea calls the BP was not met. This can have many causes, such as too few resources or external disturbances. The average difference between realized BP and contractual BP for all deep-sea vessels that did not meet the BP is -18%.

For feeder calls the BP is not contractually fixed, however, in most cases, a shorter service time is better for the shipping companies. The average BP for feeder vessels is 18.1 with a crane split of 1.2. Most feeders are serviced with one QC, only 35% of the calls was serviced by more than one QC.

B.7.3 Port stay

The port stay is the time between arrival and departure. For deep-sea vessels, the port stay is determined in the proforma schedule. This largely depends on the production, the port stay is calculated using the contractual moves and production. If the number of moves increases, but the production stays equal, the port stay will increase. Therefore, an increase in port stay is acceptable, as long as it is in ratio with the increase in moves. Figure B.11 shows all analysed deep-sea calls.

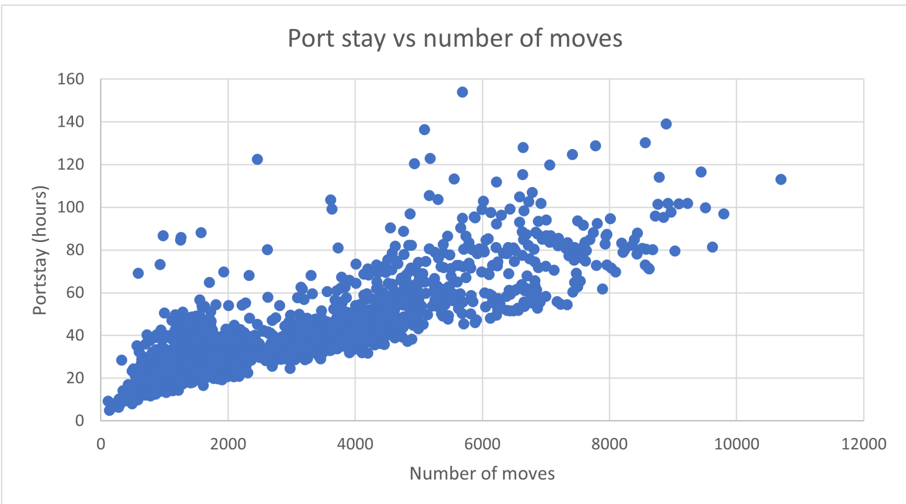

FIGURE B.11: Call size vs port stay

B.7.4 Quay occupancy

The quay occupancy is always calculated over a period and based on the product of the quay length and hours. The available capacity is the length of the quay multiplied by the number of hours in the analysed period. The used capacity is based on the length of the vessels that visited the terminal and the port stay of the visits. By dividing these two, the quay occupancy is calculated. The Gross Quay occupancy takes into account clearance meters and hours. Clearance meters is the length that is needed to secure vessels, this cannot be used by other vessels. Clearance hours are the hours that are needed to exchange vessels, it takes time for one vessel to leave the quay and the next vessel to berth. The quay occupancy can be used to analyse how efficient the quay is used, a higher occupancy is better.

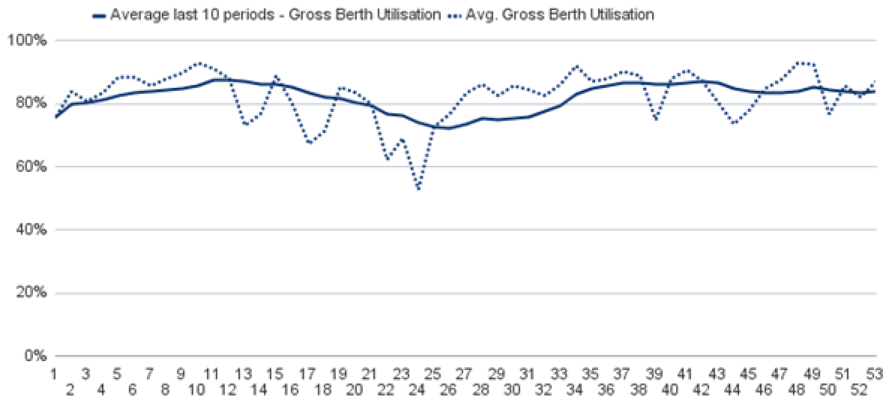

FIGURE B.12: Gross Quay Occupancy per week 2020

Figure B.12 shows the realized Gross Quay occupancy in 2020 and Figure B.13 shows the same for 2021. The occupancy fluctuates between 70% and 90%. The quay occupancy does not give a direct indication of productivity. The berth productivity can also be high while the BP is low. A low BP results in longer service times, which in turn result in longer port stays, and a queue forming. If there is a queue then there is no waiting time till the next vessel and the berth is always occupied. A high BP in combination with a high realized quay occupancy is the preferred situation.

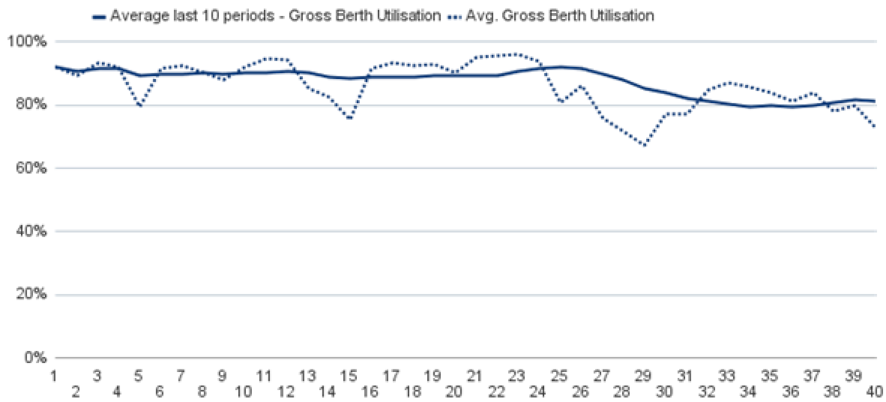

FIGURE B.13: Gross Quay occupancy per week 2021

Appendix C

Scenario data small problem instances

	ID	Name	Length	ETA	PTD	Moves	QC Hours	Type	Draft	Pref start sect	Pref mid sect	Pref berth	Max QC	In Window	Contractual BP
	100	AAAA	249	0	35	1250	63	1	16.3	8	14	1	4	0	60
	101	BBBB	162	30	47	650	33	1	12.8	8	14	1	4	1	60
	102	CCCC	94	0	10	155	8	0	9.2	1	4	0	3	0	20
Case 1	103	DDDD	100	20	29	128	7	0	11.5	1	4	0	3	0	20
	104	EEEE	87	30	36	81	5	0	8.9	8	10	1	2	0	20
	105	FFFF	98	37	42	69	4	0	8.2	1	4	0	3	0	20
	106	GGGG	93	45	55	104	6	0	10.1	1	4	0	3	0	20
	100	AAAA	249	0	35	1250	63	1	16.3	8	14	1	4	0	60
	101	BBBB	162	30	47	650	33	1	12.8	8	14	1	4	1	60
	102	CCCC	94	0	10	155	8	0	9.2	1	4	0	3	0	20
	103	DDDD	87	7	16	123	7	0	13.7	1	4	0	2	0	20
Case 2	104	EEEE	100	20	29	128	7	0	11.5	1	4	0	3	0	20
	105	FFFF	87	30	36	81	5	0	8.9	8	10	1	2	0	20
	106	GGGG	98	37	42	69	4	0	8.2	1	4	0	3	0	20
	107	HHHH	93	45	55	104	6	0	10.1	1	4	0	3	0	20
	100	AAAA	208	0	35	1550	78	1	13.2	8	14	1	4	1	60
	101	BBBB	154	42	55	550	28	1	12.5	8	14	1	3	0	60
	102	CCCC	84	0	15	278	14	0	9.2	1	4	0	2	0	20
Case 3	103	DDDD	84	12	19	98	5	0	13.7	1	4	0	2	0	20
	104	EEEE	87	20	27	26	2	0	11.5	1	4	0	2	0	20
	105	FFFF	63	30	42	43	3	0	8.9	1	4	0	2	0	20
	106	GGGG	94	37	58	69	4	0	8.2	1	4	0	3	0	20
	100	AAAA	153	25	59	1133	57	1	14.2	8	14	1	3	0	60
	101	BBBB	208	0	20	864	44	1	15.1	8	14	1	4	0	60
	102	CCCC	84	0	5	48	3	0	9.2	1	4	0	2	0	20
Case 4	103	DDDD	95	0	35	178	9	0	13.7	1	4	0	3	0	20
	104	EEEE	94	5	40	151	8	0	11.5	1	4	0	3	0	20
	105	FFFF	73	36	45	84	5	0	8.9	8	10	1	2	0	20
	106	GGGG	73	36	55	139	7	0	8.2	8	10	1	2	0	20
	107	HHHH	94	48	57	78	4	0	10.1	1	4	0	3	0	20
	100	AAAA	249	1	50	1563	79	1	17.0	8	14	1	4	1	60
	101	BBBB	125	45	59	453	23	1	12.3	8	14	1	3	0	60
	102	CCCC	96	10	20	84	5	0	13.7	1	4	0	3	0	20
Case 5	103	DDDD	99	17	25	86	5	0	11.5	1	4	0	3	0	20
	104	EEEE	98	22	30	73	4	0	8.9	1	4	0	3	0	20
	105	FFFF	74	35	45	26	2	0	8.2	8	10	1	3	0	20
	106	GGGG	100	45	58	45	3	0	10.1	1	4	0	3	0	20

FIGURE C.1: Small problem instances 1-5

Case	ID	Name	Length	ETA	PTD	Moves	QC Hours	Type	Draft	Pref start sect	Pref mid sect	Pref berth	Max QC	In Window	Contractual BP
Case 6	100	AAAA	184	0	22	797	40	1	13.9	8	14	1	4	1	60
	101	BBBB	249	20	59	999	50	1	17.2	8	14	1	4	0	60
	102	CCCC	96	5	12	67	4	0	9.2	1	4	0	3	0	20
	103	DDDD	98	13	22	129	7	0	13.7	1	4	0	3	0	20
	104	EEEE	106	19	28	97	5	0	11.5	8	10	1	3	0	20
	105	FFFF	88	25	36	137	7	0	8.9	1	4	0	3	0	20
	106	GGGG	95	35	49	165	9	0	8.2	1	4	0	3	0	20
	107	HHHH	94	48	59	99	5	0	10.1	1	4	0	3	0	20
Case 7	100	AAAA	135	0	22	897	45	1	11.1	8	14	1	3	0	60
	101	BBBB	184	25	59	1233	62	1	12.8	8	14	1	4	0	60
	102	CCCC	94	0	10	155	8	0	8.3	1	4	0	3	0	20
	103	DDDD	81	10	20	84	5	0	9.6	8	10	1	2	0	20
	104	EEEE	94	13	24	129	7	0	7.7	1	4	0	3	0	20
	105	FFFF	98	35	45	98	5	0	6.5	1	4	0	3	0	20
	106	GGGG	93	45	58	45	3	0	5.8	1	4	0	3	0	20
	107	HHHH	84	45	59	122	7	0	8.4	1	4	0	2	0	20
Case 8	100	AAAA	162	5	35	650	33	1	12.8	8	14	1	4	1	60
	101	BBBB	184	30	59	933	47	1	12.8	8	14	1	4	1	60
	102	CCCC	96	10	20	184	10	0	13.7	1	4	0	3	0	20
	103	DDDD	99	17	25	106	6	0	11.5	1	4	0	3	0	20
	104	EEEE	94	5	10	151	8	0	11.5	1	4	0	3	0	20
	105	FFFF	87	30	36	81	5	0	8.9	1	4	0	3	0	20
	106	GGGG	98	37	42	129	7	0	8.2	1	4	0	3	0	20
	107	HHHH	93	45	55	104	6	0	10.1	1	4	0	3	0	20
Case 9	100	AAAA	154	1	12	550	28	1	12.5	8	14	1	3	0	60
	101	BBBB	249	10	39	999	50	1	17.2	8	14	1	4	1	60
	102	CCCC	125	32	59	453	23	1	12.3	8	14	1	3	0	60
	103	DDDD	81	2	17	84	5	0	9.6	1	4	0	2	0	20
	104	EEEE	84	45	59	122	7	0	8.4	1	4	0	2	0	20
	105	FFFF	74	35	45	26	2	0	8.2	8	10	1	3	0	20
	106	GGGG	63	17	42	43	3	0	8.9	1	4	0	2	0	20
Case 10	100	AAAA	94	0	20	255	13	0	8.3	1	4	0	3	0	20
	101	BBBB	81	2	17	284	15	0	9.6	8	10	1	2	0	20
	102	CCCC	96	20	35	184	10	0	10.7	1	4	0	3	0	20
	103	DDDD	99	26	40	156	8	0	11.5	8	10	1	3	0	20
	104	EEEE	94	38	50	151	8	0	11.5	1	4	0	3	0	20
	105	FFFF	73	42	55	214	11	0	8.9	8	10	1	2	0	20
	106	GGGG	98	40	60	199	10	0	8.2	1	4	0	3	0	20

FIGURE C.2: Small problem instances 6-10

Appendix D

Cost justification

Based on the fuel and maintenance cost, the cost per kilometre driven by an AGV is set to [redacted]. The total cost of a QC team of three persons for one hour is [redacted]. For a QC set-up we take twenty minutes of a QC team, so [redacted]. The cost for delays vary per type and depend on if the vessel is in window. In case a deep-sea vessel arrived in window, the cost for a delay is [redacted] per hour. In case the vessel arrival was out window the cost are [redacted] per hour. For feeder vessels there are no windows so the cost are the same for each hour of delay, [redacted]. This difference reflects the priorities of the vessels.

- AGV per kilometer: [redacted]
- Delay deep-sea in window: [redacted]
- Delay deep-sea out window: [redacted]
- Delay feeder in window: [redacted]
- Dealy feeder out window: [redacted]
- Cost unplanned vessel: [redacted]
- Cost per team: [redacted]
- Cost QC set-up: [redacted]

Appendix E

Explanation of benchmarking methods

To provide a lower benchmark for the total cost of the solution we use the total number of container moves and the standard BPs. For every 20 container moves a QC hour is needed. If all container moves of a scenario are added and divided by 20, we get the total QC hours needed. As QC teams work eight hours per shift, the total number of teams needed is the total QC hours divided by eight, rounded up. As we know the total cost for each team, we know the minimum cost for QC team allocation. For the total cost for QC setups we assume that at least the number of QCs needed for meeting the desired BP are allocated for each vessels. By adding all these desired number of QCs we get an estimate for the minimum number of QC setups.

The benchmarking for the upper bound is based on the Priority rules heuristic. The method applies the same logic as the Priority rules heuristic, but only prioritizes the vessels on ETA. The QC allocation heuristic is directly applied to the resulting berth plan, without applying any refinements or changes. The solution is made valid using the same method as the Priority rules and Tabu search.

Appendix F

Detailed outcomes refinements experiments

Tables F.1, F.2 and F.3 show the detailed outcomes for each of the 11 orders that we tested for the application of refinements for Priority rules.

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	100	459	464	238	252.303,7
Order 2	100	459	447	238	251.736,2
Order 3	102	572	445	242	272.475,7
Order 4	100	459	464	238	252.303,7
Order 5	100	451	464	246	247.905,1
Order 6	103	487	464	246	261.128,7
Order 7	100	451	464	246	247.905,1
Order 8	103	487	447	246	260.561,2
Order 9	100	451	447	246	247.337,7
Order 10	101	587	448	237	275.625,6
Order 11	105	560	447	239	271.637,7

TABLE F.1: Priority rules with refinements Problem instance 1

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	104	246	460	219	156.860,3
Order 2	104	246	453	219	156.694,7
Order 3	104	246	453	219	156.694,7
Order 4	101	331	460	219	170.235,3
Order 5	98	295	460	223	163.910,3
Order 6	103	292	460	220	161.710,3
Order 7	97	305	460	218	177.610,3
Order 8	103	292	453	220	161.544,7
Order 9	97	305	453	218	177.444,7
Order 10	103	298	453	220	161.744,7
Order 11	95	372	453	221	186.169,7

TABLE F.2: Priority rules with refinements Problem instance 2

Tables F.4, F.5 and F.6 show the detailed outcomes for each of the 11 orders that we tested for the application of refinements for Tabu search.

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	97	510	399	270	225.351,2
Order 2	96	525	375	268	227.329,2
Order 3	100	578	342	269	230.187,8
Order 4	100	467	399	271	215.301,2
Order 5	102	528	399	273	228.101,2
Order 6	99	496	399	273	225.869,0
Order 7	98	531	399	267	237.144,0
Order 8	98	520	375	272	227.372,0
Order 9	96	550	375	267	238.297,0
Order 10	102	538	340	270	223.631,5
Order 11	94	565	359	266	241.425,5

TABLE F.3: Priority rules with refinements Problem instance 3

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	105	494	1.263	243	300.237,6
Order 2	107	544	1.175	246	310.595,2
Order 3	101	616	1.194	239	325.173,6
Order 4	105	537	1.263	240	313.262,6
Order 5	98	594	1.263	240	322.589,6
Order 6	103	588	1.263	241	319.184,5
Order 7	101	602	1.263	243	330.737,6
Order 8	97	611	1.175	244	338.713,1
Order 9	103	556	1.175	246	313.995,2
Order 10	104	628	1.176	241	321.492,0
Order 11	101	676	1.194	244	337.061,9

TABLE F.4: Tabu search with refinements Problem instance 1

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	99	223	1.146	219	180.065,0
Order 2	97	270	1.018	220	192.737,1
Order 3	100	225	1.014	218	175.633,0
Order 4	95	266	1.146	220	202.590,0
Order 5	97	256	1.146	220	187.240,0
Order 6	97	203	1.146	224	165.740,0
Order 7	100	248	1.146	221	184.190,0
Order 8	101	223	1.018	227	173.012,1
Order 9	100	226	1.018	227	172.837,1
Order 10	97	229	1.014	223	163.864,8
Order 11	99	261	1.012	220	181.266,7

TABLE F.5: Tabu search with refinements Problem instance 2

	QC-setups	Delay	Moor. pos. dev.	Used teams	Value
Order 1	99	586	1.095	277	280.150,2
Order 2	99	586	1.050	277	279.184,5
Order 3	99	649	1.037	276	284.893,6
Order 4	102	544	1.095	279	280.822,2
Order 5	99	564	1.095	277	270.347,2
Order 6	97	612	1.095	271	274.748,6
Order 7	97	576	1.095	275	271.247,2
Order 8	98	597	1.050	273	274.749,0
Order 9	97	622	1.050	273	280.831,2
Order 10	96	691	1.000	266	279.711,9
Order 11	95	617	1.039	273	272.318,4

TABLE F.6: Tabu search with refinements Problem instance 3

Appendix G

Detailed outcomes Priority Rules and Tabu Search experiments

G.1 Berth Allocation Problem

Tables G.1, G.2 and G.3 shows the experiment outcomes for the BAP for 10 problem instances with a realistic size. For Tabu search three replications were performed with different random seeds.

Problem	**Priority rules**		
instance	Delay	Moor. pos. dev.	Value
1	239	626	111.865,4
2	348	661	138.813,3
3	391	632	113.261,0
4	235	462	58.717,9
5	127	723	59.368,8
6	129	553	82.050,1
7	201	619	101.497,5
8	262	860	96.780,3
9	145	470	54.849,2
10	113	410	78.227,9

TABLE G.1: Detailed outcomes BAP realistic problem instances Priority rules

Problem	**Tabu search random seed 1**			**Tabu search random seed 2**		
instance	Delay	Moor. pos. dev.	Value	Delay	Moor. pos. dev.	Value
1	196	1.178	120.323,6	130	1226	111.766,9
2	221	991	106.912,7	232	906	108.143,1
3	235	1.407	125.207,3	218	1347	100.678,8
4	177	1.316	108.195,5	156	1090	90.085,5
5	78	1.297	126.602,4	669	155	74.365,1
6	118	1.035	82.429,9	126	1134	69.400,9
7	138	1.107	95.515,2	111	1384	154.680,9
8	137	1.062	111.468,8	130	1097	108.174,6
9	127	1.361	126.179,4	127	1294	113.326,1
10	49	1.009	84.214,5	45	1022	94.653,7

TABLE G.2: Detailed outcomes BAP realistic problem instances Tabu Search random seed 1 & 2

Problem instance	Tabu search random seed 3 Delay	Moor. pos. dev.	Value
1	215	1.270	148.088,8
2	259	985	118.065,3
3	257	1.244	110.195,9
4	154	1.126	106.637,4
5	81	1.193	83.782,0
6	123	1.063	73.329,5
7	162	1.266	153.890,4
8	117	1.156	106.340,5
9	119	1.079	149.083,6
10	45	1.056	95.530,6

TABLE G.3: Detailed outcomes BAP realistic problem instances Tabu Search random seed 3

G.2 Berth Allocation Problem & Quay Crane Allocation Problem

Table G.4 shows the experiment outcomes for the BAP and QCAP for 10 scenarios for Priority Rules.

Problem	Priority rules					
instance	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Team usage
1	96	438	626	231	215.740,4	89,2%
2	114	661	661	291	275.320,8	91,8%
3	108	550	632	254	205.992,6	85,5%
4	98	471	462	228	182.267,9	88,1%
5	105	586	723	232	245.316,1	91,2%
6	99	414	553	219	258.550,0	92,8%
7	94	424	619	228	206.823,8	93,2%
8	114	661	860	245	275.335,0	91,7%
9	98	599	470	224	275.216,1	91,8%
10	78	631	410	203	335.679,0	87,9%

TABLE G.4: Detailed outcomes BAP & QCAP realistic problem instances Priority rules

Tables G.5, G.6 and G.7 show the experiment outcomes for the BAP and QCAP for 10 problem instances with three random seeds for Tabu search.

Problem instance	Tabu search random seed 1					
	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Team usage
1	97	800	1.178	228	295.637,0	90,2%
2	111	642	991	285	264.471,2	91,6%
3	105	728	1.407	249	273.746,0	87,2%
4	96	361	1.316	227	215.222,7	87,9%
5	97	674	1.297	221	370.406,4	90,6%
6	96	438	1.035	219	254.004,9	92,8%
7	92	391	1.107	224	236.493,3	94,9%
8	111	555	1.062	245	298.618,5	92,7%
9	89	721	1.361	229	318.139,8	89,2%
10	85	557	1.009	203	307.053,4	89,5%

TABLE G.5: Detailed outcomes BAP & QCAP realistic problem instances Tabu search seed 1

Problem instance	Tabu search random seed 2					
	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Team usage
1	101	648	1.226	227	266.400,1	90,1%
2	107	791	906	286	282.508,6	91,6%
3	109	525	1.347	247	225.711,1	87,7%
4	99	328	1.090	229	205.887,6	87,4%
5	109	469	1.538	231	311.514,8	92,4%
6	97	536	1.134	221	279.085,8	92,2%
7	90	467	1.384	228	357.565,0	93,2%
8	110	504	1.097	245	283.245,5	92,8%
9	90	674	1.294	226	296.547,5	90,5%
10	81	677	1.022	196	334.505,6	92,5%

TABLE G.6: Detailed outcomes BAP & QCAP realistic problem instances Tabu search seed 2

Problem instance	Tabu search random seed 3					
	QC-setups	Delay	Moor. pos. dev.	Used teams	Value	Team usage
1	100	655	1.270	219	289.534,8	93,8%
2	111	727	985	293	276.147,7	91,0%
3	111	537	1.244	248	237.098,4	87,4%
4	98	384	1.126	226	229.989,5	88,4%
5	101	448	1.193	235	270.332,0	90,5%
6	101	492	1.063	217	259.693,3	93,9%
7	100	414	1.266	228	283.090,4	94,0%
8	121	537	1.156	252	302.768,0	90,2%
9	95	690	1.079	219	351.702,3	92,5%
10	84	578	1.056	200	329.871,5	91,0%

TABLE G.7: Detailed outcomes BAP & QCAP realistic problem instances Tabu search seed 3