Optimizing the flow of vessels through locks by improving the operational management of locks

A simulation study toward the most promising ways of managing locks

Master thesis
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Abstract
Nowadays, the capacity of the lock becomes more important, since ports become busier and waterways more crowded. Still, the management of locks has not changed very much. Especially since locks are one of the most important factors that determine the capacity of a waterway. A lock limits the capacity of a waterway in two ways. First of all, the lock restricts the dimensions that can pass through the locks. Secondly, the lock limits the flow of vessels that can pass through the waterway. Since the dimensions of a lock are not likely to change, the focus of this study will be on the flow of the vessels. The question that will be answered during this study is the following:

Which lock operation policies should be applied under which circumstances in order to contribute to an increase of the efficiency of the locks?

A lock operation policy is a way in which the lock can be managed. This concerns both the order of vessels as well as placing vessels in a chamber. The circumstances can be divided in two types; the factors that determine whether a new policy would contribute to better performances and the general characteristics of a lock which need to be present in order to apply such a policy. The following policies are taken into account:

1. **First come, first served (FCFS).** This category is commonly used in practice and focus merely on the arrival time of the vessels and does not take into account the use of resources for determining the order of vessels
2. **Shortest Processing time First (SPT).** By using this policy, the vessel which has the shortest processing time is chosen to pass through the locks first.
3. **Resource-based selection (RBS).** This policy ensures an efficient use of the resources, since vessels who need resources are planned before the vessels who do not need resources.

These three alternatives are compared with each other by means of a case study at the port of Amsterdam. The FCFS policy is used as the initial situation, while the other two policies are compared with this policy. By just comparing these policies based on the current arrivals at the port of Amsterdam, the results are almost equal. The reason that the capacity of the lock is not a problem yet and therefore other policies will not be more effective than the current one. By increasing the number of arrivals some interesting insights could be gained. First of all, both alternatives gave better results than the FCFS policy. The SPT reduced the waiting time for the locks and decreased the number of lockages. As a result more vessels could be handled. The RBS policy reduced the waiting time for resources and therefore increased the number of vessels that could be handled slightly. It can be said that the choice between those policies is dependent on the factor that limits the capacity. The table below shows a small part of the results of the study. It can be concluded that the FCFS policy is most efficient considering the number of lockages. The total waiting time is more or less equal. If the number of arrivals increases, the waiting time of the FCFS policy starts increasing faster than the other policies. The number of lockages remain lower than the other policies. This trend remains if the number of arriving vessels keeps increasing.

<table>
<thead>
<tr>
<th>Policy</th>
<th>Total Waiting Time</th>
<th>Number of Lockages</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCFS</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>SPT</td>
<td>450</td>
<td>110</td>
</tr>
<tr>
<td>RBS</td>
<td>400</td>
<td>120</td>
</tr>
</tbody>
</table>

The table above shows a small part of the results of the study. It can be concluded that the FCFS policy is most efficient considering the number of lockages. The total waiting time is more or less equal. If the number of arrivals increases, the waiting time of the FCFS policy starts increasing faster than the other policies. The number of lockages remain lower than the other policies. This trend remains if the number of arriving vessels keeps increasing.
The next step that has been taken is the generalization of these results. This concerns the circumstances that determine the success of specific lock operation policies and lock operation policies in general. It should be noted that the factors which are present in a lock system, but do not influence the effectiveness of a lock operation are equally important, since these factors can be neglected during the choice of the lock operation policy. These factors are the size of the chambers as long as there are multiple chambers, the pattern of arrivals and to a certain extent, the fleet mix. The factors that influence the effectiveness of the tested lock operation policies mainly concern the physical characteristics of the locks. If there are obstacles such as other locks near the lock, the effects of the tested lock operation policies are almost diminished. A second factor is planning horizon. If the arrival time of the vessels is known just before the arrival itself, it is nearly impossible to optimize the order of vessels. A last factor is the place of the lock in comparison with the sea and port. If the lock is located far from sea, the influence of the tide is larger. This results in less possibilities for changing the order of vessels, since the timeframe for most vessels is smaller. The effectiveness of the lock operation policies might also be influenced by some external factors. The first one are the weather conditions. If the weather conditions are bad, the choices might be limited. It might for example not be possible to handle large vessels or use a certain chamber. A second factor is the hydrological conditions, such as tide and current. Those factors can limit the flow of vessels regardless of the policy.

So it can be concluded that it is possible to apply the results of this study in more situations than just the port of Amsterdam as long as the factors above are either met or taken into account. Since it is clear that the results of this study can to a certain extent be applied in various locks, the main research question can be answered.

*Which lock operation policies should be applied under which circumstances in order to contribute to an increase of the efficiency of the locks?*

The first conclusion that can be drawn is that the availability of resources can influence the choice between those policies. If the resources are scarce, it is better to focus on the resources and select the RBS alternative. However, if the focus is of the managers is on the environment and reducing costs, it might be considered to use FCFS, since this limits the number of lockages, without complicated rules or algorithms for planning which can increase the costs of the policy.

The second conclusion that can be drawn is that the RBS principle is only beneficial if the number of arrivals is high and the resources are scarce. Even then, the average waiting time is not likely to decrease. This is due to the fact that the benefits of the RBS policy are diminished by the increase in waiting time for the lock itself. The number of vessels that can be handled will increase nevertheless.
The third conclusion that can be drawn is that the same conclusion can be drawn about the SPT policy. If the number of vessels that arrives at the lock is limited, the possibilities to change this order are limited as well. Therefore, the SPT policy will only be effective if the number of arrivals is larger. The choice between the RBS and SPT is mainly dependent on the preference of the decision makers and the means they have to improve the current situation.
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1. Introduction

The entrance of a port might be seen as one of the most important parts of the port considering the capacity of the port. The amount of vessels that can enter the port will be the maximum number of vessels that can be handled by the port. Eventually, this will limit the growth of the ports. The amount of vessels that can enter the port is often limited by external factors as well. Among these external factors are the weather conditions and physical characteristics of the waterway. These factors will be discussed later in Chapter 3. One of the most important factors that can limit the capacity of ports are locks (Pang & Wu, 2014). A lock can be seen as both an external as well as an internal factor. They can limit the capacity in two ways. First of all the flow of vessels will be limited, since the vessels cannot continue at the same speed as they would have done on a waterway without locks. This can be seen as an internal factor, since the flow of vessels can be improved by other ways of planning. A second way in which the capacity of a port can be limited by a lock is a limitation of the dimensions of the vessels; if the locks have a maximum length of 200 meters, vessels of more than 200 meters cannot pass (Verstichel, Kinable, Causmaecker, & Berghe, 2015). This can be seen as an external factor, since it is not likely that the dimensions of a lock will change very often or easily.

Other factors that can limit the capacity are the dimensions of the waterway, the layout of the waterway and other obstacles like bridges or activities at those waterways such as terminals. These factors can be divided into two categories. The first category is the factors that are not likely to change. This category includes the dimensions of the waterway, the layout of the waterway and activities on the waterway. Since the elements of this category are not likely to change, it is better to focus on the second category: the factors that can be changed. These factors are the locks and bridges. Even though the physical characteristics of those elements cannot be changed, it is possible to adapt the way in which those elements are used. So, it is important to constantly evaluate and if possible improve the way they are managed, in order to keep up with global developments such as larger vessels and globalization which leads to an increase in port activities.

The improvement in efficiency is important if ports are planning to increase their economic activities. An increase in economic activities is crucial for trading nations such as the Netherlands. Therefore, it is crucial to increase the efficiency of the use of the waterway in order to ensure the competitiveness of the port. An increase in economic activities and the corresponding increase in the number of vessels will put pressure on the waterways which give entrance to the port and on the port itself. Besides the limitation mentioned above, this expansion will also be limited by other factors, such as space and environmental laws. The limitation due to the capacity of the waterway is a limitation that is not easy to overcome. Especially if a port is located more landward. This location causes a longer route to the port and therefore a higher chance of obstacles, activities and difficulties in the layout of the waterways, such as tight turns or narrow passages.

This chapter will focus on the system analysis of the lock planning problem. The first step is to elaborate on the permanent obstacles as mentioned above. Then, the focus will be on the research design; the problem statement and research questions. Which is then followed by the scope of the study and an overview of the methods that will be used for answering the research questions. Lastly, the outline of the Thesis will be given.
1.1. Locks as a limiting factor
In order to understand why locks can be seen as a limiting factor for a waterway it must be clear why locks are needed in the first place, since not all seaports have locks. For example, the port of Rotterdam does not have a lock, while the port of Amsterdam does. The first reason why ports have locks is safety. The locks prevent flooding with heavy weather conditions and releases the pressure on dikes. Besides, the protection by a lock is more reliable and less costly than the protection by dikes. For example, a study is done to calculate the effects of a lock in Rotterdam (Huijgens, 2011). It turned out that the costs of a lock were five times lower than other protection along the sides of the Maas. Another reason for having a lock in a port is the supply of fresh water. A lock ensures a stable amount of fresh water independent of the water levels of rivers or canals. As long as the number of lockages is not too high, the salt exchange is limited and the water stays fresh.

As mentioned physical characteristics of the lock itself cannot be changed easily. The only thing that can be changed is the way in which it is used, the lock operation policy. By shifting the focus to lock operation policies, some other factors will start to play an important role. The first factor is the layout of the locks. Locks often contain different chambers with different dimensions. Therefore they can handle different vessels. The second factor are the processes which must be completed before vessels are ready to be transferred through the locks. This consists of lightering vessels if there draft is too large, using tugboats for large vessels and pilots for most vessels, taking into account traffic from the other side of the locks and taking into account the tidal differences. The final factor is the influence of human behavior on the performances of locks. This includes signing in for slots, the ability to navigate a vessel into the locks and the communication with other parties. Therefore, it will be necessary to investigate how these factors are and can be managed in order to increase the performance of the locks. In addition to the management of locks it is also important to see how robust the lock operation policies are to changes.

A lock operation policy can be defined as the way in which a lock is managed. This includes the chamber management as well as the order of arriving vessels and the resource management.

1.2. Goal of the research
The goal of the research is to provide guidelines on how to improve the efficiency of locks for inland seaports by improving the planning of vessels. This will be done by analyzing and optimizing the operational planning of vessels, which includes the lock and chamber planning. A contribution will be made to the operational management of locks in general. The efficiency of locks can be seen as a characteristic of a lock which is a combination of the number of lockages and the waiting time for the vessels. Whether the number of lockages or the waiting time is more important is dependent on the perception of the lock operators and owners. The focus mainly depends on the influence of the shippers and the influence of the port authorities. The shippers will prefer a short waiting time, while the port authorities will in general focus on minimizing the number of lockages, since this reduces costs and environmental impact. In order to reach this goal the following research question and sub-questions need to be answered. The main research question is the following:

 Which lock operation policies should be applied under which circumstances in order to contribute to an increase of the efficiency of the use of the locks?
The circumstances should not be seen as factors that influence the effectiveness on a short term, but on a long term. Therefore, the focus of the research is on long-term circumstances, such as the mix of vessels arriving at the locks or the physical characteristics of the locks. While short-term circumstances such as weather conditions are disregarded.

The corresponding sub-questions are the following:

1. What are the possible lock operation policies and what are the most promising practices?
2. What are the key indicators which determine the success of a certain lock operation policy?
3. Which external factors influence the effectiveness of a lock operation policy?
4. What is the influence of new ways of managing locks on the performance of a specific port?
5. How can the findings of this study help to improve lock operation management in other ports?

1.3. Scope
As mentioned earlier, a waterway can have many obstacles. Since research has shown that locks are likely to cause the most delays and given the fact that the operations within and around locks can be influenced, the operations around locks will be the scope of this study. The operations around locks can be seen as all processes that are needed to make the planning of the vessels a success. These processes include the management of the resources, determining the order of the vessels and taking into account external influences. This will mainly concern the daily operations. Operations within the locks can be seen as mooring the vessels and the sailing procedures. These operations are not taken into account since these processes only contribute to the speed of the locking process and not to the process of planning vessels. The scope of the project can be defined in a physical way as a waterway with a lock somewhere halfway. A set of vessels will arrive at both sides. This includes different routes which are allowed to be used by the vessels. The use of resources such as pilots and tugboats will also be included. Therefore, planning and optimization will be key. The lock operation policies that will be tested are policies which can be found in literature, but are applied in the real world as well. This ensures that the chosen lock operation policies can be applied in real situations. The timespan will be less relevant, but the data that will be used will be the data of ten months in the year 2014, since this data and the outcomes are available (Appendix A). The vessels that are taken into account are merely seagoing vessels which either enter or exit a port. Commercial traffic is not taken into account. The entering ships will be referred to as east going vessels and the exiting vessels as west going vessels.

Environmental factors such as wind and current are not taken into account as individual factors, but those are taken into account as a variation in the arrival time, which are derived from the data of the year 2014 that has been provided. Those factors are not taken into account as individual factors, because they do not influence the choice of the main lock operation policy, but only the results of a single vessel. In other words, the focus will be on the long term and not on the short term.

1.4. Scientific framework
The scientific framework will be used as a guideline for the research. The framework that will be used during this study is adapted from the hierarchical control conceptual modelling (HCCM) (Furian, O’Sullivan, Walker, Vössner, & Neubacher, 2015). This framework is suitable for simulation studies which make use of more than just queuing theories. This framework is chosen since the main body of the research consists of a simulation study. The parts that are added ensure a more elaborate study that
includes the literature search and the generalization of the results as well. The framework is shown in Figure 1 and will be explained in more detail below.

During the first phase, the problems which are present in the system will be specified and explained. This will result in a general problem description and initial ideas of the solutions. This step is related to the first and fourth chapter of this thesis, where the first chapter focuses on the research in general and the fourth chapter on a specific port. If the current situation is clear, the next step is to identify the objectives of the study. These objectives are not only general objectives, but also modelling objectives. It will be made explicit what the limits of the study are and how the model can be used. This will be done in Chapter 1 and 3. The third phase consists of two parts; defining the input factors and defining the output responses. The input factors are retrieved by performing data analyses and identifying the crucial factors which can influence the lock operation policies. The results of this part will be shown in Chapter 3. The output responses can be seen as the Key Performance Indicators (KPIs) of the research. It is important to
identify them early in the process, since they can influence the way of modelling, therefor this will be
done in Chapter 3, just before the actual modelling will be done. The fourth phase consists of the model
content. So, questions like what will be the structure of the model, what behavior is expected and what
behavior is generated will be answered (Chapter 4). During this phase, the focus will be on model control
as well. This part will focus on how to control the model behavior. This can be seen as a control mechanism
for the model (Chapter 4 and 5). In addition to the framework of Furian et al. three steps are added in
order to shift the focus from just modelling to a more generic study. The first step that will be added to
the framework is verification and validation. Verification is checking whether the model does what it is
intended to do and validation of the model can be seen as a check of the rightness of a model (Balci, 1997).
The sixth phase of the study will be experimentation. During the experimentation phase three theories
will be tested in order to find the most efficient way of guiding vessels through a lock. The last phase will
be the generalization phase. An attempt will is made to ensure the findings of the study are valid in a
broader context than just the case study.

1.5. Methods
This paragraph will first explain the methods for answering the main research question and the sub-
questions, followed by explanation of the human behavior principle.

The methods below are described in order to give guidance to answering the sub-questions which will
lead to the answer on the main research question.

What are the possible lock operation policies and what are the most promising practices?
The first sub-question is about the theoretical approach as well as the current practices of lock operation
policies. It will both focus on the actual lock operation policy as well as the layout of the locks. This
question will be answered in two parts. First of all, the possible layouts of locks will be explored, since this
can limit the effectiveness of lock operation policies. The possible layouts of the locks will be explored by
means of a literature search and a field research. The literature search will be done by examining case
studies and mapping all possible factors of the layout of locks which can influence the performances and
the effectiveness of lock management. While the field research is done by talking to experts who have
experience in the field and can elaborate on the different layouts of locks near ports in Western Europe.
By combining the literature search and the field research, it will be possible to construct a layout which
captures all important aspects of the layout of a lock. The second part will focus on the lock operation
policy itself. The approach will be the same. It will be possible to come up with different lock operation
policies based on the case studies and other literature. These examples found in literature can be
compared with the lock planning policies which are used in ports in North-West Europe. This will result in
some alternatives that can be tested by making use of the layout which is established during the first part
of the first sub-question.

What are the key indicators which determine the success of a certain lock operation policy?
These KPIs will be established by means of an actor analysis and interviews with the port authority of
Amsterdam, Ghent and Antwerp as well as a literature search. The actor analysis ensures a holistic view
on the system, while the port authorities can point to the most important performance indicators for the
port itself. The literature search can be used to confirm the KPIs from the actor analysis and the interviews.
Which external factors influence the effectiveness of a lock operation policy?
After the KPIs are known, it is possible to examine which external factors influence the performance of the locks. This will be done by means of expert interviews and literature search. As a result it is possible to determine which factors to include in the simulation model and which can be neglected.

What is the influence of new ways of managing locks on the performance of a specific port
In order to answer the fourth question a simulation study will be carried out. For the simulation study, the Simio simulation software is used. The first step of the simulation study is to use the knowledge gained by answering the first sub-questions in an initial model of the port of Amsterdam. By complementing this knowledge with data from the actual vessel movements of the port of Amsterdam, it will be possible to create a scenario which resembles the current state of the locks located near the port of Amsterdam. The data will be the arrivals of 2014, including all characteristics of those arrivals. In order to analyze the data, statistical analyses and visual analyses are performed. This is done by making use of SPSS, which can be used for statistical analyses, and TIBCO Spotfire for the visual analyses of the data. The next step is to include the most promising options from the second sub-question into the model in order to compare the different options.

How can the findings of this study help to improve lock operation management in other ports?
By answering the fifth sub-question, the results of this study can be generalized. This can be done in several ways. First of all by performing a sensitivity analysis on the input parameters. If slightly different parameters result in totally different outcomes, it is likely that the solution is specific for the port of Amsterdam. It is also important to look at the ease of implementation. The easier it is to implement, the more likely it is that a solution will be accepted in other ports. Lastly, it is important to look under which conditions a certain solution works. If those conditions are met in another port, the solution might be applicable. A last remark, it is also possible to look at the pros and cons of a solution. If some cons are way more important for a certain port, it might not be desirable to implement such a solution.

1.5.1. Human behavior in simulations
The last method that will be described will be used for including human behavior in the simulation. This can be seen as an addition to the theoretical approaches that will be tested. Often these factors are not clearly set by rules, but are based on gut feeling or factors that are not taken into account when considering just the KPIs. These factors might be important since in the end all decisions in this system are taken by humans. By including such factors, it is possible to test the influence of the human behavior as well as the robustness of the solutions (Elkosantini, 2015).

Human behavior would otherwise be implemented as a given parameter instead of a continuously changing variable or not even included at all (Rothrock & Narayanan, 2011). This method can be used during a simulation study to include factors which cannot be quantified. In other words: the person of interest can contribute to the simulation by sharing personal experience.

This method will be used to include the experience of the most important actors of the system. This will be done by including the most important intangible processes into the model. This will be done by consulting the planners and let them share the experience they have. The exemptions they might come up with can be tested and the effects can be monitored. Since the order of vessels in the simulation is established based on theoretical approaches, it is likely that some interventions can optimize the scheduling procedure. Those results can be used to further optimize the scheduling process. If the
difference due to the interventions is significantly better, an attempt will be made to include the underlying rules into the simulation model. The results of this method will be shown in paragraph 4.4. On the other side, it is not sure whether the interventions will increase the performance of the locks. Other interests might be more important than the performance of the lock.

1.6. Outline of the thesis

Now the goal of the research is clear, it is time to describe the path which will lead to achieving the goal. The literature research will be done in Chapter 2. This literature research is necessary for further specifying the project by combining the findings of previous research into a starting point for this thesis and in order to generate policies which can be tested later on. The third chapter will contain a description of the case study that will be carried out to test the policies which are developed in Chapter 2. This chapter will describe the KPIs for lock operation management as well. The information gathered in Chapter 3 will be used in Chapter 4 to build the model and evaluate it. This will include the evaluation of the current situation as well as the evaluation of the different policies generated in Chapter 2. The last step that will be taken in this chapter is including the human factor into the research. This is important for the acceptance of the conclusions and the willingness to implement the solutions. The fifth chapter will be the first step towards the generalization of the results. The outcomes of the previous chapter will be linked at characteristics of ports. This will result in an overview of policies and under what conditions they might be appropriate. In the last chapter, Chapter 6, the conclusions and recommendations will be stated. So, the answers to all sub-questions will be given as well as the answer of the main research question. In the last part of Chapter 6, the research will be put in perspective regarding the future.
2. Theory and practice of lock operation policies

Chapter 2 will be used to describe the most important aspects of lock operation management. This will be done by identifying the different layouts of waterways with locks in the first paragraph. The first step is identifying the key elements which are used for identifying locks. The next step is describing the currently known policies for lock operations in Paragraph 2.2. This will be done from a theoretical view as well as from a practical view. The combination of these insights will eventually lead to a most promising layout of a lock and an overview of the most frequently used policies around the world and their up- and downsides. The sub-question that will be answered in this chapter is: *What are the possibilities to manage locks and what are the most promising practices?*

2.1. Classification of locks in waterways

As mentioned, the first step is to categorize waterways. These categories can be used in the coming chapters as a guideline for the policies for lock operations. The goal of this paragraph is to establish a layout which can be used in the simulation model. This layout should include all important aspects which can influence the efficiency of locks. This is necessary to compare the policies later on during the analyses and to relate certain results to aspects of the layout. The next step is to link those waterway and lock combinations to situations in the real world to exclude the less plausible options. After the description of the taxonomy and the exclusion of the least promising options, a selection will be made of the most suitable and relevant layout for the simulation study.

2.1.1. Waterway-lock combinations

The distinction between groups of locks will be made based on the properties of the locks which can be important for the lock operation policies. The factors which determine the different categories are the number of chambers, the size of chambers, the planning horizon and the proximity of other locks (Backalic & Bukurov, 2011). The number of chambers is important since multiple chambers allow for more sophisticated lock operation policies and more variety in the planning. For example, it is possible to plan in such a way that there is always a chamber available at each side of the locks. This will reduce waiting times outside of the chambers. The second factor, the size of the chamber, relates to size difference. If chambers have different dimensions, it is possible to assign certain types of vessels to a certain chamber or make preferred combinations of vessel types and chambers. Questions rise like: is it better to send small vessels to the smallest chamber or is it more beneficial to combine them in one bigger chamber. The third factor is the planning horizon. The longer the time between the announcement and the actual time of arrival, the easier it is to make a proper planning and the more possibilities there are for a different policy. This horizon can be limited due to the presence of a port. Lastly, the proximity of other locks. If locks are located in a river and other locks are located up or downstream, the flow of vessels will be influenced by those locks. As a result, the vessels will arrive in batches which limit the possibilities for own lock operation policies. In Figure 2, an overview is given from the earlier mentioned factors and their possibilities. The most important aspects of Figure 2 is the fact that nine classes of locks can be identified.
2.1.2. Locks in ports in around the world

Locks with one chamber are usually found in small rivers and channels and are often part of a chain of locks. Due to the simple layout of the locks, most optimization is done by means of queuing theory and other mathematical methods (Dai & Schonfeld, 1998; Lave & DeSalvo, 1968; Nauss, 2008; Wilson, 1978). The main distinction that is made in those papers is the fact that either they consider a chain of locks or a lock with a single chamber. If they consider a chain of locks, like the Mississippi river, they assume a known arrival time, since it is dependent on the other locks. Such optimization problems can be solved mathematically. If a lock with one chamber is analyzed, the focus is in general on the capacity of the waterway and not on the most efficient way of guiding vessels through the locks. So, the capacity of the locks is calculated while considering stochastic arrivals and this capacity is the capacity of the waterway. As a result locks with a single chamber are not suitable for analyzing lock operation policies.

Looking at the locks with multiple chambers, the locks which are embedded in a chain of locks, so with locks nearby, can be excluded. The reason for this exclusion is the fact that those locks need a whole other policy than a single lock. If a series of locks is taken into account, the vessels already arrive in batches and the lock operation policy should focus on a lower level of detail in order to focus on all locks combined. This study aims at a detailed lock operation policy for one lock.

Therefore, the locks with multiple chambers and without nearby locks will be subject of the study, since those locks are frequently used and described in case studies which can be found in literature. First of all, the locks in the port of Antwerp resemble the locks with multiple equally sized chambers with no locks nearby and a short planning horizon. All large locks in the port of Antwerp have equally sized chambers and since it is located within the port, it is uncertain at what point in time the vessels will leave their berth and arrive at the lock (Thiers & Janssens, 1998). Therefore, the planning horizon will be short. The short planning horizon has some consequences. First of all, it will be easier to decline passing requests, since vessels are not always on the waterway yet. A downside to this is the fact that the spread between the expected time of arrival and the actual time of arrival is larger since it includes the handling time at terminals and the fact that the lock is directly located at a busy waterway which makes timing crucial in order to minimize the disturbance for other vessels. Looking at the process itself, a lock with two chambers has some advantages, especially if the chambers have the same size. It is, for example, possible to start...
the locking process from two sides simultaneously, which saves time, since vessels do not have to wait for the lock to switch sides (Verstichel et al., 2015). This is beneficial in a situation with two equally sized locks since all vessels can make use of both chambers. In comparison with a single chamber lock, the number of empty locking processes will be reduced.

The second category of locks are locks with equally sized chambers and a long planning horizon. In opposite to the layout with the short planning horizon, the spread between the estimated time of arrival (ETA) and the actual time of arrival (ATA) is less. This is less, since it is known well in advance at what time vessels arrive. The number of late subscriptions for a slot is lower and therefore the spread is lower as well. This reduction of stochastic values has some consequences. First of all, the outcomes of studies which make use of mathematical models become more valid, since the stochastic differences are reduced to a minimum (Kelton, Smith, & Sturrock, 2014). This conclusion can be drawn from the case studies found in literature as well (Pang & Wu, 2014; Verstichel, De Causmaecker, Spieksma, & Vanden Berghe, 2014; Verstichel, De Causmaecker, & Vanden Berghe, 2011). In addition, those three case studies have some unique conclusions as well. Verstichel et al. (2014) for example focus on the locking process itself, so mooring the vessels in the most efficient way is key in their opinion. Pang and Wu focus on the arrival process. They optimized it by adding some rules to the initial situation. After introducing the first come, first served rule with some exceptions, the efficiency of the lock increased. Priorities were not necessary since the chambers were equally sized. Again they did not use stochastic values for calculating the outcomes. Verstichel et al. (2011) use a rather different approach. They make use of the fact that the two chambers are from the same size and therefore it is possible to batch vessels until that size before assigning chambers. Another factor that contributes to the batching process is that there are no obstacles nearby so, the batching process would not hinder other traffic. This will simplify the planning procedures. The effects, which are the same as in the earlier mentioned layouts, are the possibility of a lockage process at both sides of the lock and the reduction of empty locking processes.

The third and fourth category of locks are the locks with different sized chambers. The third category is locks with different sized chambers and a short time horizon. Again, the short time horizon is mainly caused by the proximity of obstacles such as a berthing place. Therefore compared to the fourth category the third category will suffer more from irregular and unexpected arrivals. The different sized chambers cause some complexities while planning the lockages, since large vessels can only pass through a large chamber. While small vessels can pass through all chambers. Especially since different sized chambers have different processing times, the planning becomes rather difficult if the planning horizon is short (Coene & Spieksma, 2013). This is due to the fact that vessels of different sizes can sign in for time slots just shortly before the ETA. In that case, choices about which chamber to use have to be made. A good example of the third and the fourth category is the port of Amsterdam, due to its location, the lock system has to deal with both a short planning horizon if vessels arrive from the port itself as well as a long planning horizon if vessels arrive from sea as well as chambers of four different sizes. Currently the small chamber is mostly used for boating, while the three larger chambers are used for commercial traffic. An example of the fourth category is the Panama Canal. In the channel there are some large locks with multiple different sized chambers. Since the canal connects two oceans, the ETA’s of all vessels can be known long before the actual time of arrival since every vessel will be planned upfront (Franzese, Botter, Paulo, & Cano, 2004).
2.2. Lock operation policies
Management of locks can be viewed from two different angles. First of all there are some theoretical lock operation policies. Those policies focus on theoretical optimal situations. This includes at one side the arrival of the vessels and the lock planning, while on the other side the chamber packing or chamber management. The downsides of such an approach are often neglected. For example, a shipper is not interested in the average waiting time, the only thing that matters is his own waiting time. Secondly, there is a practical approach to managing locks. This is often based on a theory, but it is much more delicate. It includes procedures for claiming a certain slot and procedures for tidal differences, weather conditions and types of cargo. This paragraph will first describe the theoretical approaches and later on, the practices in the port of Amsterdam, the port of Antwerp and the port of Ghent. But before it is possible to describe the theoretical lock operation policies, it should be examined which types of theories could be applied and whether they are useful or not.

2.2.1. Underlying theories of lock operation policies
The earlier mentioned lock operation policies always consist of two main theories; a two dimensional bin packing problem and a queueing problem. The two dimensional bin packing problem can be seen as the chamber management. It focusses on the most optimal way of arranging vessels in the chamber by minimizing the empty space. While the queueing theory focusses on the order of vessels which enter the lock and the division of vessels over the different chambers.

Two dimensional bin packing problem
A two dimensional bin packing problem can be described as packing as many rectangle units in the minimum amount of large rectangle bins (Lodi, Martello, & Monaci, 2002). This theory can be applied in many fields, like placing advertisements in a newspaper. This theory has some shared underlying assumptions with placing vessels in a chamber (Lodi et al., 2002). First of all, the rectangles cannot be rotated in order to fit in the rectangle bin. It should be noted that vessels are considered to be rectangular. Secondly, the dimensions of the bin (chamber) are fixed and the number of bins is unlimited. The benefit of applying this theory is that the locks can be used in an efficient way. It will minimize the number of lockages and therefore the energy consumption and the salt exchange. Although this theory corresponds with the arrangement of vessels in a chamber, there are some crucial assumptions which do not correspond with fitting vessels in a chamber. The main assumption that is not valid is the ordering of the vessels related to time. The two dimensional bin packing problem assumes that rectangles can be placed in any order, while vessels who arrive at a chamber will enter the chamber in the other they arrive. This method of entering the locks saves waiting time, since vessels do not have to moor outside of the chamber or pass each other. A second assumption which is not in line with the lock process, is the placement of the vessels itself. The theory assumes that every empty space can be filled with a rectangle, while in the lock process vessels block some empty spots due to their location in the chamber.

Queueing theory
The queueing theory is often applied for analyzing locks. The reason that it is applied often, is that analyzing a lock with the queueing theory is relatively cheap and the underlying assumptions are to a certain extent equal (Wilson, 1978), especially when a lock with one chamber is observed. This is similar to an M/G/1 system, which mean that the arrivals follow a Poisson distribution, the service times have a general distribution and that there is one server available. The reason that this is possible is the fact that the system is relatively simple and there are not many choices that need to be made (Wilson, 1978). The
results become even more reliable if the characteristics of the vessels that arrive at the lock are more similar and the size of the different chambers are equal. If those characteristics are not equal, the queueing theory might not give the desired results (Ting & Schonfeld, 2001). The differentiation between the theoretically calculated waiting time and the actual experienced waiting time start to differentiate more and more as the complexity rises. This is due to the fact that it becomes possible to make choices between servers which are based on the usage of the servers, the filling rate, instead of the processing time. Therefore, it can be said that the queueing theory is a useful tool for analyzing simple locks with just one chamber, but as soon as the system gets more complicated, the theory is less valid for analyzing and improving the system.

Both theories do have added value considering the analysis of locks, but due to the restrictions of the theories themselves, they cannot be used as individual theories. They should be placed in a larger context which describes lock operations in detail. The way in which this is done is described in the remainder of this chapter.

2.2.2. Theoretical lock operation policies
The table below shows an overview of lock operation policies which can be found in literature. After a description of the different styles, the options will be compared.

<table>
<thead>
<tr>
<th>Lock operation policies</th>
<th>Applied by:</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCFS</td>
<td>(Nauss, 2008; Smith, Sweeney, &amp; Campbell, 2009)</td>
<td>The First come, first server principle handles vessels in the order they arrive.</td>
</tr>
<tr>
<td>FCFS with filling algorithm for the chamber</td>
<td>(Chien &amp; Schonfeld, 1993)</td>
<td>FCFS and if there is still place for another vessel then it can join.</td>
</tr>
<tr>
<td>JPRIO</td>
<td>(Smith et al., 2009)</td>
<td>Joint priority is a method where both sides of the lock are taken into account. The priority done according the FCFS principle.</td>
</tr>
<tr>
<td>SPT</td>
<td>(Nauss, 2008; Smith et al., 2009)</td>
<td>The Shortest Processing time First is a method where the vessel who can be handled fastest is the one that gets priority.</td>
</tr>
<tr>
<td>SPT per unit</td>
<td>(Nauss, 2008)</td>
<td>The Shortest Processing Time per unit corrects for larger vessels which have in general a larger processing time.</td>
</tr>
<tr>
<td>SAVE</td>
<td>(Ting &amp; Schonfeld, 1996)</td>
<td>Maximum processing time Savings. It checks which vessel has the most benefit from a certain chamber.</td>
</tr>
<tr>
<td>SINGPRIO</td>
<td>(Smith et al., 2009; Ting &amp; Schonfeld, 2001)</td>
<td>Single Priority. This means that vessels which do not need any support are handled first.</td>
</tr>
<tr>
<td>JIT</td>
<td>(Ting &amp; Schonfeld, 2001)</td>
<td>Just In Time principle, arrive just before it is your turn.</td>
</tr>
</tbody>
</table>
The first come, first server principle is the oldest scheduling method which can be found. Nevertheless, it is still used nowadays. The main reason that it is still used is the fact that everybody can understand it and probably thinks it is fair. There are however some limitations to this method, i.e. if a lock is getting closer to its maximum capacity or the average waiting time starts to rise. Over the years, this method has been improved by extending it. This is done by either adding priorities to preferred customers or to regular visitors or by adding chamber filling algorithms to the first come, first served principle. This algorithm ensures a more efficient use of the lock’s capacity. It means that the first in line is allowed to enter a chamber. If just FCFS was applied, the number two is allowed to enter if it fits. If not, the chamber would close. The added algorithm allows the third vessel or even the 10th vessel to join the lockage if that is the first vessel that fits into the chamber. A last amendment of the FCFS method is the JPRIO. This method takes into account the processing times of the vessels at both sides of the lock. This more holistic view can be of added value if there is a queue at both sides. The downside is that this method does not take into account the time it takes to complete a lockage process.

A whole other lock operation policy is determining the order of vessels by their processing time. Ordering the vessels by means of their processing time is mentioned in many studies as the most efficient way of ordering. It is very efficient for minimizing the average waiting time. It is very well possible that the waiting time of some vessels will be significantly higher. There are however some downsides. First of all, the theory does not mention different arrival times, so it would only be efficient if there is a queue or if the processing time plus the travel time of the second vessel is shorter than the processing time alone of the first vessel. Secondly, shippers might not accept the fact that vessels who arrives at a later point in time can pass the lock earlier. There are some variations of this theory which expand the SPT theory. First of all the SPT per unit, which works the same as the SPT method, but the processing time is corrected for the size of the vessels. As a result the smaller vessels would not benefit more than larger vessels. This might however diminish the effect of SPT. Another alternative for SPT is SAVE. This methods divides the vessels among the different chambers by checking which chamber is most beneficial for the vessel. The order per chamber is done based on FCFS.

A whole other approach is based on the amount of resources that is needed. The SINGPRIO method ranks the vessels based on the support they need, if no support is needed priority is assigned. This mostly affects the large vessels, since they need pilots or tugboats. This method might be applicable if the resources are a limiting factor. The downside is however that the vessels can be on the waiting list indefinitely.

A last method that is frequently mentioned is the Just In Time principle. This principle is different than all others, since it does not focus on the order of the vessels, but on the arrival. The theory is, that if vessels arrive just before their lockage process starts, the lost time will be less than if the vessels are laying in a queue.

Downsides of the theoretical approaches

What all those theories have in common is that in some way they are all calculated optima. This includes a calculated average capacity and a calculated average waiting time (Backalic & Bukurov, 2011), while in some cases the maximum value is more important. Not all factors which influence the efficiency of locks are taken into account. First of all, it is fair to say that the theories mentioned above are just a part of the management approach. It should be clear that other aspects have to be added before the management approach can be a success. Among these aspects are the time at which the vessels have to sign in for a
slot, the availability of tugboats and pilots, the handling procedures for different kind of vessels. The cargo of the vessels and the opening hours of the locks.

Even if the principle is embedded into a larger lock operation policy, there are still some shortcomings. First of all, only the SPT and SAVE methods divide the vessels over the different chambers, the other methods do not mention the division over the chambers. The same can be said about the lock direction management. Direction management is managing the empty lockages, so under which circumstances should an empty lockage occur. Secondly, only the FCFS with a chamber filling algorithm mentioned the notion of managing multiple vessels in a chamber. Another downside which follows from this point is the balance between lock management and chamber management. So, how long should the lock operator wait for other vessels before closing the chamber and starting the locking process? This will be a balance of average waiting time versus maximum waiting time, since the vessels which have to wait in the chamber for other vessels have a long waiting time. The average waiting time might be lower, since the chamber is filled more efficient.

It is fairly easy to determine in which order vessels should be processed, but how do you arrange that in practice if you do not know when the vessels will arrive. If all vessels arrive at different points in time, every vessel is the vessel with the shortest processing time. So, how long will you wait before closing the chamber and start the lock process. It is also not mentioned when to apply such a strategy, they just assume it is possible to apply it. For example in Ghent and Antwerp, they use some sort of SPT process. This is only possible since the locks are too crowded for FCFS. It should be noted that the shortest processing time is determined for all vessels combined and not for individual vessels.

2.2.3. Lock operation policies in practice
In order to apply the theories mentioned above, they should be embedded in a larger management approach. In order to investigate which management approaches are available, this paragraph focuses on different lock management approaches at different ports. The management approaches which will be discussed are the approaches which are used near ports in Western Europe, so this will be the port of Amsterdam, the port of Ghent and the port of Antwerp. The issues addressed in the previous paragraph will be mentioned in this paragraph.

The port of Amsterdam
The port of Amsterdam is separated from the North Sea by the locks of Ijmuiden. The locks consist of four different sized chambers. The two small chambers are mainly used for boating, where the smallest chamber only handles pleasure boats. While the two large chambers are used for commercial traffic. Since the trips for pleasure do not need to subscribe to any slot or indicate their arrival time, the management of this category is impossible and therefore not taken into account. On the west side of the lock, the North Sea can be found, while the North Sea Channel is located at the east side.

The basic principle that is used in the port of Amsterdam is the first come, first served principle. Where the first come part is based on the indication of the arrival time and not on the actual arrival at the lock. Furthermore they use the SAVE principle, meaning that the choice of the chamber depends on the shortest processing time for the vessel. It should be noted that the planners can make adaptations to this schedule if they think it is in the general interest. There are some general exceptions; commercial traffic has priority over boating and tidal dependent vessels will have priority over other vessels if it is high tide. During the planning it is taken into account that vessels with a hazardous cargo should have a minimum
distance between them and other vessels. The availability of tugboats and pilots will become crucial if the vessel is a gully vessel or a tide dependent vessel, but most large vessels have to make use of the services of a pilot or tugboat. If vessels arrive from the west side, the timeline is as follows. In order to have an efficient planning, vessels have to claim a slot 48 hours before the Estimated Time of Arrival (ETA). At that moment, the ETA will be checked and technical specifications of the vessel, like draft and stability factors, have to be handed to the planner. It is also taken into account that tugboat or pilots would not be available or that congestion might occur. A long-term planning will be made based on those factors. After contacting the vessels at ETA -24 hours, the long-term planning will be updated into a preliminary planning which will be definite when the vessel arrives at the ‘kruispunt’. The kruispunt is an imaginary point five miles offshore. If a vessel does not make it within 30 minutes of its ETA, the vessel should be placed at the back of the line again. The planning for vessels who come from the east is the same, but the long-term planning is made 24 hours before ETD and the preliminary planning at ETD -6 hours and the definite planning when the vessel is leaving berth. Due to this planning, the margin of errors is larger, since there is no time to correct disruptions. The difference between the ETD and the ATD should be less than 30 minutes otherwise the vessel is placed at the back of the line.

Since the planning is not entirely based on the FCFS principle, the planner can make some exceptions to the rule, this is often done based on experience or gut feeling. The planner will be in contact with the shipper, the agent and the manager of the tugboats and pilots in order to adapt the planning and make it more efficient. The rules the planner applies when adapting the planning are hard to grasp and can probably never be fully understood.

The port of Ghent

The port of Ghent is connected to the Westerschelde by the channel between Ghent and Terneuzen. At the border between the channel and the sea, the locks of Terneuzen can be found. This consists of three chambers. All those chambers are used for commercial traffic. The management of the locks is done based on priority. This is a method which is not described in any literature.

The first step is to subscribe to a certain time two days before the arrival. If all vessels subscribe to a certain time, the schedule for the lock is automatically generated. This schedule can be used to avoid congestion. If a vessel knows that there will be congestion, it is more beneficial to reduce speed. A second function of the schedule is the deadline. The schedule is definite 6 hours before for arriving vessels and 3 hours before for departing vessels. If a vessel does not make his slot, the vessel has to wait at least either 6 or 3 hours depending on the deadline. It is however possible to switch slots with other vessels. As said, this lock operation policy uses priority. This priority is based on vessel types. Tidal vessels have always priority, while liners get two hours priority and every vessel is entitled to an extra 30 minutes priority per tugboat or pilot that is needed. This priority time is deducted from the ETA, the new times are compared and ordered into a new schedule. Whether a tugboat or pilot is needed depends on the size of the vessel. This management approach gets more complicated since it includes the planning of three chambers, the fact that vessels have to overtake each other on a channel and the necessity of two different kind of pilots; sea and channel pilots. This increases complexity, since more resources from different locations are needed in order to complete the lock process.

The reason that this method of scheduling works is the fact that all parties benefit from these rules. The shipper knows when to arrive at the locks, so he can save fuel and the owner and planner of the locks benefit since the lock is used more efficiently. It avoids congestion as well, which is beneficial to all
involved. It should however be noted that currently the inland vessels are not included in the planning of the locks. They arrive at the locks and see whether they can pass. Whether they can join an ongoing locking process depends on whether they can be seen by the planner. The vessels become visible around 30 minutes before arrival.

*The port of Antwerp*

The locks of the port of Antwerp are located within the port. There are two double chambered locks and four single chambered locks. All those locks give access to other parts of the port. All the locks and chambers are used for commercial traffic. Boating vessels are scheduled between the commercial vessels, so the influence on the commercial vessels is negligible. The theoretical method that is used in the port of Antwerp is first come, first served with some additions, while the optimization rules is based on a high filling rate of the chambers.

The incoming vessels have to contact the pilot authority between 8 and 6 hours of the ETA. The pilot and tugboats should be claimed by the vessel’s agent at least 6 hours before the ETA. If the vessel has been assigned a berth, it is free to enter the port. The time slot at which the vessel is allowed to enter the port and therefore the locks is determined by the pilot authority by taking into account availability of pilots and tugboats and the tide. The chamber planning is done by the ‘Coco’ based on the ETA for each of the six locks. It should be noted that tidal vessels have priority over other vessels. The outgoing vessels have to send their ETA at least four hours before leaving and have to wait for permission to leave. Again, the agent has to claim tugboats and pilots. The ATA is determined by the authorities.

The planning has some clear rules about priorities, but since the final planning is made by the planner, it is still possible to adapt the schedule because of experience or gut feeling. Therefore, the real planning rules might be fairly complicated.

### 2.2.4. A framework for testing the lock operation policies

After looking at common practices in different ports, the most promising theories should be selected in order to be able to test those theories in the simulation model. By discarding the unrealistic theories it is possible to establish a list with plausible theories.

As mentioned earlier, in most cases priorities are set to some vessels. This is done in order to reduce the waiting time for those vessels. An example is the tidal vessels. Those vessels are only able to pass through the locks during high tide. Therefore it makes sense to give priority to those vessels if they are able to make it within the tidal slot. Otherwise the waiting times for these kind of vessels can increase to 12 hours or more. It is common as well to give priority to commercial vessels over non-commercial vessels. This is done, because of the value they represent for the ports. Since those priorities are broadly accepted and have proven to be beneficial for the efficiency of the locks, such priority rules should be taken into account during the simulation regardless of the different theories. This will give a more holistic view of the planning methods than if the priority rules would be neglected. Another crucial aspect that should be included if a new approach is developed, is the fact that all three ports use some sort of priority system, but all have different rules. In most ports tidal vessels have priority over other vessels. Looking at the port of Ghent, liners have priority. In the port of Antwerp vessels who can be added to the current lockage have priority and in the port of Ghent sea vessels have priority over inland vessels. Therefore, all theories that may be developed during this research should include the basic priority rules.
The theories described above can be divided into three main categories. The first is ordering based on arrival. This includes all the FCFS differentiations and the JPRIO method. Since most ports, including the port of Amsterdam, use this method, this will be the initial scenario which is used to compare the other theories with. The second scenario focuses on the processing time. This includes the three Shortest processing time first methods and the SAVE method. In this category the SAVE method is less relevant, since it focuses on the processing time of the locks, while the main focus is often on the waiting time for vessels. The last scenario is the scenario which focuses on the need for resources. If a vessel needs a pilot or a tugboat, it is allowed to enter before the other vessels. In this case the resources are used as efficiently as possible, which can reduce costs and increase the productivity of the locks.

The descriptions of the management approaches at the three ports shows that the circumstances differ so much, that it is not possible to apply an approach that fits all situations. Each of those described situations can however teach us something. First of all the approach which is used by the port of Amsterdam, they let the vessels or agents sign in either 48 or 24 hours before the expected time of arrival. By integrating this in the design of the management approach it becomes possible to integrate another planning approach without causing much losses for the vessels, since they can adapt their speed or route to the assigned time. The case of the port of Ghent shows that it is in fact possible to change the first come, first served method into another approach as long as there are benefits for everyone. This is accepted since the locks are so crowded that the first come, first served approach will cause long queues. In the port of Antwerp, the port authorities have a strong position, since they have the final call on the arrival time. So it can be said that, to a certain extent, the port authorities can determine the arrival times of the vessels.

Combining those strategies into one management approach allows for a framework that can test different theories. The framework that will be used for testing the theories in the simulation model will have the following layout.

1. Between 48 and 24 hours before arrival the ETA is sent to the planner.
2. 24 hours before the lockage, the planner determines which vessel will be in which lock and in what order based on a theoretical approach which includes priorities.
3. 12 hours before arrival the vessels update their ETA, the planner updates the schedule.
4. 6 hours before arrival the vessels update their ETA, the planner finalizes the schedule.
5. If a vessel cannot make the slot, the vessel is set back in line to the first available spot.

It should be noted that the timeframes cannot always be met, due to the limited timeframe, as has been described during the description of the layout. This timeframe can be limited due to environmental factors such as a port nearby or tidal influences. The last step that should be taken is to include the chosen theories into the framework mentioned above on order to generate alternatives that can be tested in a later stage.

2.2.5. Fitting the policies into the framework
This chapter will combine the theoretical approaches with the framework in order to generate some alternatives for the chosen layout as described in Chapter 2: taxonomy of waterways. Since the chosen layout has different planning horizons at both sides of the lock, the management approach should be described from both ways. It should be noted that it is assumed that the time slots are determined upfront and that the locking process will take place at a set time.
A0: Initial situation: first come, first served (FCFS)
In the Netherlands, it is by law enforced that vessels should be handled in the order in which they arrive (overheid.nl, 2015). Therefore, this principle will be a good starting point for the simulation project. And since most ports use some sort of priority system, it can be considered as a crucial part of the initial situation as well. The process for vessels arriving from the west side, starts between 48 and 24 hours before arrival. The schedule will be updated 12 and 6 hours before arrival. 3 hours before arrival, the estimated time of arrival will become definite. If a vessel does not arrive within 30 minutes of its estimated time of arrival, it is set back to the first available spot.

The priority rules which are in place are the following. First of all, tidal dependent and gully vessels will have priority over other vessels. Secondly, non-commercial vessels will have a lower priority than commercial vessels.

A1: Shortest processing time first (SPT)
The planning order of the second alternative will be based on the expected processing time of a vessel. This processing time can be defined as the time it takes to navigate from the “kruispunt” through the locks without any delay. So, this includes the processes with the tugboats and pilots. Again the process should be described for incoming and outgoing vessels.

The incoming vessels should again send their ETA to the planner between 48 and 24 hours before arrival and update it 24 hours and 12 hours before arrival. 24 hours before the locking process, the planner checks which vessels cannot make it to the previous locking process, but can make it to this one. Based on the dimensions, cargo and status of the vessel and the weather conditions (tides and wind), the planner estimates the processing time and ranks the vessels according to the processing time. This ranking will be done for each chamber, so the amount of vessels that can pass the locks is the largest. Again it will be checked whether a vessel has a hazardous cargo or whether another vessel fits in the chamber. The vessels which are left out of the chamber due to capacity issues are allowed to join the next round no matter which processing time they have. Vessels who are too late will be replaced by the next vessel in line.

This alternative should be implemented by taking into account some priority rules. The first vessels that will get priority are the tidal vessels. Those vessels can only enter the locks with high tide. This is a common priority strategy which can be used to make the port more attractive for large vessels. The second priority rule is the priority of liner over regular vessels. The reason for the priority is the fact that the liner come on a regular basis and the ETA is known long before the actual arriving time. In return for this early notice, liners get often priority over other vessels. A third rule that should be applied is the priority of vessels who fit in the chamber over the vessels who are first in line. This will cause a more efficient chamber use, since it happens more often that a chamber is full. These three rules which are often found in literature should ensure a more efficient use of the resources.

The process which will be used for outgoing vessels will be the same except the timeslots. They will be sending ETA to the planner between 24 and 12 hours before ETA, preliminary planning will occur 12 hours before the locking process and the final planning 6 hours before the process.

A2: Resource-based selection (RBS)
This theory is based on the fact that resources might be a limiting factor. Again this alternative will only change the order of the vessels. The procedures regarding the timeslots will remain the same. This alternative allows vessels who need support of some sort first. This can be arranged by means of “bonus”
time. By applying the same rule which is applied in the port of Ghent, for each resource they need, they get 30 minutes of “bonus” time. A resource can be seen as either a tugboat or a pilot. This rule ensures an efficient use of the resources. As a result, the vessels who need resources are planned first and the other vessels will be scheduled afterwards. So if the resources are in fact the limiting factor, this alternative should make the planning procedure more efficient.

Regarding the priority rules, the same priority rules will be applied to a different planning strategy. So, tidal vessels will be handled first in all cases and if a vessel still fits in the chamber, he gets priority over the vessel that is first in line. This can also happen if the needed resources are claimed and a vessel which does not need any resource can enter the process. The timeslots and the rules around hazardous cargo will again be the same.

Table 3 Alternative policies

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0: First come, first served (FCFS)</td>
<td>The vessels are scheduled in the order they arrive</td>
</tr>
<tr>
<td>A1: Shortest processing time first (SPT)</td>
<td>The vessels with the shortest processing time can enter the lock first</td>
</tr>
<tr>
<td>A2: Resource-based selection (RBS)</td>
<td>Vessels who need resources get planned first. The other vessels are scheduled afterwards</td>
</tr>
</tbody>
</table>

2.2.6. Testing conditions for the alternative lock operation policies

These different alternatives will not only be compared with each other based on an initial situation, a possible growth in the number of vessels will be taken into account as well. The reason a possible growth is taken into account is the fact that a good lock planning policy is only important if the capacity of the locks is limited. So, the effects of the different lock planning policies are likely to be higher if more vessels arrive at a port. It is also plausible that some policies are more beneficial than others if the number of arriving vessels is low and vice versa.

2.3. Conclusion

The main goal of this chapter was to answer the first sub-question: *What are the possibilities to manage locks and what are the most promising practices?* The first step during this process was to identify different categories of locks and as a result the most promising category which can be used to test different waterway-lock combinations. The second part which is crucial to answer the sub-question is identifying the possible lock operation policies and compare them with the policies which are used in practice. Combining those two gives a full overview of the possibilities to manage locks and the most promising practices.

2.3.1. The most promising waterway-lock combination

As has been stated, in order to come up with a general theory about the lock operation policies, it is important to include all aspects which might determine the success of a certain management approach. So, since external factors such as the proximity of a port, limit the planning horizon it is important to take this into account during the study. The same can be said about whether the chambers have the same size or not.
As was described, not all aspects are useful to take into account. First of all, the single locks are not taken into account, since their maximum flow of vessels can be calculated fairly easy. Secondly, a chain of locks is not taken into account either. Those locks ask for a more holistic approach. All consecutive locks should be modeled, as a result the management approach for a single lock becomes less important. The layouts which are suitable consist of locks with multiple chambers. If the chambers are equally sized, the complexity would be lower than if the chambers are of different sizes. Management approaches which are suitable for different sized chambers are suitable for locks with equally sized chambers, but not the other way around. Therefore the chosen layout will be of a lock with different sized chambers which are not part of a chain of locks.

Looking at the time component, both the short and long planning horizon have some aspects which can influence the management approach. If the planning horizon is long, it is possible to use all kinds of management approaches since it is possible to let the vessels arrive at certain points in time. A short time horizon demands the management approach to be dynamic and adaptable, since vessels can arrive almost without notice. So, the chosen layout should ideally include both a long planning horizon as well as a short planning horizon. This can be achieved by choosing a lock which is located near a port and adjacent to the sea. The choice of a suitable lock will be discussed in Chapter 3.

2.3.2. Chosen lock operation policies
The earlier mentioned lock operation policies are divided into three categories. These categories will be used as alternatives which will be tested by making use of the most promising waterway-lock combination. The three categories are:

1. First come, first served (FCFS). This category is commonly used in practice and focusses merely on the arrival time of the vessels and does not take into account the use of resources for determining the order of vessels
2. Shortest Processing time First (SPT). By using this policy, the vessel which has the shortest processing time is chosen to pass through the locks first.
3. Resource-based selection (RBS). This policy ensures an efficient use of the resources, since vessels who need resources are allowed to pass through the locks first.
3. Aspects and key performance indicators of locks

This chapter will be used to describe the subject of the case study, the port of Amsterdam. Besides a description of the port of Amsterdam in detail, the situation will be compared with the port of Ghent and the port of Antwerp as well. This will be done based on the characteristics described in Chapter 2 and the KPIs which will be described in this chapter. This will result in answering the following sub-question: *What are the key indicators which determine the success of a certain lock operation policy?*

The first two paragraphs of this chapter will be used to describe the case study in detail. After that, the KPIs and external factor will be described in paragraph 3.3. The last paragraph will be used to compare the different KPIs and external factors of some ports with each other, which can later be used during the generalization phase of the study.

Before, the description of the case study starts one important question should be answered; why is a case study the best method for this problem? After this question is answered, the description of the case study itself will follow. The first reason in favor of a case study is the fact that the research focusses on the lessons that could be learned about the past and the improvements for the future, which is an area that is well fitted for case studies (Yin, 2004). Secondly, an input knowledge about the topic of lock operation policies is necessary in order to draw conclusions about it, this knowledge can be gained by using a case study (Yin, 2004).

### 3.1. Introduction of the port of Amsterdam

Since the most suitable layout and the different policy options are discussed in the previous chapter, it is time to combine those two. This will be done by comparing the three ports mentioned in Chapter 2. First of all, the port of Antwerp is considered. This locks of this port are located within the port, this leads to a very short planning horizon and therefore limits the planning possibilities. Moreover there is not a single lock that gives access to the port, but there are six locks that give access to different parts of the port. The choices that are made during the planning of these locks are mainly choices between locks and not between chambers. Those two aspects are not in line with the description of the lock operation policies and the layout of the locks which are used during this study. Therefore, the port of Antwerp is not a good case study that can be used during this research. The other two ports are quite similar. They both meet the requirements that are mentioned above. The only difference is the fact that the port of Ghent uses an automated system to plan the vessels into the locks. Their main struggle is to fit the inland barges into the system, since this cannot be solved with other lock operation policies. The port of Ghent will not be taken into account as a case study during this research. The remaining port, the port of Amsterdam, can capture all aspects which are mentioned in this chapter and they do not have an advanced system such as the one used in Ghent. Therefore this port will be used as a case study during this research.

The port of Amsterdam is an example of a port that is likely to struggle with the problems of an inland port as described in Chapter 1. There are four chambers present; two big and two small chambers. Therefore, the chamber size should be taken into account when planning the locks. If vessels arrive from the west side, the planning horizon is rather large. Vessels have to sign in 48 hours upfront, so there is a lot of time for management of the arrivals. If vessels arrive from the east side the planning horizon is sometimes just two hours, since vessels are departing from the port of Amsterdam and do not know their ETA until they are finished with loading and unloading. As a result lock operation policies can be tested for both a short planning horizon as well as a long planning horizon. The layout of the port of Amsterdam
corresponds with the demands set in this chapter, namely the different sized chambers and the absence of other locks. Currently they use the first come, first served principle with priority for large vessels. Since they are planning to expand in the coming years, they are willing to adapt their current process in order to be able to handle a larger amount of vessels. Therefore, the port of Amsterdam will be the case study for this research. The port is located land inwards and is connected to the North Sea by the North Sea channel, which includes locks. The port of Amsterdam is one of the most competitive ports in Europe nowadays (Europeish, 2014). With a throughput of 95 million ton per year and sixteen large terminals (Port of Amsterdam, Terminals stukgoed & containers, 2015; Port of Amsterdam, Terminals Natte bulk, 2015), the port of Amsterdam is ranked 4th port of Europe (Port of Amsterdam, Projecten, 2015). In order to maintain this high ranking and keep up with the ongoing economic growth and the globalization of the world market (Spaventa, 2013), it is important to constantly increase the capacity of the port (Port of Amsterdam, visie 2030, 2015). The goal of the port of Amsterdam is to increase their freight handling by 70% in the coming years (Ridder, 2015).

The port of Amsterdam does not have the intention to expand in surface (Schueren, 2015). Another way to look at expanding ports is not increasing the size of the port, but improving the efficiency of the port. This can be done by increasing the amount of vessels that can be handled simultaneously or by decreasing the handling time per vessel. This is quite difficult, since it is not directly visible where to change and such a change affects a lot of parties within the port. The goal of the port of Amsterdam is to maintain the annual growth rate by taking into account the limited space (Port of Amsterdam, Gemeentelijke visie 2008-2020: Een slimme haven, 2014). Either way, the amount of vessels will increase.

So combining the fact that the port of Amsterdam is limited in its growth by the locks and the fact that growth is expected in the coming years, makes the port of Amsterdam a perfect example to test the earlier mentioned theories.

### 3.1.1. Usability of the research

Next to the goal of the research, it is equally important to define how the model can be used. This defines partially the scope and gives direction to the way of analyzing. If the results should be used on a daily basis, the structure would be different than if it will be used once or yearly. This study focusses on different ways of managing locks and which factors influence the choice between different policies. Therefore, the long-term is more important than the short-term. The model can be used to check under which conditions a certain policy is effective. The effectiveness is mainly dependent on the amount of arriving vessels and the growth in arrivals, therefore this will be a decision that will be made once or the decision will be reviewed if the situation changes. Since it concerns a decision about the way the operations should be performed, the model and the results are meant to be used by the managers who are responsible for the long-term policies. It will be both possible as well as necessary to evaluate the situation every year by making use of the model in order to keep the model up to date and the assumptions valid.

### 3.1.2. Scope

The scope of the case study will be a part of the North Sea Channel. So the physical boundaries will be from outside the North Sea Channel, namely the Kruispunt, to the Houtrak near the start of the port of Amsterdam. The timeframe of the study will be the year 2014, since the data for this period of time is available. The case study can be used to test the theories developed in the first phase of the project. It should be kept in mind that tugboats and pilots are included in the research even though they are claimed before entering the simulation. This is possible since the planning horizon of the simulation is up to 48
hours. The part from the kruispunt to the locks and from the locks to the Houtrak is not modelled to the smallest detail. This is reserved for the locking process.

Figure 3 Scope of the case study (dotted line) (adapted from: (Unknown, 2015)

The second part of the description of the scope is dedicated to the parts that are excluded from the study. The mix of vessels that arrive at the locks consists of both pleasure as well as commercial traffic. Pleasure boats are mostly small sailing vessels and motorboats. They pass through the small chamber, which is dedicated to pleasure boats, sometimes through the southern chamber and once in a while through one of the other chambers. During the year 2014, 914 pleasure vessels sailed through the southern, 107 through the middle and 28 through the northern chamber. Of those 28 vessels, 23 went through the northern lock together. Since 8896 and 7559 vessels pass through the middle and northern chamber per year, the pleasure vessels that pass through those chambers can be neglected. Especially since most of the vessels who went through these larger locks passed during the race of the classics which is a sailing competition that caused a great peak load (classics, 2014). There are a couple of reasons why the two larger chambers are not used for pleasure vessels. First of all, commercial vessels do not have any priority and they do not notify the planners before their arrival. Therefore, the waiting time of the pleasure vessels is less important. Secondly, the current caused by the large vessels is so strong that it might be hard on the smaller vessels. Thirdly, the pleasure vessels have to cross the routes of the commercial traffic, which might be dangerous or cause delays. All those reasons combined result in an exclusion for the pleasure vessels in the two larger chambers. The pleasure vessels in the southern chamber should be taken into account, since almost 20% (914 out of 4991) of the vessels that pass through the southern lock are pleasure vessels.

A question that is closely related is whether or not to include the small chamber into the system, since it is dedicated to the pleasure vessels. An argument in favor of including the fourth chamber into the research can be found in logistic theories. Since an extra chamber provides an extra degree of freedom. By dividing the vessels over four chambers, where pleasure vessels are only allowed in two chambers, the filling of the chambers can be done more efficient and the average processing time is likely to be lower, since smaller chambers have a smaller processing time. There are some downsides as well. First of all, the maximum dimensions of vessels that can pass through this chamber are 110X11X3.5 meters. This results
in a percentage of 32% (9269 out of 29188) which can pass through the chamber including the pleasure vessels and tugboats, without these vessels the percentage drops to 25%. It is due to safety reasons that the pleasure vessels are not allowed in the same chamber as commercial vessels. The movement of water due to sailing into a chamber and the movement of water caused by the engine of the commercial vessels is too much for the pleasure vessels. As a result, it is better to not include the fourth chamber, since it would increase the waiting times for the pleasure vessels, without a possibility of nullify this increase.

3.2. Model characteristics of the port of Amsterdam

This paragraph will give an overview of the steps that are taken in order to create the model. The first step was making a conceptual model. This is done by means of an IDEF0 diagram and a UML diagram, both can be found in Appendix D. The IDEF0 diagram can be used to describe the processes in detail. This graph shows the order of the processes in detail. It shows the resources which are needed as well. This is useful since the model itself is constructed out of consecutive processes as well. The UML diagram shows an overview of the elements of the system together with their dependencies and attributes. This can be used to include all important elements of the system. These two conceptual models give an overview of the whole system. The next step is to define the most important parameters of the system. This is done by a data analysis of the vessel arrivals of the year 2014. The important parameters are for example the processing time of the lock, the arrival distribution and so on. This analysis can be found in Appendix A and 0. After the parameters are defined, the model itself can be constructed. This process is an iterative process. After the construction of each element, this element is tested and if necessary improved. This evaluation is done with the help of the port of Amsterdam and supported by the comparison with the data. After the model is constructed, the verification and validation can be performed. This is crucial for the usefulness of the model, since it will confirm that the model does was it should do and that the results are comparable with the results of the real system.

3.2.1. Processes of the objects in the simulation

The actions of the different objects that are present in the simulation will be described in this paragraph. The first object that will be described are the commercial vessels, the second are the, pleasure vessels and last the tugboats and pilots.

**Commercial vessels**

The commercial vessels can be seen as all vessels that make a living out of their vessels. As a consequence, every minute they have to wait, reduces their profit. In order to minimize the waiting time, they have a strict process they follow. First of all they pass on their estimated time of arrival (ETA) to the lock operators who are in charge of the lock planning. The second step is that they update their ETA frequently to minimize variances between the estimated and actual time of arrival (ATA). Before arriving they have to claim pilots and tugboats if necessary. When they arrive at the locks, there are two options. The first option is that they can sail directly into the assigned chamber and the second option is that they have to wait and moor at a waiting jetty. When they arrive in the chamber they have to moor again and unmoor when leaving. The last step is to release the tugboats and pilots. This process is visualized in Figure 4.

![Commercial vessels process](image)
**Pleasure vessels**

Pleasure vessels have less incentives to participate in the whole process around lock planning for two reasons. First of all, the time lost due to waiting is less important than it is for commercial vessels since the profit aspect is not present. Secondly, they do not plan their journey to the greatest detail upfront. They leave and arrive when they want to and therefore they do not mind to wait for their passage through the locks. Therefore, the first step in the process of the pleasure vessels is arriving at the locks. The second step is either wait for a chamber to become available or to sail into the chamber. Since the dimensions of the pleasure vessels are rather small, tugboats and pilots are not necessary for continuing the process. The next step is to moor and unmoor in the chamber.

![Diagram of Pleasure vessels process](image)

**Figure 5 Pleasure vessels process**

**Tugboats and pilots**

The processes around tugboats and pilots are somewhat more complicated than the processes around commercial and pleasure vessels. Tugboats and pilots are hired by the port authorities from private companies, so their processes cannot be influenced as easily. It should be noted that the tugboats and pilots work in shifts, as a result the processes that will be described below can be disrupted by either breaks of the tugboats and pilots or by a lack of either tugboats or pilots. The process starts at the moment a tugboat or pilot receives a notification of a vessel that needs either a pilot, a tugboat or both. The rules about which vessels needs those resources and which vessels do not can be found in Appendix E. After it is known which resources are needed, it will be checked at which point in time the resources can be available. This includes an evaluation of the location of the available resources, since the tugboats do not have a fixed waiting point. The pilots can be brought to the vessels either by helicopter or by boats. The next step is to attach the tugboats to the vessel. This takes approximately 30 minutes. The same time should be taken into account if the tugboats are disconnected. As a result, disconnecting the tugboats during the locking process is not taken into account. After the tugboats are attached and the pilot has entered the vessel, the vessel can be navigated through the locks. It is often not necessary to have multiple tugboats to guide a vessel through the locks, therefore the second tugboat is often disconnected from the vessel depending on the weather conditions, experience of shippers, the schedule of the tugboats and the proximity of other vessels. If a tugboat is disconnected, it either return to a waiting jetty or it goes to the next commercial vessel.

The tugboats and the pilots are implemented as resources, meaning they do not go through the system together with the vessels, but can just be claimed and marked as occupied by the vessels. This is convenient from a modelling perspective and represents the real system in such a way that it is simple but not too simple. The actual tugboats do pass through the locks, but not combined with the corresponding vessels. They pass through the locks as individual vessels with a random arrival pattern.
3.2.2. The main processes of the system

The system consists of three main processes. The arrival process, the planning process and the passage of the lock itself. Despite the fact that these processes should be aligned perfectly, it is possible to describe them individually.

Arrival process

The arrival process consists of two important parts, the arrival logic and the assignment of the characteristics of the vessels. A third part is necessary for the presentation of the model, which is the model dimensions. The arrival distribution is based on the arrivals of the year 2014 and is specified for both directions by means of a random interarrival time of 0.8 hours with an exponential distribution (Appendix A). The second part is assigning the characteristics of the vessels. This is done by a random draw from the arrivals of 2014. This is done to have both random as well as realistic properties for the vessels, such as a good ratio between length, width and draft. The characteristics which are assigned are the vessel type, length, width, draft, cargo category, direction and the expected arrival time of the vessels. The vessel type is equal to the minimal chamber a vessel is allowed to pass. The cargo category is important for the choice of the chamber. Some category require a certain distance to other vessels and are therefore not allowed in a chamber together. It is decided as well whether other resources are necessary. This consists of the choice for pilots and tugboats. These resources are claimed based on the dimensions of the vessels. The underlying assumptions for the assignment of the vessel type and claiming the resources can be found in Appendix E. The last part is solely used for the presentation of the model. Small vessels will be smaller in the model as well and the vessels which are only allowed in the northern chamber are the largest.

Planning process

After the vessels are created, the vessels arrive at the planning process. This takes place 3 hours before the actual arrival of the vessels, since the planning becomes definite at this point in time. The planning process is based on shortest processing time, first come, first served or resources based selection. For each vessel that arrives, the expected processing time for each chamber is calculated. Then the vessel is assigned to the chamber which has the shortest processing time. Before making the choice, the following factors are taken into account:

- The direction of the chamber
- The state of the chamber
- The arrival time of the vessel and the other vessels in the previous lockage
- The width and length of the vessel and the previous vessels
- The cargo category of the vessel and the previous vessels

If the direction of the chamber is not equal to the direction of the vessel, an extra lockage process is needed, if the state of the vessel is not idle, the remaining processing time is added to the expected processing time. Extra time is added as well if the vessel does not fit into the current lockage. The time component is more complicated. A vessel is allowed into the current batch if the additional waiting time
for the first vessel in the chamber is smaller than 30 minutes. In order to optimize the process of planning vessels, it might be crucial to allow multiple vessels in a chamber together. This decision is made based on multiple rules. First of all, every vessel that is added to the current lockage process should arrive within 30 minutes of the first vessel. This is done to minimize the additional waiting time. Secondly, it is checked whether the vessel fits next to or behind the vessels that are currently in the chamber. This is not only done by checking the dimensions of the vessels, but also by taking into account the restrictions for hazardous cargo (see Appendix E). The last step is to assign the batch size and number to the vessels.

3.2.3. The decision logic

This paragraph will describe the underlying logic of the model and the main decisions that are made within this logic. The first decision that needs to be made is the decision about the tide. Secondly, the decision with regards to lightering is made, followed by assigning a different chamber despite the lockage time and lastly deciding whether to execute an empty lockage.

Tide decision

The tide decision is made in two steps. First of all, it is decided whether it is high tide or not. This is done based on the time of the day rather than on the depth of the water. This is due to the simplicity of the implementation of this rule. If the tide is low, the vessels have to wait if the second condition is also met. This concerns the decision about the draft. If the draft of a vessel is more than 13.1 meter, a vessel has to wait for high tide. Since the vessels arrive in a random order, the time slots of the ride can be modelled at
every point in time during a day as long as high tide and low tide happen twice a day. Therefore, it is chosen to fix the time the tide for each day at the same times.

**Lightering decision**

The vessels who can pass through the locks should have a draft of less than 13.1 meter. If the draft is more than 13.1 meter, vessels have to be lightered. Meaning that a part of the cargo is transshipped to inland barges before the lockage process starts. This takes approximately 4 hours. After the shipped have been lightered, the vessels can pass through the locks by following the normal process.

**Assigning different chamber**

In addition to the general rule of assigning the chamber which allows the fastest passage through the locks, another principle plays an important role. This principle is based on the performance of the lock instead of the processing time of the vessels. If a vessel arrives at the locks and it does not fit in a certain chamber, but the vessel fits, together with the other vessels, in a larger chamber, all vessels are sent to this chamber. As a result, the average processing time of the vessels will be larger, but the amount of lockages will be lower.

**Empty lockage decision**

This decision will be made by the lock itself. The lock checks the queues at both sides and performs an empty lockage if the queue on the current side is empty and the queue on the other side is not and an empty lockage plus a normal lockage process can be performed before a vessel arrives at the current side of the lock. This choice is necessary if the arrivals from the east and west are not in balance at a certain point in time. If this aspect was neglected, long waiting times could occur.

### 3.2.4. Origin of the current lock operation policy

As mentioned earlier, the base of the lock operation policy that is currently in place is First Come, First Serve. However, the rules above show a lot of extensions and variations on this policy which are generally accepted. The reason that these rules are accepted by all parties involved, is because the lock operators have a final say in every decision. As long as the consequences of the choices are either marginal or understandable, the choices will be accepted. Especially since most vessels come to the port of Amsterdam on a regular basis. The long lasting relations are often more important than a one-time benefit of a shorter waiting time. Despite general acceptance of the applied rules, an inquiry should be made as to the reason for such choices. The answer to this question is fairly simple, other performance indicators than the waiting time may also be important. These performance indicators will be discussed in the next paragraph.

### 3.3. Performance measurements for lock policies

The last step that needs to be taken before the simulation model can be built is the identification of the KPIs and the external factors which can influence the effectiveness of the lock operation policy and thereby answer the following sub-question: *Which external factors influence the effectivity of the lock management?* The KPIs need to be identified to grade the current situation of the port of Amsterdam and the alternative lock operation policies. Those factors are also important to judge whether the external factor do or do not influence the system. The external factors are important to include in the simulation, since those factors partially determine the success of a management approach. In this case, external factors are all factors which can influence the efficiency of the locks, but are not included in the policy. All of those factors can cause a certain variance in the duration of processes. The external factors can be
divided into three categories; the environmental factors, the human factors and the factor beyond environmental and human factors.

3.3.1. Key performance indicators

The first step to establish a list of KPIs is a literature search. By comparing case studies for similar KPIs it is possible to determine the most important performance indicators. After the literature search, it is wise to include the port of Amsterdam in order to determine which aspects of the locking process they find important. The last step is to use an actor analysis to include the most important demands of important stakeholders into the list of KPIs. This ensures the involvement of those stakeholders and makes sure that most effects of the system are covered by the KPIs.

The KPIs that occur the most in literature are the waiting time (Franzese et al., 2004; Ilati, Sheikholeslami, & Hassannayebi, 2014; Martagan, Eksioglu, Eksioglu, & Greenwood, 2009; Özbaş & Or, 2007; Thiers & Janssens, 1998), time is system (Cortés, Muñuzuri, Nicolás Ibáñez, & Guadix, 2007; Demirci, 2003; Ilati et al., 2014), the utilization of resources (Özbaş & Or, 2007) and infrastructure (Almaz & Altioi, 2012; Ilati et al., 2014; Kia, Shayan, & Ghotb, 2002) and the queue length before the locks (Franzese et al., 2004; Özbaş & Or, 2007). All of these KPIs are frequently used as performance indicators for lock performances and should therefore at least be considered as relevant KPIs. Other factors which can be found in literature are environmental factors such as CO2-pollution, energy consumption and noise (de Langen, Nijdam, & Horst, 2007; Kia et al., 2002; Puig, Wooldridge, & Darbra, 2014). These KPIs focus on the external effects of the lock operations. The second source for KPIs is the port of Amsterdam itself. This list is fairly short. Their main concern is the customer satisfaction which is expressed by the waiting and processing time. They use the filling rate as a KPI as well. This is a measure for the efficiency of the locks and can be calculated by dividing the surface of the vessel by the surface of the chamber for each lockage process. This will be described in more detail in paragraph 3.4.

The third source for the KPIs of the locking process is a stakeholder analysis. The first step in obtaining the KPIs from the stakeholder analysis is constructing a list of all involved stakeholders. By investigating these stakeholders, it is possible to identify the main interest in the problem and thereby their KPIs regarding lock management. This analysis can be found in Appendix C. The connection between the stakeholders and the KPIs can be found in Table 4.

The first category of stakeholders which needs should be met are those stakeholders which are powerful, but not very interested in the process. These stakeholders are not crucial, but can delay or block the process of a possible implementation of a new lock operation policy. The shippers and the ministry of Infrastructure and environment are part of this category. Their corresponding demands for the process are a fast passage through the locks and a policy that minimize the effects on the environment and a minimal impact on road traffic. The demand of the shipper will be included into the list of KPIs since their goal is equal to the goal of the port itself. The effect on the environment consists of the exchange of salt between the sea and the inland waterways, the energy consumption of the locks and the pollution caused by the vessels. Since these factors would not be included in the model since they do not directly affect the performance of the locks. The exchange of salt and the energy consumption are both directly linked to the number of lockages. The more lockages, the more salt exchange and energy consumption. Therefore these factors will be included as the number of lockages. The pollution is a factor which is not affected by the locks, since the movement of the vessels would not change, the pollution would not change. The only
thing that will change is the time at which the pollution takes place, so this indicator would not be taken into account.

The second category are the key players. These stakeholders have power to influence the process as well as interest in the process. As a results their demands should be taken very seriously. The first is the department of public works and waterways. They are the owner of the locks. Their main interest is a process that is safe and would not harm the infrastructure. Since accidents are not taken into account, because they are not relevant in a general lock operation policy, this demand would not be taken into account. The VTS coordinators and the lock operators are the ones who have to carry out the chosen policy. So, their demand will be a policy that has clear rules which are easy to apply. As mentioned, those demands are not taken into account as KPIs, but they will be included by letting them intervene in the process of improving the current policy if possible. The last stakeholder in this category is the municipality of Ijmuiden. The lock is built on their territory, therefore they have the power to intervene in the process. Their main interest is an environmentally friendly process that does not affect the wellbeing of the inhabitants of Ijmuiden. Again, this factor can be captured by the number of lockages.

The remaining stakeholders are uninterested in the process and/or lacking enough power to be relevant actors. It will be sufficient to inform those stakeholders without taking their demands into account.

Combining those three sources of performance indicators results in the following list of KPIs:

<table>
<thead>
<tr>
<th>KPI:</th>
<th>Unit:</th>
<th>Stakeholder:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average waiting time for the lock</td>
<td>[hour/vessel]</td>
<td>Lock operators, shippers</td>
</tr>
<tr>
<td>Maximum waiting time for the lock</td>
<td>[hour/vessel]</td>
<td>Lock operators, shippers</td>
</tr>
<tr>
<td>Variance in waiting time for the lock</td>
<td>[(hour/vessel)²]</td>
<td>Lock operators, shippers</td>
</tr>
<tr>
<td>Average waiting time for resources</td>
<td>[hour/vessel]</td>
<td>Lock operators, shippers</td>
</tr>
<tr>
<td>Utilization of resources</td>
<td>[percentage]</td>
<td>Port of Amsterdam, VTS-coordinators</td>
</tr>
<tr>
<td>Number of lockages</td>
<td>[lockage]</td>
<td>Port of Amsterdam, Department of waterways and public works, VTS-coordinators, municipality of Velsen, Ministry of infrastructure and environment</td>
</tr>
<tr>
<td>Average filling rate</td>
<td>[percentage]</td>
<td>Port of Amsterdam, Department of waterways and public works, VTS-coordinators</td>
</tr>
</tbody>
</table>

**Definitions of KPIs**

The average waiting time for the lock is chosen, since it gives an overview of the performance of the system and the lock operation policies in general. It is the time between the arrival of the vessel and the actual lockage time. Although the average waiting time seems to be a good indicator for the performance, the maximum waiting time and the variation in waiting time might be more important. As long as the variation in waiting times is low, the shippers can take into account the delay and reduce speed or depart
at a later point in time. For example, if the maximum waiting time is very high, but it only occurs one time a year, the lock operation policy is likely to be accepted. As soon as the variation in waiting time and the maximum waiting time rise, the certainty of the lockage time will be lower and the shippers will tend to arrive as early as possible to ensure their spot in the lock. This can cause congestion at the locks. Therefore, all three factors should be as low as possible. The same can be said about the waiting time for resources. Resources can be seen as the tugboats and the pilots. This factor is important, since it is a measure for the bottleneck of the system. If the waiting time for resources is high, the resources are the limiting factor instead of an inefficient planning of the vessels.

The utilization rate of the resources is defined as the percentage of time a resource is busy. This is taken into account since it shows whether the waiting time increases because the limits of the system are reached or because of the applied lock operation policy.

The number of lockages is a KPI that represents several factors which are important for the performance of the system, but cannot be taken into account as an individual factor. The number of lockages is important since it represents many of the environmental factors. The first factor is the energy consumption. The lower the energy consumption, the lower the costs. This factor will not be taken into account as an individual factor, since it is dependent on details which are not included, such as the current and the height of the water. The second factor that is represented by the number of lockages is the salt exchange. The salt exchange is the amount of salt water that is mixed with the fresh water at the other side of the lock. This is important since this can affect the fresh water supply of the region. Since the salt exchange is dependent on the number of lockages, the size of the vessels, the direction of the lockage and many other factors, it is only represented by the number of lockages.

The last KPI is the average filling rate of the chambers. This factor is a measure for the utilization of the chambers and the effectiveness of the planning. It can be calculated by dividing the sum of the surfaces of the vessels in a chamber by the total surface of the chamber. It cannot be said whether this KPI should be high or low, since it is dependent on the preference and the point of view of the decision makers.

*Link between KPIs and ports*

This paragraph will elaborate on the differences between ports and whether different policies can be applied in other ports as well. If the KPIs of other ports are not taken into account, it will not be possible to conclude whether other lock operation policies will have a positive effect on the performance of the locks, since the chosen policy and the KPIs are obviously linked. For example a focus on environmental factors will try to limit the exchange of salt, which will ask for a policy that limits the number of lockages. While a focus on the waiting time of vessels might increase the number of lockages since it will decrease the waiting time. Therefore, it is crucial to include the most common KPIs that are used in other ports if possible.

In the port of Amsterdam the main focus is on the processing time of the vessels. This includes the waiting time as well as the time it takes to pass through the locks. Due to restrictions set by various governments, the environmental factors such as salt exchange, play an important role as well. This should be included as a KPI. However these factors are hard to quantify and will be experienced different by different parties. Therefore these factors are taken into account as the number of lockages.

In the port of Ghent, the focus is mainly on the efficiency of the locks, so the filling rate is more important. Besides the filling rate, the waiting time and time in system are taken into account as well. Those factors
are together with the queue length a measure for the efficiency of the locks. So, it can be said that the KPIs are similar to the KPIs of the port of Amsterdam, but the priorities between the KPIs is different.

At the port of Antwerp, the main focus is on the filling rate of the locks. Although the waiting time and time in system are important, they are subordinate to the filling rate. In general it can be said that by taking the KPIs shown in Table 4 into account, it is possible to draw conclusions which are valid for a variety of ports.

3.3.2. External factors

In order to give a full overview of all factors that can influence the performance of locks, this paragraph will be used to describe the external factors which cannot be influenced by the port itself, but can influence the planning process or the actual passage of the locks.

Environmental factors

The first environmental factor which can influence the performance of a lock is the tide (Smith et al., 2009; Ting & Schonfeld, 2001). Since the average depth of a vessel becomes larger over the years, the tidal differences become more important, since large vessels cannot enter the port with low tide. This limits the flexibility for lock operation policies; a part of the vessels has 12 hours a day in which they can pass the locks instead of 24. The second factor is the hydrological and meteorological conditions (Backalic & Bukurov, 2011). These conditions can limit the accessibility of the locks or can increase the duration of a locking process. A third environmental factor is the availability of resources. Often the resources which are needed to pass through a lock are the limiting factor (Smith et al., 2009). Every locking process needs mooring men, lock operators and locks men to complete the process (Appendix C). If locks are located near a port and near open sea, some additional resources are needed, namely tugboats and pilots. It should be noted that the availability of the tugboats and pilots is often not coordinated by the port authorities, but by private parties. So, although the waiting time for resources is the responsibility of the port authorities, the availability of these resources is not their responsibility. So, this factor can be seen as an environmental factor. The forth factor that is identified is navigational complexity (Backalic & Bukurov, 2011). This occurs if the waterway is small, or if there are a lot of obstacles in the waterway. This will limit the flexibility of the vessels. It might even occur that once a vessel is heading towards the lock, there is no way back. Another example is the possibility that two vessels cannot pass each other, since the waterway is too narrow. This makes the need of a proper planning even more crucial. A temporary obstruction of the waterway or the locks is the fifth factor. This can occur due to accidents or due to construction works (Ramanathan & Schonfeld, 1994). This can seriously reduce the capacity of the locks for a certain period of time. A sixth environmental factor is the type of cargo. Legislation prevent vessels with a certain cargo to be close to other vessels (PGS projectbureau, 2015). Therefor other vessels are often excluded from the locking process if such a vessel arrives in the chamber. A last environmental factor is failure. The equipment of anyone involved can break down. This can seriously affect the performance of a lock. For example, if the planning of communication system of the lock operators or planners breaks down, it will become impossible to make an efficient planning if the information is not up to date. The same can be said about the vessels. The engine of the vessel can break down, which will result in an uncontrollable vessel. In the worst case scenario this can lead to a blockage of the locks.

Looking at these factors, some are included in the simulation model and some are not. Looking at the tidal influences, this factor is included as a delay for vessels with a large depth if the tide is low. The hydrological and meteorological conditions are nearly impossible to include as an individual factor. These conditions
represent the weather conditions. Since the goal of this study is to develop an optimal management approach for the locks, the focus should be on the most common situation and not on the exceptions. It will be assumed that the weather conditions are good enough to not cause problems for the vessels. Therefore, it will not be necessary to include it at all. Those are exceptional circumstances and therefore not interesting for a management approach. This factor mainly influences the processing time and the processing time of the lock will be validated. This factor is indirectly included into the process. The availability of resources is included in the model as they are just in the real system. The entering of a pilot and the attachment of a tugboat will not be taken into account as a time consuming process, since the scope of the study does not include the time it takes to enter or attach, but only the fact that a resource is claimed. The differentiation in time is taken into account in the variation on the time between ETA and ATA. The navigational complexity is the fifth factor that will be taken into account as a fixed external factor. This factor will be nonexistent in the model, since it will only take into account the locking process. The way towards and from the locks is assumed to be non-limiting for the model. This is possible, since the largest possible vessels that can arrive at the port of Amsterdam, can pass or overtake each other during the trip through the North-Sea channel. The chance of failure of different parts of the system will not be taken into account. The reason is that failures can never be included in the general management approach. There should be procedures for such events, but those procedures are not within the scope of this project. The same can be said about obstructions in the waterway. The type of cargo is taken into account as a set of rules which comply with the current legislation. Failure is not taken into account, since it will be an exception on the general lock operation policy and therefore not interesting to include during the development of a policy.

Human behavior
Opposite the environmental factors, human factors are hard to grasp. It is often about human behavior or the way in which procedures are applied. The first human factor which is identified is the experience of the planners, locks men and lock operators. The experience of those people can contribute to a locking process which is very efficient. They can change the schedule at the last moment in order to gain some time or they know that the shipper is experienced as well and therefore he is allowed to enter the locks, even though it is officially not allowed. The problem is that if those experienced people retire, the new people lack the experience and the process will be less efficient. This factor is hard to measure, since it is impossible to say how experienced someone is. The second factor is the way in which people interpret the planning rules. Some planners use a proactive way of planning, they interact with the shippers about the possibilities and try to come to the most optimal situation together. Other planners are more passive, they merely react on the incoming messages of the shippers. Both of those approaches fall within the boundaries of the rules, but have totally different results. The same can be said about the shippers. Their experience contributes to a more accurate prediction of the ETA and they may choose an optimistic planning as opposed to a more realistic planning. Both have some advantages; an optimistic planning can ensure a spot in an earlier locking round, while a more realistic planning establishes a good working relationship with the planners of the lock. A last human factor is related to the other external factor, namely dealing with exceptions and extreme conditions. These exceptions and extreme conditions can seriously affect the lock performance, but are impossible to include in the management approach. However, it is possible to let those problems be solved by human.

Besides the factors mentioned above, which are all intentional, there is the possibility for unintentional behavior as well. Planners can overlook a vessel, which needs to be added to the schedule moments
before it arrives or shippers can forget to send their ETA, so they need to wait until there is a slot available. Shippers can make a navigational error and might be delayed due to that error. Those factors will occur and will influence the performance of the locks in a negative way. These factors will be discussed in paragraph 4.4.

Other external factors

The factors in this paragraph concern the characteristics of the lock other than the layout which is described in Chapter 2 and the arrival characteristics of the vessels. The characteristics of the locks are specifically mentioned, since it these factors do not apply to all vessels. Subdividing those factor to other factors would not give a proper reflection of reality. So although the following factors are dependent on the ones that are already mentioned, they will be treated as separate factors. The first factor is pre-locking time. This consists of the entrance of a pilot, the attachment of a tugboat and sailing into the chamber. This pre-locking time, can cause a differentiation on the ETA. The locking time is the second external factor in this category. This includes the time it takes to order the vessels, the mooring time and the time it takes to operate the locks (closing doors, filling/emptying chamber, opening doors). This can vary if more vessels are mooring in the chamber or if the vessels are bigger. The last factor will be the post-locking time. This includes unmooring and sailing out of the chamber.

The arrival time of vessels is mostly determined by the shipping companies and can affect the performance of the locks. If vessels come in batches, it is likely that the waiting time will be higher than if the vessels come at convenient intervals. Since there are a lot of companies who want to make use of the services of the port, it is likely that the arrivals will be spread over time. The spread might be influenced by seasonal and daily cycles. These factors will be included as either processing times or a delay in the simulation model. The exact numbers that will be used can be found in Appendix A.

3.4 Comparing criteria for ports

So, the question arises how to compare different ports with each other if the effectiveness of the lock planning policies is dependent on the number of vessels. Especially since the number of vessels is only a valid criteria for comparison if the capacity of the locks is equal. So, in order to be able to compare different locks with each other, some shared characteristics should be found. A possible indicator which can be used to compare locks is the utilization rate. The utilization rate is a measure for the performance of the lock. It can be calculated by multiplying the filling rate of a chamber with its occupancy rate. The occupancy is the time where a chamber is busy with activities that add value. So the occupancy rate is the percentage of time when a lock performs value added activities. There is just one activity that falls within this category, namely the lockage process with vessels. This can be subdivided into incoming lockages with one vessel, incoming lockages with multiple vessels, outgoing lockages with one vessel and outgoing lockages with multiple vessels. The activities that do not add value are the idle time and empty lockages, which can be incoming or outgoing. The filling rate of a lock can be defined as the surface of the vessels which are in one chamber divided by the total surface of that chamber. It should be noted that it is only theoretically possible to reach a 100% utilization rate, since it is impossible to fill a chamber 100% due to the size of the vessels, the minimum distance between vessels and there will be idle time between two lockages, since incoming vessels have to wait for the exiting vessels to leave the chamber. An example of the calculation of a utilization rate can be found in Paragraph 4.1.4.

In order to extract the most important elements out of the chart of the occupancy rate, the chart is simplified. The one vessel incoming, one vessel outgoing, multiple vessels incoming and multiple vessels

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outgoing are combined into the busy state of the lock and the empty lockage incoming and outgoing are combined into empty lockages. The next step for generating a general characteristic in order to compare locks, is combining the utilization rates of the different chambers with each other. This is done by means of a weighted average. For example, if a lock consists of two chambers and chamber one handles twice the amount of vessels, the utilization rate is counted twice and the second chamber once.

3.5. Conclusion
As mentioned, the goal of this chapter was to answer two sub-questions. The first question was: What are the key indicators which determine the success of a certain lock operation policy? and the second: Which external factors influence the effectivity of a lock operation policy?. These questions are answered by discussing the case study of the port of Amsterdam and by means of a literature search.

The process which led to the KPIs started with a literature search. Since most literature that is available about lock operation policies consists of case studies, the KPIs of those case studies are collected and compared. By using the most common KPIs in combination with the KPIs of the port of Amsterdam, the port of Ghent and the port of Antwerp, the following KPIs can be seen as a good representation of the most commonly used KPIs for lock operation policies.

The waiting time is the time a vessel has to wait before it can enter the lock. The average waiting time is important to look at the system as a whole and to compare the different lock operation policies on the general performance. The maximum waiting time is important in combination with the variation in waiting times. This represents a measure for the reliability of the system. A low maximum waiting time and variation gives a more reliable waiting time. These factors mainly focus on the shippers, since they can take into account a longer waiting time, but not a waiting time that differs a lot. The utilization of resources and infrastructure is a measure for the limiting factor of the system. It is defined as the percentage of time that a resource or piece of infrastructure is busy. If the resources such as pilots and tugboats have a high utilization rate, the lock operation policy cannot be improved since this is not the limiting factor. The same can be said about the capacity of the infrastructure. The number of lockages and the average filling rate are used to measure how a lock is used. This is an extension on the utilization of the infrastructure. Not only is the time taken into account but the efficiency of the locks as well. The number of lockages is the number of lockages per year, while the average filling rate is the average surface of the vessels divided by the surface of the chambers corrected for the number of lockages per chamber.

The process that led to a list of external factors that may influence the performance of a lock has been constructed in more or less the same way as the list of KPIs. Except that the external factors are divided into three different categories. The first category is the environmental factors. These factors are mainly found by means of literature search on the case studies. Secondly, the human factors, which are found by making use of an actor analysis. This actor analysis is done by literature search and expert interviews at the three earlier mentioned ports. The third category are the external factors that do not belong to any of the previous two categories. These external factors mainly affect the performance of the lock operation policies on the short term and not the general effects of the lock operation policies. The environmental factors that are identified can be found in Table 5.
### Table 5 Environmental factors

<table>
<thead>
<tr>
<th>Environmental factor</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>Vessels with a large draft cannot enter the locks at all times</td>
</tr>
<tr>
<td>Hydrological and Meteorological conditions</td>
<td>Current and wind might cause a delay to some vessels</td>
</tr>
<tr>
<td>Availability of resources</td>
<td>Vessels have to wait for resources to become available</td>
</tr>
<tr>
<td>Navigational complexity</td>
<td>Narrow waterways can cause more stress on the planning of the locks</td>
</tr>
<tr>
<td>Temporarily obstructions</td>
<td>Has the same effect as navigational complexity, but it is temporary</td>
</tr>
<tr>
<td>Cargo type</td>
<td>Some vessels are not allowed in a chamber together</td>
</tr>
<tr>
<td>Failure of objects</td>
<td>Either a vessel is not able to pass through the locks or a chamber is out of service</td>
</tr>
</tbody>
</table>

The human factors are harder to grasp. They are often less predictable and the affects can often not be made explicit, but it is clear that they affect the performance of a lock operation policy in some way. The first factor is the experience of the planners. In general it can be said that more experienced planners influence the performance of the lock operations in a positive way while less experienced planners negatively influence the process. The same phenomena with the same effects can be identified by analyzing the shippers. These effects will in general positively influence the performance of the lock operation policies over time. Besides the experience of humans, the failures of human influence the lock performance as well. Planners can overlook a vessel, shippers can forget to sign in for a slot or human actions do not turn out as intended.

The third category of external factors are the factors that do not belong to the first or second category. This mainly concerns the pre- and post-locking time. These times do not affect the process itself, but do affect the flow of vessels if these times are long or unpredictable. Related to those factors is the arrival pattern. The arrival pattern influences the performance of the locks due to the peak loads. If there are peaks in the arrivals, it is possible that the same amount of vessels causes an increase in waiting times and at the same time an increase in idle time of the locks. Peak loads can make the use of better lock operation policies necessary and the effect larger.
4. Performance of the port of Amsterdam

In this chapter, the first step is to do the validation and verification of the model. This will be done by comparing the results and behavior of the model with the historical data and by testing whether the model is working as it should. After the comparison with the real data is made, it is time for the testing of the alternatives. Lastly, the model will be improved by including the results from human behavior into the model. The related sub-question which will be answered during this chapter is: What is the influence of new ways of managing locks on the performance of the port of Amsterdam?

4.1. Verification and validation

In this paragraph the initial situation of the port of Amsterdam will be compared with the model. Verification is checking whether the model does what it is intended to do and validation of the model can be seen as a check of the rightness of a model (Balci, 1997). In other words, verification is checking the internal consistency of the model and validation is checking the external consistency of the model. This can be seen as a more elaborate description of the relation between the provided data and the simulation model.

The underlying principle of the initial situation is first come, first served with priority. The priority rules are shown in Table 6. The choice between the different chambers is done based on the expected processing time of the different chambers. This is dependent on the direction of the lock, the state (idle/not idle) and the amount of vessels in the chamber.

Table 6 Priority rules for initial situation

<table>
<thead>
<tr>
<th>Rule</th>
<th>Implementation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessels larger than 180X23X8 meters should be handled by the northern chamber</td>
<td>Send vessels which exceed these dimensions to the northern chamber</td>
<td>These vessels fit in the middle chamber, but for the total waiting times and efficiency of the lock, these vessels are handled by the northern chamber</td>
</tr>
<tr>
<td>Tidal and gully vessels have priority if they can enter the port</td>
<td>Let vessels wait for the tidal slot, if the slot is closed, the vessels will enter a queue. If the slot is open, all vessels have to pass through the queue, therefor the tidal and gully vessels will be first</td>
<td>Tidal and gully vessels can only enter or exit the lock during high tide. Therefor they should have priority. Otherwise they have to wait more than six hours.</td>
</tr>
<tr>
<td>The maximum waiting time for other vessels is 30 minutes</td>
<td>A timer is set during the planning step if a vessel passes and the subscription for the same is closed after 30 minutes</td>
<td>This is done to increase the batch size and at the same time minimize the additional waiting time</td>
</tr>
</tbody>
</table>
The verification and validation has been done in six steps which are derived from the work of Sargent in 2005 (Sargent, 2005). The verification and validation steps that will be performed in order to check whether the model is right are the following:

1. **Animation**: Does the animation represent the real system in a good way? (Sargent, 2005).
2. **Extreme condition tests**: If extreme conditions are used as an input, do the results comply with these extreme conditions? (Sargent, 2005).
3. **Face validity**: Asking experts about the validity of the model and the usefulness in practice (Sargent, 2005).
4. **Historical data validation**: Comparing the results of the simulation with historical data (Sargent, 2005).
5. **Internal validity**: Are the results of different runs of the simulation internally consistent (Sargent, 2005)?

### 4.1.1. Animation

In order to make the model explainable, animation is included in order to make the choices visible. This will help during the validation as well, since bottlenecks can easily be traced. It is also possible to follow the general flow of vessels as well as individual vessels.

Looking at the animation, it becomes clear that large vessels only pass through the northern chamber, medium sized vessels pass through the middle and the northern chamber, while small vessels are divided over all three the chambers. This seems consistent with the real system. The same can be said about the tidal portal. If the tide is low, vessels with a large draft wait for high tide. The lightering process is working as well. Vessels which have to be lightered, moor at the lightering spot. Therefore, this test can be seen as passed.

![Animation of the model](image-url)
4.1.2. Extreme condition test

During the extreme condition test, some variables will be set to zero or to a high number. If the underlying logic is right, some parts of the system should be disabled. If the model passes this test, the underlying logic can be seen as a valid representation of the real system.

The variables which will be altered during this test are the following:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Initial value</th>
<th>Extreme value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing time southern chamber</td>
<td>0.55</td>
<td>10</td>
</tr>
<tr>
<td>Processing time middle chamber</td>
<td>0.8</td>
<td>14</td>
</tr>
<tr>
<td>Processing time northern chamber</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>Penalty southern vessels</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Max waiting time for other vessels</td>
<td>.5</td>
<td>0</td>
</tr>
<tr>
<td>Number of pilots</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Number of tugboats</td>
<td>11</td>
<td>0</td>
</tr>
</tbody>
</table>

Processing time chambers

By setting a high value to the processing time of a chamber, it can be expected that the number of vessels that pass through this chamber will be close to zero, since the choices for a certain chamber are based on the shortest processing time through the chambers. The only exception will be the northern chamber, since certain vessels are only allowed through this chamber. Therefore the amount of vessels which pass through this chamber will be equal to the initial situation as long as the total time is sufficient. The waiting time for this chamber will be higher though. Looking at the middle chamber, there will still be vessels passing through this chamber. This is because of the rule set for a limited space in the southern chamber. If a vessel arrives at the southern chamber, but does not fit into the batch, but the whole batch fits in the middle chamber, this batch is send to the middle chamber regardless of the processing time.
Table 8 Extreme conditions - Processing time chambers

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Chamber</th>
<th>Initial value of number of vessels</th>
<th>New value of number of vessels</th>
<th>Initial value of waiting time</th>
<th>New value of waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing time southern chamber</td>
<td>Southern chamber</td>
<td>7453</td>
<td>0</td>
<td>.34</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>10239</td>
<td>.41</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>11523</td>
<td>1.29</td>
<td>5.13</td>
</tr>
<tr>
<td>Processing time middle chamber</td>
<td>Southern chamber</td>
<td>7453</td>
<td>9172</td>
<td>.34</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>0</td>
<td>.41</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>12539</td>
<td>1.29</td>
<td>5.13</td>
</tr>
<tr>
<td>Processing time northern chamber</td>
<td>Southern chamber</td>
<td>7453</td>
<td>7450</td>
<td>.34</td>
<td>10.04</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>6138</td>
<td>.41</td>
<td>15.37</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>573</td>
<td>1.29</td>
<td>533.02</td>
</tr>
</tbody>
</table>

Looking at the scenario where the processing time of the southern chamber is set to zero, the model reacts as expected. The amount of vessels that pass through this lock is zero as well, since the time it takes to pass through another chamber is always shorter. Vessels which do not pass through the southern chamber anymore are divided over the two other chambers. The same can be said about the waiting time of the middle chamber; the waiting time is significantly higher. The waiting time for the northern chamber is lower, which is not as expected. It can however be explained by the filling rate and the average batch size. Both the filling rate and the average batch size are higher, which indicates that the small vessels which would pass through the southern lock are now added to current batches. The decline in waiting time is mainly caused by a low waiting time for the “southern” vessels. The average waiting time for the vessels who already passed through the northern chamber is likely to be the same.

The same can be said about the scenario where the processing time of the middle chamber is set to an extreme value. The number of vessels that pass through this lock is zero and the vessels which used to pass through this chamber are divided over the other chambers which causes a higher waiting time for the vessels in the northern chamber. The waiting time for the southern chamber does not increase, because the capacity of this chamber was apparently enough.

By setting the processing time of the northern chamber to an extreme value, the number of vessels that pass through the northern lock drops to a minimum. The reason that there are still vessels passing through is that some vessels have to pass through this chamber due to their dimensions. The waiting time for the lock is low, since it only records the waiting time of the vessels that pass through the locks. This measure puts great pressure on the middle lock, since all medium sized vessels have to pass through the middle lock.
chamber. As a result the average waiting time is very high. As expected the influence on the performance of the southern lock is minimal.

**Penalty for southern vessels**
The penalty for southern vessels is a fictive time penalty for southern vessels if they want to pass through either the middle or the northern chamber. Currently the value is set to zero, since the vessels are allowed without preference in all chambers. If the value is set to 10 hours, it is likely that most, if not all, vessels who can pass through the southern chamber, will pass through this chamber. This will increase the waiting time for the southern chamber, but it is likely to decrease the waiting time at other chambers, since there will be more space left for bigger vessels.

*Table 9 Extreme conditions - penalty for southern vessels*

<table>
<thead>
<tr>
<th>Scenario</th>
<th>chamber</th>
<th>Initial value of number of vessels</th>
<th>New value of number of vessels</th>
<th>Initial value of waiting time</th>
<th>New value of waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penalty for southern vessels</td>
<td>Southern chamber</td>
<td>7453</td>
<td>9435</td>
<td>.34</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>6286</td>
<td>.41</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>6003</td>
<td>1.29</td>
<td>0.92</td>
</tr>
</tbody>
</table>

By setting a penalty for southern vessels for the two larger chambers, the resulting behavior is as expected. The number of vessels that pass through the southern lock become larger and the waiting time higher. This causes more room for the larger chambers, which especially affects the northern chamber where the waiting time drops significantly.

**Maximum waiting time for other vessels**
The initial value of the maximum waiting time for other vessels is 0.5 hour. By setting this value to 0, the dynamics of the model change. This new value means that if a vessel arrives, it would not wait for a second vessel to enter a chamber together. The only way in which the batch size can be larger than 1, is if vessels arrive at the same time. Since this is very unlikely, the average batch size will be close to 1. It is also likely that this will have a negative influence on the waiting times.

*Table 10 Extreme conditions - maximum waiting time for other vessels*

<table>
<thead>
<tr>
<th>Scenario</th>
<th>chamber</th>
<th>Initial value of average batch sizes</th>
<th>New value of average batch size</th>
<th>Initial value of waiting time</th>
<th>New value of waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum waiting time for other vessels</td>
<td>Southern chamber</td>
<td>1.32</td>
<td>1</td>
<td>.34</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>1.40</td>
<td>1</td>
<td>.41</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>1.83</td>
<td>1</td>
<td>1.29</td>
<td>2.49</td>
</tr>
</tbody>
</table>
As can be seen in Table 10, the average batch size drops to 1, which was expected. The same can be said about the waiting times. Therefore, the extreme condition test with the variable waiting time for other vessels can be seen as a success.

**Availability of resources**
The extreme values for the number of tugboats and pilots can be seen as the same restriction with more or less the same results. Since the initial lock operation policy is first come, first serve, each vessel has to wait for the previous vessel to claim his spot. If the number of resources available is set to 0, the process will get stuck as soon as a vessel needs a tugboat or a pilot. As a result, it is likely that the number of vessels that pass through the locks will be very low. This will be the only visible effect since it would not be possible to compare the results due to the amount of vessels that will pass through the system.

Table 11 Extreme conditions availability of resources

<table>
<thead>
<tr>
<th>Scenario of resources</th>
<th>chamber</th>
<th>Initial value of number of vessels</th>
<th>New value of number of vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of tugboats</strong></td>
<td>Southern chamber</td>
<td>7453</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Number of pilots</strong></td>
<td>Southern chamber</td>
<td>7453</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
<td>6178</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Northern chamber</td>
<td>8034</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The table above shows that the number of vessels that pass through the system is reduced to a minimum. This behavior was expected, since only the vessels that arrive first and do not need resources are able to pass through the system. During some replication runs, there were zero vessels that passed through the system. This is in compliance with the expected behavior of the model, so it can be said that the model passed this test as well.

### 4.1.3. Face validity

Face validity is a way to test whether a model is both valid as well as verified. By talking to experts in the field, it is possible to extract the usefulness and the rightness of the model. The face validity test is done by three different ports; the port of Amsterdam, the port of Ghent and the port of Antwerp.

**The port of Amsterdam**
The verification and validation sessions at the port of Amsterdam are done in cooperation with Evert Koster. These sessions took place every other week during the construction of the model. By going through the model step by step it was possible to check the correctness of the model, i.e. whether it does what it was supposed to do. Every time some slight alterations had to be made. This concerned both the animation and presentation of the model and the results as well as alterations in the underlying logic. The
most important aspect of those sessions was to keep the goal in mind. Each process that was added should contribute in reaching the goal of developing a tool that could be used to test different lock operation policies. Therefore, it could be said that the model can be used to test policies with regard to the port of Amsterdam.

Next to the verification, which is described in the previous paragraph, part of these sessions was dedicated to the results of the model. By comparing the results of the model with real data together with Evert Koster, some alterations were made and some rules were added in order to make the model more realistic. In general it could be said that the model is a useful tool for testing lock operation policies in the port of Amsterdam.

The port of Ghent

The verification and validation session at the port of Ghent was organized in a different way. First of all, it only took place one time when the model was finished. Secondly, not all steps were validated one by one, but the model as a whole was observed. This was done in cooperation with Dirk Vernaeve.

The first step was looking at similarities between the port of Amsterdam and the port of Ghent. The two ports have a lot in common considering the locks. Both locks are located at the beginning of the port and both use the same lock operation policy for handling the vessels, the first come, first served principle. A difference is that the vessels at the port of Ghent can claim their own spot, while at the port of Amsterdam the lock operators are responsible for the scheduling of the vessels. Most characteristics, like multiple chambers, different sized chambers and the planning horizon, were equal as well. This was a first indication that the model could be considered right for the port of Ghent as well.

The second step was to check the usefulness of the model. As was stated before, the port of Ghent uses a tool which is used for the planning of the vessels through the locks, the GTI-tool (Ghent-Terneuzen information tool). This tool can only be used for the planning and does not show the implications which can occur as a result of the planning. In the future they want to include this aspect as well and they see this model as an opportunity to do so. The part that is most useful is the way in which the results can be shown. By comparing the current situation with alternative lock operation policies, it is possible to make their intentions clear to the involved parties. Therefore, it can be said that the tool is useful for the port of Ghent. Overall it can be concluded that this is a verified tool for the port of Ghent if the parameters are altered to fit their specific needs.

The port of Antwerp

The layout of the verification and validation session at the port of Antwerp was similar to the session at the port of Ghent. Marnix Delée was kind enough to help during this session.

During the first step, comparing the port of Antwerp with the port of Amsterdam and the port of Ghent, it became clear that there are some major distinctions between the port of Antwerp at one side and the port of Amsterdam and Ghent on the other side. First of all, the locks are not located at the beginning of the port, but are spread over different parts of the port. As a result, the underlying decision logic which is used to guide vessels through the locks is different. Their focus is on the division of the vessels over the different locks instead of the division over different chambers. Therefore, the tidal influence is larger and the influence of the chamber choice is smaller. Their general lock operation policy is first come, first served as well, but with the focus on safe and fast. Therefore, it can be concluded that this model is not the right model for the port of Antwerp. As a consequence the model cannot be considered useful.
Conclusion
Considering the three ports combined, the model has definitely added value to the current way of analyzing and improving the lock operation policies, but it has its limits. The layout of the port is crucial for the validity and the usefulness of the model. If the locks are located at one central point, which gives access to the whole port the model can be used to analyze the lock operation policies. If the layout is different, it should be considered whether another model might be of more use.

4.1.4. Historical data validation
The historical data validation is a useful analysis tool. By performing this analysis it can be determined whether the results of the study are a valid representation of the real system. The data of 2014 has been made available by the port of Amsterdam. A full analysis of the data can be found in Appendix A. The most important findings are shown in this paragraph. After showing the most important findings, the results of the initial model are shown. Data retrieved from both analyses will be compared in order to validate the model.

Historical data of the port of Amsterdam
The amount of vessels that is logged in the historical data is 21466 vessels. First of all, the values of the transfer time per chamber per batch size is inconsistent with the general opinion (Figure 10). This value represents the difference between the time of sailing out and the start of the lockage. The transfer time per vessel for batch sizes higher than 1 should be at least as high as the transfer time for batch size 1, since the minimal time of a lockage, is the time it take to fill a chamber. Each extra vessel will lead to additional time, so an increase in the transfer time per vessel. This value is important for both the validation of the model as well as the acceptance of the results. As a solution for the lack of consistency within the data, the average value of the lockage time, without making a distinction between the batch sizes, is used. This value is verified by the experts of the port of Amsterdam and can therefore be considered as right. In Table 12 the average transfer times are shown. As can be seen in Figure 10, the general trend for each chamber is downwards if the batch size increases. With an exception for the largest chamber and batch size 7. Since this only occurred 1 time in 2014, it can be considered as an outlier. The general trend can be explained in two ways. First of all, the processing time might be divided by the number of vessels. This would explain a downward trend. Secondly, the processing time might be unreliable due to human errors. Since the processing time is recorded manually by different operators, the time of recording might be different for each operator. It is possible that the time of sailing in is recorded for all vessels at the moment that the last vessel enters the chamber and the exiting time is recorded when the first vessel leaves. For this reason, the chosen processing time for the chambers is based on the available data, but the expert opinions from the port of Amsterdam were considered more valuable.
The next KPI that is analyzed for the data is the filling rate of the chambers. This value is an important measure for the efficiency of a chamber. The higher this value is, the more efficient the process. The shape of the figure is as expected, since the planning rules for the southern chamber are less strict, it is likely that the filling rate will be higher. The planning rules for the middle chamber are stricter and the rules for the northern chamber even more so. The value is less than 0.5, meaning that, on average, the chambers are not even half full. The exact numbers can be found in Table 12.
Table 12 Characteristics historical data

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Average transfer time (hours)</th>
<th>95% confidence interval transfer time</th>
<th>Average filling rate</th>
<th>Number of lockages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>0.62</td>
<td>[0.60-0.64]</td>
<td>0.47</td>
<td>4171</td>
</tr>
<tr>
<td>Middle chamber</td>
<td>0.92</td>
<td>[0.90-0.93]</td>
<td>0.33</td>
<td>7113</td>
</tr>
<tr>
<td>Northern chamber</td>
<td>1.14</td>
<td>[1.12-1.16]</td>
<td>0.28</td>
<td>5692</td>
</tr>
</tbody>
</table>

Initial model

In this paragraph the results of the initial model will be shown. The amount of vessels handled on average is 21662. This is an average, since the number of replications is 10 in order to reduce the effect of outliers. Again, the results that will be shown are the KPIs. The figure of the transfer times of the different chamber-batch size combinations (Figure 12) is more according to the general opinion than the historical data. The processing time increases as the chamber gets bigger and the batch size gets larger. The details can be found in Table 14. According to the experts of the port of Amsterdam, these data can be seen as plausible. The only exceptions on the general trend are the batch size of 6 in the northern chamber (red). This can be explained by the number of times this occurred. 6 vessels in the northern chamber occurs on average 1.2 times per year. Therefore, the average transfer time can be an outlier. Table 13 shows the model characteristics of the initial model. These characteristics will also be used for the experimentation runs. The number of replications is set to 10 in order to limit the effects of randomness, so it provides meaningful averages. The warm-up period is set to two days, since the average waiting time at the beginning of a simulation run never exceeds two days. This value is necessary since the system is never empty at the beginning of a run. It cannot be less than two days since the vessels have to sign in well before they arrive at the locks. The run time of 12 months is chosen to include the seasonal effect if there are any.

Table 13 model characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of replications</td>
<td>10</td>
</tr>
<tr>
<td>Warm-up period</td>
<td>2 days</td>
</tr>
<tr>
<td>Run time</td>
<td>12 months</td>
</tr>
</tbody>
</table>
The filling rate of the different chambers (Table 14) fits the same distribution as the filling rate in the data of 2014, thus it follows the same logic. So given the rules which are applied in the model (Chapter 2), there will be room for improvement. Although it should be noted that a filling rate of 1 would never be possible.

Table 14 Initial model - Characteristics

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Direction</th>
<th>filling rate</th>
<th>Batch Size</th>
<th>Lockage Time (Hour)</th>
<th>Batches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>East going</td>
<td>0.47</td>
<td>1.17</td>
<td>0.6</td>
<td>4471</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.47</td>
<td>1.19</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Middle chamber</td>
<td>East going</td>
<td>0.32</td>
<td>1.21</td>
<td>0.86</td>
<td>3382</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.34</td>
<td>1.22</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Northern chamber</td>
<td>East going</td>
<td>0.28</td>
<td>1.54</td>
<td>1.1</td>
<td>2779</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.29</td>
<td>1.52</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>average</td>
<td>0.36</td>
<td>1.31</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weighted average</td>
<td>0.38</td>
<td>1.28</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>
As was discussed earlier, a possible way of comparing locks of different ports with each other is to compare the utilization rate the locks. This is the occupancy rate of the locks multiplied by the average filling rate. The occupancy rate is the percentage of the year a chamber is busy. In order to combine the three chambers, the average occupancy rate of the three chambers is taken. The filling rate of the three locks combined is calculated by taking the average filling rate per lockage. As can be seen in Figure 13, the average occupancy rate is 39%. The average filling rate is 38% (Table 14). Therefore the utilization rate is 15%.

Comparison between the data and the model
During the comparison it is checked whether the data provided by the port of Amsterdam is consistent with the results from the model. This will be done based on some indicators. An indicator passed this test if the data from the real system has approximately the same average. The indicators that will be used during this analysis are:

- Transfer time of the chamber. This will be compared with the lockage time of the vessels in 2014
- Division of vessels over the chambers. This will be done based on the number of vessels as well as the share of each vessel type.

### Table 15 Historical data validation

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Average in 2014 (10 months)</th>
<th>95% confidence interval</th>
<th>Average in simulation</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer time southern chamber</td>
<td>0.62</td>
<td>[0.60-0.64]</td>
<td>0.62</td>
<td>[0.62-0.62]</td>
</tr>
<tr>
<td>Transfer time middle chamber</td>
<td>0.92</td>
<td>[0.90-0.93]</td>
<td>0.88</td>
<td>[0.87-0.88]</td>
</tr>
<tr>
<td>Transfer time northern chamber</td>
<td>1.14</td>
<td>[1.12-1.16]</td>
<td>1.13</td>
<td>[1.13-1.13]</td>
</tr>
<tr>
<td>Number of vessels southern chamber</td>
<td>5989</td>
<td>-</td>
<td>5120</td>
<td>-</td>
</tr>
<tr>
<td>Number of vessels middle chamber</td>
<td>8371</td>
<td>-</td>
<td>7712</td>
<td>-</td>
</tr>
<tr>
<td>Number of vessels northern chamber</td>
<td>7375</td>
<td>-</td>
<td>9527</td>
<td>-</td>
</tr>
<tr>
<td>share of vessels in southern chamber</td>
<td>(1/0/0)</td>
<td>-</td>
<td>(1/0/0)</td>
<td>-</td>
</tr>
<tr>
<td>share of vessels in southern/middle/northern</td>
<td>(0.87/0.13/0)</td>
<td>-</td>
<td>(0.58/0.42/0)</td>
<td>-</td>
</tr>
<tr>
<td>Share of vessels middle chamber</td>
<td>(0.24/0.33/0.43)</td>
<td>-</td>
<td>(0.37/0.29/0.34)</td>
<td>-</td>
</tr>
</tbody>
</table>
As has been stated, if the averages are approximately the same, it can be said that the results of the model are similar to the historical data and therefore, that the model is valid. It is also possible that the averages of the results are different from the historical data. If this is the case, the parameters or the model logic should be altered or a valid explanation has to be given in order to make it plausible that the model can be used for testing lock operation policies. The averages of the two datasets are compared with each other based on the 95% confidence interval. If the simulated data falls within the 95% confidence interval of the historical data, it can be said with 95% certainty that the results of the model are valid. During the historical data validation the data of the year 2014 is compared with the results of the model. During the simulation runs, the arrival pattern of the year 2014 is used, including the time the southern chamber was out of business. The southern chamber was out of service between the 15th of April and the 15th of June. Therefore, vessels who could pass through the southern chamber are divided over the middle and northern chamber.

Looking at Table 15, it can be concluded that the transfer times of the locks fall within the 95% confidence interval. Looking at the division of vessels over the chambers, it can be concluded that the division over the chambers is different than the division in the historical data. This can be explained by the underlying logic of the model. During the real time planning, the decisions are based on the same rules as in the simulation model, but there are some additional rules which cannot be implemented into the simulation model. These additional rules can be the cause of the difference in the division pattern. These rules have to do with the weather conditions, the experience of the shippers, the experience of the pilots and the experience of the tugboats. Since it is not possible to make tangible rules for such elements, these elements are not taken into account and the difference in division over the chambers is taken for granted. The difference in division over the chambers, caused by the previous stated conditions, is discussed at the port of Amsterdam and is taken for granted. Nevertheless, it should be considered when conclusions are drawn. In general it can be said that the model passed the historical data validation test.

4.1.5. Internal validity
A model is internally valid if different simulation runs show the same results. This can be tested by statistical tests. This will be done with a two-way ANOVA test. By using this test, it can be verified whether two or more groups can be from the same population. In this case, it can be used to test whether different simulation runs are likely give the same results. The results of this test are shown below. The first step is to check whether the variances are equal. If this is the case, an ANOVA test is sufficient, otherwise more tests are necessary.
Looking at Table 16, it can be concluded that the transfer time of the vessels and the processing times of all three chambers have homogeneous variance. Therefore, the ANOVA test can be performed for these four variables. The results of this analysis can be found in Table 17. It can be concluded that the transfer time of the lock and processing times of the chambers are equal for the different runs of the base case.

### Table 16 Test of homogeneity of variances

<table>
<thead>
<tr>
<th></th>
<th>Levene Statistic</th>
<th>df1</th>
<th>df2</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer time</td>
<td>1,127</td>
<td>9</td>
<td>216934</td>
<td>.247</td>
</tr>
<tr>
<td>vessel Processing</td>
<td>0,678</td>
<td>9</td>
<td>216934</td>
<td>.729</td>
</tr>
<tr>
<td>NC</td>
<td>0,250</td>
<td>9</td>
<td>216934</td>
<td>.987</td>
</tr>
<tr>
<td>SC</td>
<td>0,950</td>
<td>9</td>
<td>216934</td>
<td>.480</td>
</tr>
</tbody>
</table>

### Table 17 ANOVA test

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer time of the vessels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>0.740</td>
<td>9</td>
<td>0.082</td>
<td>1.424</td>
<td>.171</td>
</tr>
<tr>
<td>Processing Time NC</td>
<td>3.607</td>
<td>9</td>
<td>0.401</td>
<td>0.645</td>
<td>.760</td>
</tr>
<tr>
<td>Processing Time SC</td>
<td>1.759</td>
<td>9</td>
<td>0.195</td>
<td>0.686</td>
<td>.722</td>
</tr>
<tr>
<td>Processing Time MC</td>
<td>4.164</td>
<td>9</td>
<td>0.463</td>
<td>0.925</td>
<td>.502</td>
</tr>
</tbody>
</table>

### 4.2. Experimentation with the initial situation

#### Increasing the arrivals

Now that the model of the locks near Ijmuiden can be seen as a valid representation of the real situation, the next step can be initiated. During this step, the number of arrivals will be increased with 10% at the time. By comparing the results of the scenarios with the gradual increase, it is possible to define the limits of this lock operation policy. It should also be taken into account that there is a limit on the available resources as well. Therefore, the waiting time will be displayed as the total time as well as the two individual waiting times. This visualization will have the utilization rate as an indicator and the waiting time (three times) and the number of lockages as results. Looking at Figure 14, the utilization rate is an indicator for the amount of arrivals. In Table 18 the relation between the utilization rate and the number of arrivals is shown. As mentioned, this will be used as an indicator of the number of vessels since it is possible to compare the utilization rate of different locks with each other.
The utilization rate which can be found in Table 18, corresponds with the x-axes of Figure 14. This figure shows that using the current lock operation policy can easily handle 30% more arrivals. This corresponds with an inter-arrival time of 0.56 hour. Since the processing time of the southern chamber is 0.5 hour, it is expected that if the inter-arrival time comes near to 0.5, the waiting times for the locks would increase. If it would be possible to execute every lock process during a day, it would still cause a delay if not every chamber contains at least two vessels. However, another restriction that can be deduced from this figure might be more crucial. This is the restriction on resources. Looking at the total waiting time, it can be concluded that the resources are the main cause of the delay. During the two scenarios which exceed the threshold of +30% arrivals, the average waiting time for the locks and for resources start to rise exponentially. Especially the waiting time for resources starts to rise. This increases so badly, that the number of lockages drops to a minimum and the system collapses. Looking at the variance, it follows the same pattern as the waiting time. In the initial situation, the variance in waiting time for the locks was 1.37 hours, this increased to 42.21 if the arrivals increased by 50%. The variance in waiting time for resources was initially 0, since the waiting time was zero. This increased to almost 2500 by an increase of 50%. So it is clear that not only the average waiting time, but also the variance in waiting time becomes problematic if the number of arrivals increases with 20% or more. The utilization rate starts rising if the number of arrivals increases. This trend stops if the number of arrivals increases with 40%. The reason is that the number of resources start to be the limiting factor. As a results the vessels have to wait for the resources which causes inactivity of the chambers.

Therefore, the next step is to find the limit of the lock operation policy of first come, first served with priority. This can be done by increasing the amount of arrivals with an infinite number of resources.
As has been stated, the number of pilots and the number of tugboats is set to infinity to determine the boundaries of the first come, first served principle. The scenarios which will be used to determine the limit of the policy are an increase in arrivals compared to 2014 with 30 to 70%.

### Table 19 Arrival time infinite number of resources

<table>
<thead>
<tr>
<th>Utilization rate</th>
<th>Arrivals</th>
<th>Inter-arrival time (for each side) (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>Arrivals of 2014 +30%</td>
<td>0.56</td>
</tr>
<tr>
<td>0.21</td>
<td>Arrivals of 2014 +40%</td>
<td>0.48</td>
</tr>
<tr>
<td>0.23</td>
<td>Arrivals of 2014 +50%</td>
<td>0.40</td>
</tr>
<tr>
<td>0.25</td>
<td>Arrivals of 2014 +60%</td>
<td>0.32</td>
</tr>
<tr>
<td>0.27</td>
<td>Arrivals of 2014 +70%</td>
<td>0.24</td>
</tr>
<tr>
<td>0.28</td>
<td>Arrivals of 2014 +80%</td>
<td>0.16</td>
</tr>
<tr>
<td>0.28</td>
<td>Arrivals of 2014 +90%</td>
<td>0.08</td>
</tr>
</tbody>
</table>

As can be seen in Figure 15, the waiting time for the lock and the waiting time for resources are quite stable until a utilization rate of 0.28. Meaning that without the restriction of the resources, it is possible to increase the number of arrivals with 70%.

### 4.3. Testing the lock operation policies

In the previous paragraph, the results of the current situation, first come, first served with priority, are shown. Now that it is clear what the limits of the current lock operation policy are, it is time to compare these limits with the limits of other lock operation policies. The first policy will be shortest processing time first and later on the resource-based selection will be tested.

#### 4.3.1. Shortest processing time first

In order to implement this lock operation policy, new logic needs to be added to the model. This logic has to determine the shortest processing time of each vessel. Since the processing time of the vessels is mainly determined by the chosen lock, the shortest processing time is always at the smallest lock. Therefore, each vessel should be sent to the smallest chamber that is available. If this chamber is not available, the next biggest chamber should be chosen and so on. If all chambers are occupied, the vessel should wait for
the next locking process. The biggest difference with the first come, first served principle is the order of the vessels. This planning method allows vessels to pass each other, if the first vessel that arrives does not fit in the chamber, but the second does, it is allowed to overtake the first vessel.

The first step is an elaborate analysis of the base case with the shortest processing time first principle in place.

Table 20 SPT characteristics

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Direction</th>
<th>filling rate</th>
<th>Batch Size</th>
<th>Lockage Time (Hour)</th>
<th>Batches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>East going</td>
<td>0.46</td>
<td>1.18</td>
<td>0.62</td>
<td>4857</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.47</td>
<td>1.17</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Middle chamber</td>
<td>East going</td>
<td>0.32</td>
<td>1.22</td>
<td>0.87</td>
<td>3670</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.34</td>
<td>1.22</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Northern chamber</td>
<td>East going</td>
<td>0.28</td>
<td>1.52</td>
<td>1.12</td>
<td>3013</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.28</td>
<td>1.51</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>average</td>
<td>0.36</td>
<td>1.30</td>
<td>0.87</td>
<td>3847</td>
</tr>
<tr>
<td></td>
<td>Weighted average</td>
<td>0.37</td>
<td>1.28</td>
<td>0.83</td>
<td></td>
</tr>
</tbody>
</table>

Comparing the shortest processing time characteristics (Table 20) with the characteristics of the first come, first served principle (Table 14), it can be concluded that the differences are very small between the base cases. As has been described, the shortest processing time principle becomes beneficial if the number of arrivals increases. Therefore, this will be the next step in the process.

Increasing the arrivals

Figure 16 SPT - Results for extra arrivals (average and max)

Figure 16 shows that an increase in arrivals means an increase in the waiting time for a vessel. The difference with the first come, first served principle are the limits of the principle and the value of the waiting time for locks. By using the SPT principle, it is possible to handle up to 30% more vessels, while the FCFS principle can handle up to 20% more vessels. It should be kept in mind that the waiting times of
the vessels increases till almost 4 hours on average, but at least it is possible to handle all the vessels that arrive. When applying the first come, first served principle the waiting times can increase to almost 6 hours when less vessels are handled by the locks. At the beginning, the waiting time is mainly waiting time for the lock, while at the end, the waiting time consists for a large part of waiting time for resources. Therefore, the next step is to increase the number of available resources.

**SPT with extra resources**

The number of resources is increased with 100%, meaning that there are 22 tugboats and 100 pilots available. The results will be shown in the same way as the base case with extra arrivals.

![Figure 17 SPT - Results for extra arrivals and resources (average and maximum)](image)

The results for the SPT principle with and without extra resources are comparable. The only difference is the value of the average waiting time for the resources. In the scenarios with extra resources, this value is higher compared to the initial situation if the number of arrivals increases. The reason that this value is higher and not lower as expected with more resources, is the number of vessels that pass through the lock. Since not all vessels pass through the lock in both situations, the average waiting time is determined by the vessels that went through the lock. More vessels pass through the lock if the number of resources is higher, these extra vessels are the vessels that could not be handled in the initial situation and therefore their waiting was already present in the initial situation, but it was not visible in the results.

### 4.3.2. Resource-based selection

The resource based selection can be implemented by adding new logic as well. This logic consists of an assign step which assigns a new fictive arrival time and a queue which sorts the copies of the vessels in the queue on their fictive arrival time. Since the vessels who need one or more resources get a ‘bonus’ time, they will be put in front of the line if the bonus is sufficient. The vessels can pass the hold if their copy is in front of the line at the hold. This will result in a resource-based selection of the vessels. The benefit of this method of planning is the more efficient use of resources.

After this rule is added to the model, the same steps are taken to analyze the rule. So the first step is to run the base case model, the model with the same amount of arrivals as the real system in 2014. As expected, the same patterns occur as they did in the base case run of the first come, first served policy.
### Table 21 RBS – Characteristics

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Direction</th>
<th>filling rate</th>
<th>Batch Size</th>
<th>Lockage Time (Hour)</th>
<th>Batches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>East going</td>
<td>0.47</td>
<td>1.18</td>
<td>0.60</td>
<td>4861</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.47</td>
<td>1.17</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Middle chamber</td>
<td>East going</td>
<td>0.32</td>
<td>1.54</td>
<td>0.86</td>
<td>3670</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.34</td>
<td>1.55</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Northern chamber</td>
<td>East going</td>
<td>0.28</td>
<td>1.49</td>
<td>1.10</td>
<td>3030</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.29</td>
<td>1.55</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>average</td>
<td>0.36</td>
<td>1.41</td>
<td>0.85</td>
<td>3854</td>
</tr>
<tr>
<td></td>
<td>Weighted average</td>
<td>0.38</td>
<td>1.38</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>

Comparing the occupancy of the FCFS base case with the RBS base case, it can be concluded that the percentage of empty lockages is equal. The percentage of idle time is lower in the SPT base case. This can be explained in two ways. First of all, there is a shift in lockage time and number of lockages. Secondly, the division over the chambers is different, due to the new lock operation policy.

Looking at Figure 19, the same trends can be identified as during the increase in arrivals with the first come, first served policy. The next step is to compare the maximum values of the waiting time, these values might be equally important for the attractiveness of a port. The same conclusion can be drawn about the maximum values in comparison with the average values, if the two graphs in Figure 19 are compared. The utilization rates of the different policies in combination with the amount of arrivals are comparable as well.
Increasing the arrivals

Since the main bottleneck is the number of available resources, the next step is to increase the number of resources and perform the same analysis again. This will lead to a better comparison of the policies instead of the limitation of the current situation in the port of Amsterdam. The amount of tugboats and pilots will be set to 22 and 100, which is twice as much as the current situation. It is expected to be sufficient, since the waiting times for resources are acceptable until an increase in arrivals of 30%. Looking at the variance in waiting time, the same pattern can be discovered. It differs between 1.37 hours in the initial situation and 15.84 when the arrivals increase with 50% considering the waiting time for the lock and 0 and 666.18 hours for the waiting time for resources.

RBS with extra resources

The difference between the initial RBS and the RBS with extra resources is not as large as expected. The reason is likely to be the capacity of the chambers. Since the larger vessels are put first in line, the possibility to combine vessels in one chamber is limited. Even though the number of lockages is larger if more resources are available, the total waiting time increases as well. Therefore, it can be concluded that the focus on resources by means of the resource based selection, is not beneficial for the performance of the lock, since the time that is gained by the extra resources is diminished by the lack of capacity of the locks itself. This is supported by the comparison of the initial situation, and the scenarios with a limited growth, of the first come, first served principle and the resource based selection principle. Those scenarios
give the same results, so the addition of the RBS principle does not result in better results than the FCFS principle. There is only an improvement if the limits of the lock’s capacity are almost reached.

4.4. Human behavior

This paragraph will start with an explanation why human behavior is important and how this is applied to the case of Amsterdam. The next step is to include the results of human behavior in simulations and see what the model can contribute to the current policies and what the influence of human factors on the policies is. Furthermore, the effects of the applied rules will be compared with the three tested theories in order to see whether the lock operation policies are effective at all.

After consulting with the planners of the port of Amsterdam, some rules came up which were not in the initial model. Those rules mostly concerned dealing with the behavior of other people. The first rules that came up concerned locking vessels together. If two large vessels can be handled together, it is often chosen not to do so. This is due to the fact that it is often not known what the experience of the involved parties is. If the crew of the arriving vessel, the pilot or the tugboats are not very experienced, it can happen that some errors are made, which cause huge delays. If this occurs it is faster to do two lockages instead of waiting for the second vessel to correct their mistake. This is partially included due to the rule about the maximum size for a vessel that may pass through the middle chamber. This is due to the ease of entrance. A second rule that came up has to do with dealing with external conditions. If the weather conditions are bad, it is common to use the tugboats for a longer period of time than normal in order to reduce the risks for the vessels. A next aspect that is sometimes applied, has to do with the resources. If the shipper, in consultation with the pilot, is not confident enough that he can pass through the locks, he can ask for the help of an additional tugboat. Lastly, there might be strategic behavior by one of the parties. Vessels might claim a spot that they cannot make for example.

All these rules are exceptions on the first come, first served concept that is used in the port of Amsterdam. These extra measures will influence the performance of the lock, but the question is to what extent, since all those rules are used in order to improve the process.

4.4.1. Locking two large vessels together is prohibited

In order to apply this rule, large vessels get additional space in the chambers. This results in less room for other large vessels to enter the chamber. Each vessel that can only pass through the northern chamber is assigned 20 meter to the width of the vessel and 40 meters to the length. This will simulate the precautions that are taken to deal with inexperienced pilots, tugboats or crew. The results are shown in Table 22. Comparing these results with the results of the initial situation of the port of Amsterdam (Table 14), it can be concluded that the filling rate, batch size and lockage time can be considered equal, while the number of lockages and the division over the chambers is different. The total number of lockages in the initial situation was 10632. If locking two large vessels together is prohibited, the total number of lockages increases to 11606. Meaning that it is in the current situation possible to take into account the experience of the involved parties without decreasing the performance of the lock. This even reduces the waiting time for all vessels slightly from 0.78 hours on average to 0.76 hours on average.
### Table 22 Results of extra room for large vessels

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Direction</th>
<th>filling rate</th>
<th>Batch Size</th>
<th>Lockage Time (Hour)</th>
<th>Lockages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>East going</td>
<td>0.47</td>
<td>1.18</td>
<td>0.60</td>
<td>4892</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.47</td>
<td>1.19</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Middle chamber</td>
<td>East going</td>
<td>0.34</td>
<td>1.22</td>
<td>0.86</td>
<td>3698</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.32</td>
<td>1.22</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Northern chamber</td>
<td>East going</td>
<td>0.28</td>
<td>1.51</td>
<td>1.10</td>
<td>3017</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.28</td>
<td>1.53</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>average</td>
<td>0.36</td>
<td>1.31</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weighted average</td>
<td>0.38</td>
<td>1.28</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4.2. Extra pressure on resources

Both the extreme weather condition as well as the confidence of the crew, pilots and tugboats cause extra pressure on the use of the resources. This might result in a shortage of resources and therefore more waiting time for the resources. This will be simulated by adding a chance of 10% for the need of extra tugboats to vessels that need a tugboat. The results are shown in Table 23. By comparing the results of this scenario with the base case, the same conclusions can be drawn as with the extra room for large vessels; most KPIs remain more or less equal, while the number of lockages increases. On average the waiting time remains the same (0.78) and the average waiting time for resources does not change that much either. It remains almost 0. Due to the fact that some vessels have to wait for resources, the distribution over the chambers changes. Therefore, the extra pressure on resources does change the behavior of the system, but does not influence the performance. However, it will influence the performance if the number of arriving vessels increases, since more lockages are necessary for the same amount of vessels.

### Table 23 Results extra pressure on resources

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Direction</th>
<th>filling rate</th>
<th>Batch Size</th>
<th>Lockage Time (Hour)</th>
<th>Lockages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>East going</td>
<td>0.47</td>
<td>1.18</td>
<td>0.60</td>
<td>4879</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.47</td>
<td>1.18</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Middle chamber</td>
<td>East going</td>
<td>0.34</td>
<td>1.22</td>
<td>0.86</td>
<td>3685</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.32</td>
<td>1.22</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Northern chamber</td>
<td>East going</td>
<td>0.28</td>
<td>1.52</td>
<td>1.10</td>
<td>3018</td>
</tr>
<tr>
<td></td>
<td>West going</td>
<td>0.28</td>
<td>1.54</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>average</td>
<td>0.36</td>
<td>1.31</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weighted average</td>
<td>0.38</td>
<td>1.28</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>
4.4.3. Conclusion

It is possible to take into account the experience of the involved parties out of precaution with the current number of arrivals. If the number of arrivals start to increase it might be problematic, since it requires more lockages than without this rule. It is likely that the average waiting time for vessels will increase more when applying this rule than without this rule. Therefore, it would be wise to find indicators which can identify the involved parties with less experience. By applying this rule to the vessels that need the extra space, the number of extra lockages will not increase that much and the overall performance of the system will be increased. The same can be concluded about the extra pressure on resources. The major problem is that the need for extra resources is not something that can be controlled by the operators or port authority. Therefore, this factor should be taken into account and the effects should be accepted.

Although it is known at the port of Amsterdam that these aspects affect the performance of the locks, it was not known how severe these effects were. The main cause is that it was never investigated what the performance of the locks was without these aspects. By making the effects tangible, it is possible to link these aspects to the previous discussed lock operation policies, as can be read in the next paragraph.

4.5. Comparison of the management styles and the human factors

In this paragraph, the rules will be matched to the alternative lock operation policies, if possible. It should be noted that all the rules given above will influence the process in a negative way. To what extent it will influence the choice between the lock operation policies will be discussed below.

First of all, it is hard for the vessels to act strategically, since at any given point in time, the planners can ask for the GPS location of a vessel. Therefore, they can calculate the estimated time of arrival themselves. Therefore, this will not be taken into consideration.

Given the rules above, it can be concluded that the influence of a certain factor can contribute to the choice for a certain policy. If the shippers fail, the utilization of the lock becomes larger due to less vessels per lockage, but more lockages. This effect can be seen in Paragraph 4.4.1. As a result the waiting time for the lock increases if the number of arriving vessels increases. If this factor is dominant in the system, the shortest processing time first principle might be more appropriate, since this increases the use of the lock. The opposite can be said about the increase of the use of resources due to weather conditions or confidence of the shippers. If the availability of resources becomes a problem due to the increase in either the duration of a claim or the number of claimed resources, the resource based selection might become more appropriate, since this method deals with a shortage of resources.

4.6. Conclusion and recommendations for the port of Amsterdam

This paragraph will be used to compare the different lock operation policies and relate them to the solutions proposed by the involved parties. This will be done by comparing the different lock operation policies with each other. Finally, some recommendations will be given.

4.6.1. Conclusion

Currently, the first come, first served principle is applied in the port of Amsterdam. This principle ensures, considering the arrival pattern of the year 2014, decent performances. On average the waiting time is 0.78 hours with a variance of 1.37 hours. By means of almost 11,000 lockages, 21,694 vessels were guided through the locks. Without any adaptations to the principle it is possible to guide almost 20% more vessels through the locks without much more delays. After this growth is reached, the waiting times start to
increase. If the number of arriving vessels is 20% more than the situation of 2014, the average waiting time becomes 1.66 hours and the variance 6.43 hours. Larger increases in the number of arrivals will increase the waiting times at an even faster pace.

The resource based selection principle does not contribute to a better lock operation policy on the short term, since this lock operation policies starts to be effective if the number of arrivals is large and the number of resources limited. So, it can be said that the availability of resources can influence the choice of the lock operation policy. Even then, it will only increase the number of lockages and does not decrease the waiting time for vessels. It merely decreases the waiting time for resources, while the waiting times for the locks keeps increasing. Therefore, it would not be advisable to use this lock operation policy, since it requires adaption to the current way of working, while the effects are limited and can even be solved by increasing the number of resources, as can be seen with the scenarios with unlimited resources.

The same conclusion can be drawn about the SPT policy. If the number of vessels that arrive at the lock is limited, the possibilities to change this order are limited as well. Therefore, the SPT policy will only be effective if the number of arrivals is larger. This was expected, since the SPT policy changes the order of the vessels and ensures higher filling rates. If the number of vessels is low, the vessels have to wait, on the other hand if there is a queue due to a high amount of arrivals, this lock operation policy ensures a more efficient way of handling vessels. The amount of vessels per lockage is higher and therefore the queue and the waiting time are shorter.

So, in general it could be said that it would be wise to keep using the first come, first served principle as long as the number of arrivals keeps more or less the same as it is now. This will ensure the lowest waiting times and the lowest variance in waiting times. Moreover, the number of lockages is lower than with the other two lock operation policies, which ensures a lower energy consumption and a lower salt water exchange. If the number of vessels that arrive at the locks increases, the choice becomes more difficult. Other factors start to play a role, for example, the ease of implementation and the effects of the alternatives. Both the shortest processing time as well as the resource based selection lead to improved results. The RBS principle lead to more vessels being handled in a more efficient way, while the SPT principle results in lower waiting times. It should be weighed which factors are more important; the costs and the environment or the satisfaction of the clients. Even if the choice is made, it is still hard to implement a new lock operation policy. Each involved party should be convinced of the benefits of a new policy or compensated otherwise. The way in which this should be done is describe in the next paragraph (paragraph 4.7).
The earlier mentioned utilization rate cannot be considered as a good indicator for the performance of a lock for two reasons. First of all, the difference in utilization rate is not very high and sometimes even equal for a different amount of arriving vessels. Therefore, it is hard to make a distinction between two scenarios based on the utilization rate. Secondly, the utilization rate is dependent on factors that are not influenced by different lock operation policies. Among these factors are the availability of the tugboats and pilots. If these factors are considered as the limiting factor for the performance of the locks, the utilization rate of the locks will be lower, while the lock operation policy might increase the utilization rate at the same time.

### 4.6.2. Recommendations

This paragraph is dedicated to the recommendations for the port of Amsterdam. The first recommendation has to do with the data that was provided for this study. The processing time of the individual vessels was not reliable enough. If the number of vessels in a chamber increased, the data showed that the processing time per vessel decreased. This should be impossible, since the processing time is the difference in time between sailing in and sailing out of the chamber. Therefore, it would be recommended to improve this process by either setting rules for the operators or by making this process automatic. More reliable input data will lead to more reliable output data. Secondly, the amount of intangible rules is fairly high. Therefore, it would be wise to document these rules. First of all, for improving the results and reliability of this study and secondly to make planners and operators aware of their choices. This might lead to improvements in practice as well.

### 4.7. Implementation of new policies

This paragraph will describe the relation between the policies and the human factors. It will be something like: “by taking this and this into account and implementing it in such a way, the policy has the highest chance of success”. The first step of implementation is to check whether the current lock operation policy should be replaced with another one. This can be done by analyzing the waiting times, filling rate, utilization and number of lockages. If the results of this analysis fall within the boundaries of what is acceptable, there is no need for replacement. If this is not the case, it should be checked whether the characteristics of the lock are in compliance with the boundaries set in this chapter. If the characteristics of the lock fall within these boundaries, it is possible to use the finding of this study in the specific lock. The next step is to identify the consequences for the involved parties. These consequences should either be positive or the involved party should be compensated in some way. This can be done by changing priority settings, financial compensation or any other way. The last step is the switch towards a new lock operation policy. The change of the policy is not something that should be done on a regular basis, since the implementation of a new policy will have some consequences. First of all, the planning is made up front, so there will be some sort of transition period where either two or zero policies are in place. After this period there will be a period where everybody has to get used to the new rules which will be in place. For example, some vessels will pass the first vessel in line to increase the performance of the lock and the planners might get a more complicated task due to these new rules.

![Figure 21 Mix of arrivals (red= large vessels, green= medium vessels and blue = small vessels)](image)
5. Generalization of the results

The previous chapter described the situation of the port of Amsterdam and the influence of other lock operation policies on the performance of the lock. The next step is to see how the findings of the case study can contribute to lock operation policies in general. Therefore, this chapter relates to the sub-question: How can the findings of this study help to improve lock operation management in other ports? The first step is to identify the relations between the characteristics of a port and the policies and the requirements for a successful lock operation policy. The next step is to identify the steps that need to be taken to implement such a lock operation policy. Afterwards, these results will be discussed.

5.1. Relation between the characteristics of locks and the policies

The situation of the port of Amsterdam will be used as a reference point and it will be compared with the situation of other ports. As a result it will be possible to tell whether the results of the study can be generally applicable. This paragraph will focus on the target group for the generalized results and which circumstances are necessary for a successful lock operation policy.

5.1.1. Generalization based on system characteristics

Whether or not the characteristics of a lock affect the level of generalization will be determined by means of a simulation study. The characteristics will be varied to a certain extent and the results of those different scenarios will be compared. The characteristics that will be tested are: the mix of arrivals, the pattern of arrivals and the size of the chambers. These characteristics are chosen because they are likely to differ between different locks. Other factors such as the processing time of the vessels, the opening hours of the lock and the number of chambers are likely to differ as well, but are not taken into account for various reasons. The processing time of the different chambers will affect the performance of a certain lock, but given a lock, the processing time would not change if the lock operation policy changes, it can only limit the number of vessels that pass through. The opening hours of the lock are not taken into account, since it is likely that the opening hours of the lock are strongly related to the number of arrivals. If there are no expected arrivals during the night, it is likely that the lock will be closed. Secondly, it does not matter whether the planning is done for 12 hours a day or for 24 hours. The effect will be the same. As has stated in Chapter 2, the number of chambers should be higher than one in order to use the policies described during this research. Since, the number of arriving vessels and the number of chambers are strongly related, it is not possible to compare the results of two scenarios with a different amount of chambers.

Mix of arrivals

The first characteristic that will be investigated is the mix of arriving vessels. The larger the allowed variance in the mix of arriving vessels is, the more ports are suitable for applying the results of this study. In order to analyze this effect, this paragraph is dedicated to the analysis of the mix of arrivals. This will be done by varying the mix of arrivals instead of the numbers. After doing this, the results will be compared with the base case of the port of Amsterdam and if the results diverge from the initial results, the target group can be set. The same method can be applied on other characteristics of the locks.

The mix of arrivals consists of three types of vessels. The vessels that can pass through the southern chamber, vessels that can pass through the middle chamber and vessels that can pass through the northern chamber. Figure 21 shows the division of the three categories among each other. It should be noted that while the amount of vessels is equal for every scenario, the ratio between the three categories differs. The variation in the mix of arrivals will be done by varying the three categories between 0% and
100%. This is done by means of a full factorial design with steps of 25%. The details of the scenarios are shown in Appendix F.

These scenarios will be tested by making used of the first come, first served principle, since this is the initial situation. This will be tested against the initial situation by the following KPIs: average waiting time, maximum waiting time, variance in waiting time, number of lockages, batch size and the filling rate.

Table 24 Results for mix of arrivals

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average waiting time</th>
<th>Maximum waiting time</th>
<th>Variance in waiting time</th>
<th>Number of lockages</th>
<th>Batch size</th>
<th>Filling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.69</td>
<td>15.40</td>
<td>1.00</td>
<td>10963</td>
<td>1.36</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>0.58</td>
<td>12.90</td>
<td>0.69</td>
<td>11296</td>
<td>1.33</td>
<td>0.28</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>13.17</td>
<td>0.53</td>
<td>11026</td>
<td>1.33</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>0.52</td>
<td>15.40</td>
<td>0.52</td>
<td>11464</td>
<td>1.31</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>1.42</td>
<td>29.07</td>
<td>5.29</td>
<td>10070</td>
<td>1.32</td>
<td>0.34</td>
</tr>
<tr>
<td>6</td>
<td>0.58</td>
<td>11.94</td>
<td>0.62</td>
<td>11047</td>
<td>1.31</td>
<td>0.33</td>
</tr>
<tr>
<td>7</td>
<td>0.48</td>
<td>8.14</td>
<td>0.39</td>
<td>11480</td>
<td>1.30</td>
<td>0.37</td>
</tr>
<tr>
<td>8</td>
<td>3.72</td>
<td>102.45</td>
<td>25.58</td>
<td>624</td>
<td>1.30</td>
<td>0.34</td>
</tr>
<tr>
<td>9</td>
<td>0.65</td>
<td>11.26</td>
<td>0.83</td>
<td>10829</td>
<td>1.31</td>
<td>0.38</td>
</tr>
<tr>
<td>10</td>
<td>1.78</td>
<td>26.64</td>
<td>8.02</td>
<td>9832</td>
<td>1.31</td>
<td>0.38</td>
</tr>
<tr>
<td>11</td>
<td>0.50</td>
<td>10.00</td>
<td>0.42</td>
<td>11364</td>
<td>1.31</td>
<td>0.42</td>
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<tr>
<td>12</td>
<td>0.73</td>
<td>15.55</td>
<td>1.11</td>
<td>10632</td>
<td>1.31</td>
<td>0.43</td>
</tr>
<tr>
<td>13</td>
<td>2.66</td>
<td>40.54</td>
<td>16.49</td>
<td>9441</td>
<td>1.32</td>
<td>0.43</td>
</tr>
<tr>
<td>14</td>
<td>3.70</td>
<td>188.33</td>
<td>30.56</td>
<td>514</td>
<td>1.29</td>
<td>0.38</td>
</tr>
<tr>
<td>15</td>
<td>3.91</td>
<td>104.15</td>
<td>32.35</td>
<td>1</td>
<td>1.24</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The first part of analyzing these results is checking the number of lockages. If this number is much lower, it means that not all vessels can be handled. The 9th, 14th and 15th scenarios have a much lower number of lockages. So, it can be said that these scenarios are not suitable for generalizing the results. Secondly, the scenarios with 0% small vessels are excluded, since without small vessels not every chamber will be in use.

The next step is to explain the numbers that are shown in the table. Looking at the filling rate of the scenarios, it can be concluded that the general trend is that the filling rate rises as the number of the scenarios becomes higher. This can be explain by the composition of the mix of arrivals. The first scenario
is the initial mix of arrivals. The next scenario has a mix of 100% small vessels, therefore, the surface of the combined fleet will be lower. Since the filling rate is the surface of the handled vessels divided by the number of lockages times the surface of the lock, the filling rate is automatically low. As the number of the scenarios increases, the share of large vessels increases as well. So it is expected that the filling rate rises.

The opposite direction can be identified when looking at the batch size, since the larger the vessels the less vessels fit in one chamber. This trend is shown in Figure 23. So it can be concluded that these values follow the expected pattern which is consistent with the input of the scenarios. The last step is to check whether the waiting time of the vessels differs significantly. If this is the case, the results of this study are not valid for other mixes of arrivals than the mix that can be found in the case of the port of Amsterdam.

The last step is to look at the waiting time of the different scenarios. This is done by means of statistical analyses. By performing a one-way ANOVA test, it is possible to distinguish differences between the average waiting times of the different scenarios. The results are shown in Table 25. As expected, it can be concluded that not all scenarios have the same average.

Table 25 Mix of arrivals - ANOVA table

<table>
<thead>
<tr>
<th>Sum Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>254.578</td>
<td>15</td>
<td>16.972</td>
<td>446.461</td>
</tr>
<tr>
<td>Within Groups</td>
<td>5.474</td>
<td>144</td>
<td>.038</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>260.052</td>
<td>159</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The next step is to compare individual scenarios with each other. The results of this analysis are shown in Table 26. The averages that are compared are the averages of the different replications. If two scenarios are connected by a 1, it means that the average waiting time can be assumed equal with 95%. In order to make the results of this analysis easily understandable, some scenarios are excluded. These scenarios are marked in orange. The first scenarios that are excluded are the scenarios that do not contain small vessels, since an exclusion of small vessels means that the southern chamber will not be used. The scenarios that are excluded are scenarios 11 to 15. The next scenarios that are excluded are the scenarios which do not have any other matching scenarios. These are scenarios 5, 8 and 10. The only empty cells are the cells that link scenario 2 and 7. Since all other average waiting times can be assumed equal with 95% confidence.
and it can be said with 90% confidence that scenarios 2 and 7 have equal average waiting times, the remaining scenarios can be considered to have equal outcomes considering the waiting times.

Table 26 Mix of arrivals - Comparing individual scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tr>
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</tbody>
</table>

The findings of the statistical analysis will be made visual in the coming part. The approach that is used for analysis is the difference in waiting time per vessel type. In order to be able to exclude scenarios, some boundaries should be set. The maximum average waiting time of small vessels is 0.75 hour, for medium sized vessels 1 hour and for large vessels 1.50 hours. These limits are based on the maximum values of the scenarios that are taken into account after the statistical analysis. It should be noted that the x-axes of the three figures are not the same as they are sorted for each category from high to low. The limits are shown in the figures below by the dotted lines. By excluding all scenarios that exceed one of those limits the following scenarios remain within the valid ranges: scenarios 1, 2, 3, 4, 6, 7, 9 and 11. These scenarios correspond with the following ranges.
As has been stated earlier, the percentage of small vessels should not be zero, since it would imply that the southern chamber will not be used. Therefore, scenario 11 should be excluded as well. The last step that needs to be taken is to set ranges to the different vessel categories. These limits are based on the statistical analysis of the average waiting times of the different scenarios and the ranges are shown in Table 27.

**Table 27 Ranges of the vessel categories**

<table>
<thead>
<tr>
<th></th>
<th>Small vessels</th>
<th>Medium vessels</th>
<th>Large vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>min</strong></td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>max</strong></td>
<td>100%</td>
<td>75%</td>
<td>25%</td>
</tr>
</tbody>
</table>

**Pattern of arrivals**

The pattern of arrivals that has been used during the simulation runs was equal over time, meaning that the average interarrival time was equal. By introducing two peaks in arrivals every day, the characteristics of the system will change. The number of arrivals in the alternative arrival pattern is two times higher than the initial situation at some points in time and four times higher than during the off-peak hours. The total number of arriving vessels should be more or less the same in order to make a fair comparison. It is chosen to use two peaks, since this is an imitation of the pattern that would occur if the tidal influence was large. Looking at the alternative pattern of arrival, it is expected to increase the waiting times and the variance, since it is more common for vessels to arrive at more or less the same time. In order to prove that the results of this study can be applied in a broader field than just the port of Amsterdam, the effects of the policies should be equal between the flat arrival pattern and the alternative arrival pattern. The initial inter arrival time is exponential (0.8) distributed, while the alternative arrival pattern is shown in Table 28. Looking at the other characteristics, it is expected that the filling rate will be more or less the same, since the same mix of arrivals will be used, the only thing that changes is the interarrival time. Since the vessels are likely to be arriving more in groups if the alternative arrival pattern is in place, the chambers
can be used more efficiently. It is more likely that vessels are batched in a chamber, therefore the number of lockages is expected to be lower and the batch size higher.

Table 28 Inter arrival times for alternative pattern of arrival

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Inter arrival time (Exponential(average))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6</td>
<td>Exponential (0.4)</td>
</tr>
<tr>
<td>6-12</td>
<td>Exponential (1.6)</td>
</tr>
<tr>
<td>12-18</td>
<td>Exponential (0.4)</td>
</tr>
<tr>
<td>18-0</td>
<td>Exponential (1.6)</td>
</tr>
</tbody>
</table>

Table 29 shows the results of the experiment described above. It should be noted that the real values are not that important during this analysis. The most important aspect is the relative difference between the flat arrival pattern and the alternative arrival pattern. If this relative difference is more or less equal, it can be concluded that different arrival patterns do not influence the effectiveness of the lock operation policies and therefore the results of this study are not dependent on the arrival pattern.

Table 29 Results of alternative pattern of arrivals

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average waiting time</th>
<th>Maximum waiting time</th>
<th>Variation in waiting time</th>
<th>Number of lockages</th>
<th>Batch size</th>
<th>Filling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial with FCFS</td>
<td>0.78</td>
<td>17.65</td>
<td>1.37</td>
<td>10633</td>
<td>1.31</td>
<td>0.37</td>
</tr>
<tr>
<td>Alternative pattern with FCFS</td>
<td>1.28 (+64%)</td>
<td>23.80 (+35%)</td>
<td>3.09 (+126%)</td>
<td>9362</td>
<td>1.42 (+8%)</td>
<td>0.39 (+5%)</td>
</tr>
<tr>
<td>Initial with SPT</td>
<td>0.76</td>
<td>17.55</td>
<td>1.26</td>
<td>11541</td>
<td>1.28</td>
<td>0.37</td>
</tr>
<tr>
<td>Alternative pattern with SPT</td>
<td>1.24 (+63%)</td>
<td>23.41 (+33%)</td>
<td>2.84 (+125%)</td>
<td>10140</td>
<td>1.41 (+10%)</td>
<td>0.39 (+5%)</td>
</tr>
<tr>
<td>Initial with RBS</td>
<td>0.78</td>
<td>17.65</td>
<td>1.37</td>
<td>10633</td>
<td>1.31</td>
<td>0.37</td>
</tr>
<tr>
<td>Alternative pattern with RBS</td>
<td>1.28 (+64%)</td>
<td>23.80 (+35%)</td>
<td>3.09 (+126%)</td>
<td>9362 (-12%)</td>
<td>1.42 (+8%)</td>
<td>0.39 (+5%)</td>
</tr>
</tbody>
</table>

The results of the SPT scenarios are slightly different than the results of the FCFS scenarios. This was expected since the planning method is different. The most important part for this analysis is the difference between the initial situation and the alternative arrival pattern for both lock operation policies. The difference is expressed in percentages which can be found in the table above. The largest difference percentage point wise is 2, while the absolute differences are 17.4 minutes in maximum waiting time and 0.02 in the batch size. Since these differences in percentages and in absolute values are small, it can be assumed that the results of this study are valid for both lock operation policies.
Comparing the first come, first served principle with the RBS, it becomes clear that the results are almost identical, after rounding the results are even identical. As a result the differences between the two scenarios is equal to the difference between the two scenarios of the first come, first served principle. Therefore, the effects of the lock operation policy are not dependent of the arrival pattern considering the RBS principle. This is supported by the difference in percentage.

Since the results of the scenarios with the resources based selection are equal to the results of the first come, first served policy, it can be concluded that the results of this study are valid for the resourced based selection principle as well.

None of the comparisons among the lock operation policies had significantly different outcomes, so it can be concluded that the arrival pattern does not influence the effect of the lock operation policies.

**Size of the chambers**

The influence of the size of the chamber on the effectiveness of the lock operation policies should be tested as well, since the size of the chambers is according to literature (Chapter 2) an influence on the effectiveness. Since this paragraph is dedicated to the generalization of the results, it is not the absolute size of the chambers that is important, but the relative difference in size of the chambers. So, it will be tested whether an increase or decrease of 10% in chamber size will influence the effectiveness of the lock operation policies and what the effect is of equally sized chambers. The characteristics of the scenarios can be found in Table 30. The equally sized chamber dimensions are based on the maximum dimensions of the arrivals. This results in more capacity for the locks.

**Table 30 Characteristics of scenarios - size of chamber**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum vessel size for the northern chamber (meters)</th>
<th>Maximum vessel size for the middle chamber (meters)</th>
<th>Maximum vessel size for the southern chamber (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial situation Amsterdam</td>
<td>380x47.6</td>
<td>200x25</td>
<td>103x17.5</td>
</tr>
<tr>
<td>Size +10%</td>
<td>418x52.36</td>
<td>220x27.5</td>
<td>113.3x19.25</td>
</tr>
<tr>
<td>Size – 10%</td>
<td>342x42.84</td>
<td>180x22.5</td>
<td>92.7x15.75</td>
</tr>
<tr>
<td>Equally sized chambers</td>
<td>294x45.07</td>
<td>294x45.07</td>
<td>294x45.07</td>
</tr>
</tbody>
</table>

The results are shown in Table 31. The results of all three scenarios should be comparable with the results of the base case in order to be generally applicable. Further increases or decreases in size are not realistic, since the amount of vessels and the size of these vessels remains the same. If the vessel characteristics would be changed as well, it would not be possible to compare the scenarios. It is also not possible to further decrease the size, since it conflicts with the vessel dimensions.
Table 31 Results - size of chambers

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average waiting time</th>
<th>Maximum waiting time</th>
<th>Variance in waiting time</th>
<th>Number of lockages</th>
<th>Batch size</th>
<th>Filling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial situation Amsterdam</td>
<td>0.78</td>
<td>17.65</td>
<td>1.37</td>
<td>10633</td>
<td>1.31</td>
<td>0.37</td>
</tr>
<tr>
<td>Size +10%</td>
<td>0.74</td>
<td>15.73</td>
<td>1.25</td>
<td>10627</td>
<td>1.33</td>
<td>0.31</td>
</tr>
<tr>
<td>Size – 10%</td>
<td>0.84</td>
<td>15.64</td>
<td>1.56</td>
<td>10751</td>
<td>1.26</td>
<td>0.44</td>
</tr>
<tr>
<td>Equally sized chambers</td>
<td>0.73</td>
<td>17.64</td>
<td>1.37</td>
<td>10512</td>
<td>1.36</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The table above shows the effect of differentiations in the size of the chamber on the performance of the locks. The filling rate shows the behavior that was expected. Since the number and characteristics of the arriving vessels are equal, a larger chamber should give a lower average filling rate and the other way around. The relation between the size of the chambers on the one hand and the number of lockages and batch size on the other hand is less certain. It is very plausible that the number of lockages will decrease if the size of the chambers is larger, since more vessels can fit in the chambers. It is not sure that this will happen since it is dependent on the distribution over the chambers as well. The relation between the number of lockages and the batch size can be explained with certainty as long as the number of vessels that is handled is equal. If the number of lockages is lower, the batch sizes will be higher and the other way around. Looking at the waiting time, the same problem arises as the problem that was present with the mix of arrivals. Due to the large number of vessels, all differences are significant. Therefore, the same analyses are applied. It is checked whether the averages fall within an acceptable range. These ranges are 0.75 hour for small vessels, 1 hour for medium vessels and 1.5 hour for large vessels. Since all values fall within those ranges, it can be concluded that the chamber size does not determine the effectiveness of the lock operation policies.

In general it can be concluded that the characteristics of the system do not influence the lock operation policies as long as the mix of arrivals falls within the set boundaries. The percentage of vessels that can pass through the smallest chamber should be more than 25%, the maximum share of medium sized vessels should be 75% and the percentage of vessels that can only pass through the largest chamber should not exceed a share of 25%.

5.1.2. Circumstances for generalization
The first step that should be taken is looking back at the parameters that were set at the beginning of the research. The first premises is the chosen layout. In paragraph 2.1, a distinction is made between different layouts of locks. The chosen layout was a lock with multiple chambers, different sizes, different planning horizons and without the proximity of other locks. Since the planning process focusses on the choice between different chambers and the distribution of batches over multiple chambers, locks with a single chamber are not well suited for this approach and it is likely that the findings of this study would not comply with the characteristics of a single chamber lock. Whether the chambers have the same or different sizes is probably not of any influence on the applicability of the findings of the study. Since the study focus on the processing times of the locks, the size does not matter. This is only taken into account as a physical constraint. Since the study includes both a short as well as a long planning horizon, the
findings of this study will be applicable in both situations. The proximity of other locks is a factor that can be seen as whether or not the locks are placed in the waterway in series. This will have influence on the order of arrival. If locks are placed series, the arrival pattern would not be random, but it will be the same as the departing pattern of the previous lock. This study is performed by assuming a random arrival pattern. Peak loads may influence the maximum waiting times and the capacity of the locks. Therefore, the results of this study would not be applicable to locks in series.

In addition to the physical characteristics of a lock, it is also important to look at the lock in its environment. This will be demonstrated by an example of the port of Antwerp. As mentioned earlier, the locks in the port of Antwerp are not placed at the beginning of the port, but the different locks offer entry to different parts of the port. Looking at those locks on an individual level, they meet all the previous described requirements to make the findings of this study valid for the situation of the port of Antwerp. But if the environment of those locks is taken into account, a lot of other factors will start playing an important role. The tide becomes much more important since the time the vessels spend on a river which is exposed to tide becomes much longer. As a result the choice between different locks is dependent on the tide as well, while in the initial situation, the tide only influenced the time of arrival. This tidal influence results in peak arrival and departure times as well. Twice a day, a huge increase in vessel movements occur. Therefore, the applicability of the findings of this study are not very likely to fit a port which does not have one lock at the beginning of the port, but instead has multiple locks spread over a larger area.

Requirements for the effectiveness of a certain management approach

In order to apply a new lock operation policy, it is important to know which requirements should be met before a new lock operation policy will be effective. First, the current lock operation policy should be the limiting factor. Comparing Figure 14 and Figure 15, it can be concluded that the resources are a limiting factor. It is not likely that another lock operation policy will increase the performance of the locks significantly. Secondly, the number of arriving vessels should be sufficient. If the number of arriving vessels is too low, every lock operation policy will be effective, since it is not necessary to have an effective policy. This can be derived from Figure 14 and Figure 19. Looking at those figures, the scenarios with a low number of arrivals show more or less the same results, despite the different lock operation policies.

5.2. Discussion of the results

Looking back at the parameters that were set at the beginning of the case study, one important aspect, that is specific for the port of Amsterdam, is worth mentioning. The port of Amsterdam uses the smallest chamber just for pleasure vessels. This has two main consequences. First of all, the number of chambers that is taken into account is reduced by one and secondly the number of pleasure vessels is reduced to a minimum. The fact that most locks do not have the luxury to assign a chamber to pleasure vessels and the fact that pleasure vessels have whole other dynamics than commercial vessels, might complicate the implementation of the results of this study. There are however some arguments that rule against the previous statement. First of all, pleasure vessels are not likely to have any priority at a lock near a port, since commercial interests are more important than that of the pleasure vessels. Secondly, generally the pleasure vessels do not sign in for a slot at the locks. Therefore they cannot claim a certain spot, since commercial vessels sign in up to 48 hours upfront. This line of reasoning makes it plausible that, although the case study does not include pleasure vessels, the results can be applicable to locks which handle pleasure vessels.
Comparison with other studies

After conducting literature research it became clear that almost all studies that are done, are case studies on specific locks. Other studies that are not case specific are usually focused on one aspect of the lock operation policy; either the queueing problem or the bin packing problem of the chambers (Lodi et al., 2002). Therefore, this study is a good addition to the current literature, since it made an attempt to generalize the results of the case studies. This results in findings that can be applied in multiple locks without doing a detailed case study. Moreover, this study combines the experience and practical approach from the case studies with the theoretical approach of the lock operation policies.

It should be said that this study is based on a case study as well, but extra efforts are made in comparison with other studies. Some studies aim at a general conclusion about lock operation policies, but are not able to reach that goal due to various reasons. Looking at the studies done by Backalic and Bukurov and Coene and Spieksma (Backalic & Bukurov, 2011; Coene & Spieksma, 2013), both studies set up a research framework that aims at a general approach, but in the end, those aims are not achieved. They fix numerous factors that might influence the results if the policies were used somewhere else. For example, they fix the mix of arriving vessels, the characteristics of the lock or even the processing time of the vessels. Although they are not specifically mentioning a certain case, it becomes a case study since the characteristics of the system are fixed. The study performed in this research does not fix such factors and therefore, the results are more suitable to be generalized. Moreover, the study performed by Backalic and Bukurov does not show any results although it would be a good comparison for the results of this study. Coene and Spieksma focus on certain lemmas which are tested by means of a model. These lemmas are theoretical dilemmas which are not comparable with the results of this study, since this study focusses on the performance of a lock while the study of Coene and Spieksma focusses on the limits of lock operation policies. Their study stops at the moment the model is constructed.

Not only the results are often case specific, the KPIs are case specific as well. They often measure the performance by number of lockages, number of vessels that went through the locks or number of vessels in the waiting queue. Although these factors are important, the results cannot be applied generally. The reason is that these factors do not mean a thing if they are not compensated for the characteristics of the locks and the mix of arriving vessels (Smith et al., 2009). This is done during this study as well. Some studies focus on other aspects of the lock operation policies which might be crucial for some lock as well. Their focus is on costs or environmental factors (Wang, Zhao, Sun, & Wang, 2013). These factors are not explicitly taken into account during this study, but are bundled under the factor number of lockages. By making these factors visible, the study might be more appealing for some.

The studies that are performed towards the theoretical approaches of the lock operations focus mainly on one aspect of the policies. For example, the focus on the queueing theories (Wilson, 1978) or the focus on the bin packing problem. Since all three aspects of the policies, the scheduling, assignment and packing problem, are all equally important aspects of the lock operation policies, the results will not be compared with these studies.
6. Conclusions and recommendation
This chapter will be dedicated to the general conclusions, recommendations and reflections of both the research as well as the process which led to the results of this research. The first step will be to summarize the research. This will be done in order to give an overview of the process that led to the answers of both the research questions as well as the main question, which will be done in the next two paragraphs. In paragraph 6.4, some advice will be given on how to use the research and its conclusions. Possible further research or extensions of the current research will be given as well. The last part of the research will consist of a reflection on the results, conclusions and the process itself.

6.1. Summary of the research
The analysis of the three different lock operation policies started with identifying which combinations of locks and waterways were common. This is important for the effectiveness of different lock operation policies. The chosen layout for testing lock operation policies had to be general enough to be applicable in a large amount of ports. The chosen layout was a lock with different chambers of various sizes. This lock is located close to a port and without a proximity to other locks. As a result, the most important aspects of a lock and the most complicated options are taken into account. The next step was to find the most frequently used methods in practice as well as the most common policies mentioned in theory. This resulted in an overview of different policies derived from literature and practice. After the overview, the different policies are divided into three general lock operation policies which can be found in literature as well as in practice. An overview is given in Table 32.

Table 32 General lock operation policies

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0: First come, first served (FCFS)</td>
<td>The vessels are scheduled in the order they arrive</td>
</tr>
<tr>
<td>A1: Shortest processing time first (SPT)</td>
<td>The vessels with the shortest processing time can enter the lock first</td>
</tr>
<tr>
<td>A2: Resource-based selection (RBS)</td>
<td>Vessels who need resources get planned first. The other vessels are scheduled afterwards</td>
</tr>
</tbody>
</table>

Since both the situation as well as the policies are known, the next step was to start with model building. This consists of conceptual modelling, model testing, model validation and experimentation. This part of the research was done with close cooperation with the port of Amsterdam. By means of frequent meetings, the validity of the model was guaranteed. This process made it possible to answer the main and sub-questions. The most important part was the experimentation part. This consisted not only of comparing the different policies, but also finding the limits of those policies. This was done by increasing the arrivals and seeing what the results were on the lock operation policies.

6.2. Answers on the sub-questions
This paragraph is dedicated to answering the sub-questions. This will be done in order to contribute to answering the main research question.

What are the possible lock operation policies and what are the most promising practices?
As has been stated, in order to come up with a general theory about the lock operation policies, it is important to include all aspects which might determine the success of a certain management approach.
So, since external factors such as the proximity of a port limit the planning horizon, it is important to take this into account during the study. The same can be said about whether the chambers have the same size or not.

As described, not all aspects are useful to take into account. First of all, the single locks are not taken into account, since their maximum flow of vessels can be calculated fairly easy. Secondly, a chain of locks is not taken into account either. Those locks ask for a more holistic approach. All consecutive locks should be modeled, as a result the management approach for a single lock becomes less important. The layouts which are suitable consist of locks with multiple chambers. If the chambers are equally sized, the complexity would be lower than if the chambers are of different sizes. Besides that, lock operation policies which are suitable for different sized chambers are suitable for locks with equally sized chambers, but not the other way around. Therefore, the chosen layout will be of a lock with different sized chambers which are not part of a chain of locks.

Looking at the time component, both the short and long planning horizon have some aspects which can influence the management approach. If the planning horizon is long, it is possible to use all kinds of management approaches since it is possible to let the vessels arrive at certain points in time. A short time horizon demands the management approach be dynamic and adaptable, since vessels can arrive almost without notice. So, the chosen layout should ideally include both a long planning horizon as well as a short planning horizon. This can be achieved by choosing a lock which is located near a port and adjacent to the sea.

The earlier mentioned lock operation policies are divided into three categories. These categories will be used as alternatives which will be tested by making use of the most promising waterway-lock combination. The three categories are:

1. First come, first served (FCFS). This category is commonly used in practice and focusses merely on the arrival time of the vessels and does not take into account the use of resources for determining the order of vessels
2. Shortest Processing Time first (SPT). By using this policy, the vessel which has the shortest processing time is chosen to pass through the locks first.
3. Resource-based selection (RBS). This policy ensures an efficient use of the resources, since vessels who need resources are planned before the vessels who do not need resources.

What are the key indicators which determine the success of a certain lock operation policy?  
The indicators for success of a certain lock operation policy are dependent on two main groups of characteristics; the factors that can and the factors that cannot be influenced. The factors that do have a big influence on the success of lock operation policies but cannot be influenced by the port itself are the following. The first factor is the layout of the port. The lock operation policies used in this research focus on a certain layout. Although this layout is still quite general and broad, not every lock complies with this layout. The locks should be located on a waterway which give access to a port, canal or river. In other words, the lock operation policies that are tested during this research are only valid if a choice between chambers has to be made and not if the choice is between different locks. Secondly, the locks should not be influenced by the tide too much. If the tidal influence is large, the time planning becomes more important. Therefore, the study is, for example, not applicable in the port of Antwerp, where the locks are located more landward and the influence of the tide is higher. It is also critical to look at the
environment of the lock. If the waterways to the locks have a limited capacity or are somehow restricted in the dimensions of vessels they can handle, the effects of other lock operation policies might be limited since the capacity of the lock is not the limiting factor. This limited capacity is likely to be more than just the amount of vessels per hour. It might happen that a large vessel wants to enter the port at the same time another large vessel wants to leave and their combined width is larger than the width of the waterway. In this case, the limitation is on the dimensions of the vessels arriving at the same point in time. This factor becomes more of a limiting factor if the navigational complexity increases. The navigational complexity can be seen as the layout of the waterway; a lot of turns or other obstacles increases the navigational complexity.

The second group of indicators which determine the success of a certain lock operation policy are the factors that can be influenced. The first factor is the arrival pattern. The arrival pattern is important for the peak load of the system and the effects of the peak load can be compared with the effects of an increase in arrivals at a certain point in time, as been tested in Chapter 4. So, if the spread of the arrivals is even over time, the average waiting time will be less. This can be accomplished by communicating the effects of this study with the shippers. If they see the effect of a larger spread of vessels, they might consider working together in order to decrease the total waiting time. If vessels know that they will be transferred through the locks at a later point in time, it is possible to reduce speed and cruise at the economically most advantageous speed, which will reduce the costs for a vessel. The benefit for the port authorities is that the arrivals of vessels become more predictable which contributes to a bigger effect of lock operation policies. The second factor of this group is the priority rules. Priority rules are designed for a smoother handling of the vessels. For example, tidal dependent vessels have priority if the tide is high. This reduces the waiting time of these vessels, because otherwise it would be possible that they have to wait up to 12 hours. This is an example of a priority rule which reduces the waiting time. However, there are also rules used in lock operation policies of which it is doubtful whether they reduce waiting times. For example, giving priority to a liner which visit the port every couple of weeks. This is an extra service for frequently visiting customers, but it might cause additional waiting time if a couple of other vessels have to wait. In general, it can be said that the priority rules are exceptions on the lock operation policy which is in place, therefore they undermine the policy which might harm the success of the policy. The last indicator which determines the success of a lock operation policy is the availability of resources. If the most waiting time is caused by a deficit of resources and not by waiting on the locks to be available, it is likely that other lock operation policies would not be effective, since it does not solve the issue of a deficit of resources such as pilots and tugboats. A remark about this indicator should be. It is doubtful whether this indicator can or cannot be influenced by the port authorities. In most ports, the pilots and tugboat companies are independent and therefore the port authority cannot force them to increase the capacity. On the other hand, if the reduction in waiting time, expressed in Euros, is higher than the costs of an extra tugboat or pilot, it may be advantageous to pay for it.

Which external factors influence the effectivity of a lock operation policy?

The answer to this sub-question can be used to determine the boundaries of a lock operation policy as well as the variations on the policy. Although the lock operation policies have been proofed to be useful in practice, they are still theoretical approaches. Therefore, the effects of the lock operation policies can deviate from the intended effects. This paragraph will discuss those deviations and the reason why the results deviate from the intended results.
The first factor that might have effect on the results are the weather conditions. Heavy winds or strong current can influence the decision logic which is used during normal operations. If one of those conditions is met, it is likely that a change will be made to the choice between chambers from the fastest way of transferring through the lock to the safest way. This means that on average a vessel will be sent through a larger chamber than during normal circumstances. The tide limits the effectivity of lock operation policies as well. Due to the tidal influence, vessels with a large draft cannot pass through the locks during a period of the day. This limits the flexibility of the locks and causes more peaks in the arrival pattern if the number of arrivals increases. The tidal influence is likely to become larger over time, since the dimensions of the vessels keep increasing. Although these are external factors, it is possible to take those factors into account in the planning. This is possible since the external factors are linked to general weather trends, like seasons or day and night. In the future, if the locks are more crowded, it might be necessary to include such factors into the planning procedures of the locks.

The type of cargo that is transported through the locks is crucial for the effectivity of a lock operation policy as well. Certain types of cargo are not allow to be within a certain distance of each other. As a result some vessels cannot pass through the locks together. This limits the freedom of the planner. If the amount of vessels with a hazardous cargo increases, it is likely that other lock operation policies would not make much difference since the planning possibilities are limited. This amount of vessels with a hazardous cargo and the arrival pattern of those vessels cannot be controlled by the planners and is therefore something that should be taken into account.

The next factors are harder to grasp and less predictable. These factors are the experience of the involved people and the experience of the lock operators. The experience of the involved people can be seen as the experience of the shippers, the pilots, the boatmen and the tugboat shippers. A lack of experience of the involved people can lead to longer processing. It is hard to include those factors into the general planning procedure, since the experience causes exceptions to the rules. It can lead to extreme processing times, which do not follow from any tangible rule of a certain lock operation policy. Therefore, although important, the experience of involved people cannot be taken into account during the development of lock operation policies. The experience of the planners is slightly different than the experience of the involved people, since it involves choices instead of just a random delay. A lack of experience of the planners can lead to an inefficient use of the dimensions of the chambers. The choices are based on the situations they encountered earlier, therefore, it is likely that those choices can be fitted to some rules which can become an integral part of the lock operation policy. Since the planners themselves often do not know that they use the same rule over and over again, it is hard to include those rules, but not impossible. The way in which those rules can be included is by presenting a lot of situations to the planners and let them make a decision about them and discuss these decisions afterwards. This will be done by answering the next sub-question.

**What is the influence of new ways of managing locks on the performance of a specific port?**

This sub-question is answered by means of experimentation with the initial situation of the port of Amsterdam. The first step is to identify the KPIs which can be used to compare the different scenarios with each other. The KPIs that are used are not specific for the port of Amsterdam, but some are derived from other case studies about locks or from studies about locks in general. This is done to make the step towards more general findings easier. The KPIs that are used during this study can be found in Table 33. It should be noted that the number of lockages represents several KPIs, namely the energy usage of the locks, the salt exchange between fresh and salt water and a measure for the occupancy of the lock.
Table 33 Key Performance Indicators

<table>
<thead>
<tr>
<th>KPI:</th>
<th>Unit:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average waiting time for the lock</td>
<td>[hour/vessel]</td>
</tr>
<tr>
<td>Maximum waiting time for the lock</td>
<td>[hour/vessel]</td>
</tr>
<tr>
<td>Variance in waiting time for the lock</td>
<td>[(hour/vessel)^2]</td>
</tr>
<tr>
<td>Average waiting time for resources</td>
<td>[hour/vessel]</td>
</tr>
<tr>
<td>Utilization of resources</td>
<td>[percentage]</td>
</tr>
<tr>
<td>Number of lockages</td>
<td>[lockage]</td>
</tr>
<tr>
<td>Average filling rate</td>
<td>[percentage]</td>
</tr>
</tbody>
</table>

The scenarios that were tested are explained by answering the first sub-question and will therefore not be discussed here. Only the results of the different scenarios will be shown for the port of Amsterdam.

Results FCFS

The first come, first served principle is strictly applied. Therefore, it is not allowed to overtake other vessels. This affects the performance of the lock if the number of arrivals increases. This can be seen if the number of arrivals is increased by 30%. At that point, the number of lockages drops. This is due to the fact that vessels have to wait on average more than 4 hours before they can enter a chamber. This affects the number of vessels that can be handled by the locks. Therefore, this can be seen as the limit of this lock operation policy.

Results SPT

The shortest processing time first principle is a principle that focus more on the lock itself, while the FCFS principle focus solely on the vessels. As a result the number of lockages should be less than the other two principles. The downside is that the waiting time is likely to be higher than the waiting time of the other two principles, if the number of arrivals is low. This is due to the fact that vessels have to wait on other vessels before proceeding through the locks.

Especially if the number of arrivals is low, the shortest processing time first principle give more or less the same results as the FCFS principle. If the number of arrivals increases, it is more beneficial to use the SPT principle since it can handle up to 30% more vessels than the current situation.
Results RBS

The Resource Based Selection principle focusses on the resource, so it gives preference to the vessels that need resources, tugboats and pilots, this results in a more efficient use of these resources. Since it was already concluded that the resources are one of the limiting factors, this method might be a promising way to solve this issue. This can be seen to a certain extend as true. The lock can handle up to 30% more vessels without increasing the waiting time for resources significantly. As a result it is possible to handle more vessels with the same amount of resources.

The downside is that the number of lockages is higher for every number of arriving vessels. This is due to the fact that larger vessels need more resources and are handled first. Since those vessels do not always fit in the same chamber, the number of lockages is higher. For the same reason, the waiting time increases faster if more vessels arrive.

How can the findings of this study help to improve lock operation management in other ports?

In order to make it possible to say something about lock operation policies in general, the most important step is to find common grounds between different locks, which can be used to compare locks. These indicators should not only be applicable on most locks, but should also mean the same at every lock it is applied to. Since the effectiveness of the different lock operation policies is dependent on the amount of vessels that arrive, some measure should be found which represents this factor. The most suitable value is the percentage of capacity that is used. Although this sounds quite easy, it is not. The main reason is that the capacity of a lock cannot be determined without taking into account a bunch of factors. First of all the capacity can be measured by the number of vessels, the gross tonnage that is transported, the value of the cargo or a combination of those. Secondly, the capacity of a lock is dependent on the arrival pattern and characteristics of the vessels. If the vessels come in irregular patterns, the capacity cannot be calculated, since the capacity of a lock is zero if no vessels arrive. The dimensions of the vessels determine the capacity as well. If a vessel that perfectly fits a chamber arrives, the amount of vessels that can be handled per lockage is one, while it is also possible to fit two smaller vessels in the chamber. Lastly, the capacity of a lock is also dependent on the characteristics of the chambers. The dimensions of the chambers limits the capacity anyway, but the processing time of the chambers limits the capacity as well. If the processing time is large, the amount of vessels (or value or gross tonnage) that can be handled during a day will be lower. Another connection that should be taken into account is the connection between the processing time and the amount of vessels in one lockage. Both influence the capacity of the lock, but they also influence each other. The larger the number of vessels in one lockage, the larger the processing time is. By assessing these relations, it is not even clear whether multiple vessels in a chamber have a positive or negative influence on the capacity. A measure for the capacity usage of a lock is the utilization rate. The utilization rate of a chamber is the average filling rate of a chamber multiplied by the time a chamber is busy divided by the total time. The utilization rate of a lock is the weighted average of the utilization rate of the chamber of the lock. In principle this is a good factor, since it is not dependent on any specific aspect of a lock and the factor means the same for every lock. There are however some
problems. First of all, this factor does not vary that much if the number of arriving vessels increases. Secondly, two runs with the same utilization rate had different waiting times and number of arriving vessels. Therefore, another method should be found. The chosen approach for generalizing the results is an extended sensitivity analysis. Factors which can be of an influence on the performance of a lock are varied. If the results of the scenarios with the carried factors is more or less equal to the initial situation, it can be concluded that the choice between different lock operation policies is not dependent on that factor and can therefore, considering that factor, be applied generally. The factors that are used as variables are the number of arriving vessels, the pattern of arriving vessels, the mix of vessels and the size of the chambers. It should be noted that the results will be different for each scenario, but the relative difference should be more or less equal.

The first factor considered is the number of arriving vessels. It should be noted that if the number of vessels that is handled is far from the maximum amount of vessels that can be handled by a lock, the results of the different lock operation policies do not differ that much from each other. Other lock operation policies might become useful if the number of handled vessels is closer to the maximum number of vessels. It is however not possible to determine when the maximum number of handled vessels is reached, since this is lock specific. It can be concluded that the mix of arriving vessels does influence the effect of the lock operation policies, but as long as the mix falls within certain boundaries the effects can be neglected. First of all the percentage of vessels that fit through all chambers should be at least 25\% and secondly, the share of medium sized vessels should be a maximum of 75\% and the share of large vessels should not exceed 25\%. This can be seen as a reasonable variety of mixes of arriving vessels. The same can be said about the arriving pattern of the vessels. Although the performance of a lock is less if the arrivals are irregular, it can still be considered possible to use the findings of this study for such a lock. Lastly, the performance of a lock is not dependent on the size of a lock as long as all vessels fit through a chamber. Smaller chambers merely reduce the maximum number of vessels that can be handled by the lock and the maximum size of the vessels.

6.3. Answer to the main research question

This paragraph is dedicated to answering the main question of this research. The answer to the main question is supported by the answers to the sub-questions. Therefore, this paragraph will be a summary of the whole research which will lead to the answer to the main question. The question that was attempted to be answered was the following:

*Which lock operation policies should be applied under which circumstances in order to contribute to an increase in the efficiency of the locks?*

In this case, the circumstances can be seen as a broad concept. This include specific characteristics for locks as well as external factors. The characteristics that influence the efficiency of lock operation policies are the following. The first characteristic is a single lock that gives access to a port, river or canal. Meaning that the choices that need to be made with the lock operation policy should be choices between chambers and not between different locks. If the choice would be made between different locks, a lot of other aspects become important which are not taken into account during this study. The influence of the tide should be minimal. Where minimal means that it is fine that the locks cannot be used during a period of low tide, but it is not fine if the tide influences the whole journey of the vessels. So, the locks should be located in an area without tidal differences or close to open sea, so the tide does not affect the water level in the port, canal or river. The proximity of obstacles is the next factor, since this can influence the
arrival pattern of the vessels. If another lock is located just before the lock that is investigated, it is possible that vessels come in batches already which makes the use of a sophisticated lock operation policy redundant. The number of chambers (equally or different sized) is another crucial factor. Since single chamber locks do not have many opportunities to vary with the planning; in other words, the minimal number of chamber should be two in order to make the lock operation policies applicable. These circumstances should occur in order to make the conclusions of this research applicable.

Circumstances which differ, but do not influence the performance of a lock operation policy are crucial to identify, since those factors determine whether the most optimal lock operation policy can be generally applied. This will ensure that the findings of this study contribute to an increase in efficiency of the locks and therefore the waterway near busy ports instead of a contribution to the efficiency of the lock of the port of Amsterdam exclusively. These factors are the size of the chambers, the mix of arriving vessels and the arrival pattern of the arriving vessels. To a certain extent these factors do not influence the performance of a lock, so the results of this study can be used for improving the lock performance of other locks as long as the circumstances above are met.

The first conclusion about lock operation policies that can be drawn is that the availability of resources can influence the choice between those policies. If the resources are scarce, it is better to focus on the resources and select the RBS alternative. However, if the focus is of the managers is on the environment and reducing costs, it might be considered to use FCFS, since this limits the number of lockages, without complicated rules or algorithms for planning which can increase the costs of the policy.

Secondly, the RBS principle is only beneficial if the number of arrivals is high and the resources are scarce. Even then, the average waiting time is not likely to decrease. This is due to the fact that the benefits of the RBS policy are diminished by the increase in waiting time for the lock itself. The number of vessels that can be handled will increase nevertheless.

The same conclusion can be drawn about the SPT policy. If the number of vessels that arrive at the lock is limited, the possibilities to change this order are limited as well. Therefore, the SPT policy will only be effective if the number of arrivals is larger. The choice between the RBS and SPT is mainly dependent on the preference of the decision makers and the means they have to improve the current situation.

### 6.4. Recommendation

This paragraph is dedicated to the way in which the results of this study should be used. The first part of this paragraph is dedicated to the implementation of the results. The second part dedicated to the use of the results and the third part to effects of a new lock operation policy.

Looking at the implementation, the first thing that should be considered is whether it is necessary to change the lock operation policy. This depends on the current performance of the locks, the expected increase in arrivals and the attitude of all involved parties towards the current and the new lock operation policy. If it is decided by the port authorities to change the lock operation policy, it is crucial to check the parameters that are set during this study and whether it is legally allowed to change the policy. It is not possible to apply the results of this study if the parameters of this study do not match the characteristics of the new lock. The parameters that should be met are the following. The lock should consist of multiple chambers, the waterway should be free of any obstacles and vessels should sign in for a slot. The last check that needs to be performed is checking the willingness to change. All involved parties benefit from the change or should be compensated in some way. It should be noted that benefits does not necessarily
mean a decrease in waiting time for the shippers. A higher waiting time with less variation might be more desirable.

The use of the results mainly focus on how to apply it in a different environment than the one described in this study. Although the different policies are tested under various conditions, like the number of arriving vessels, the mix of arrivals, the size of the chambers and the number of available resources, there are still some choices made which are not varied. This mainly concerns the priority rules. These rules are always case specific and should therefore be adapted accordingly. It is not recommended to make the lock operation policy too dependent on the number of arrivals. Meaning that it is hard to change the lock operation policy every time the number of arrivals increases or decreases. This is due to the fact that it takes time to switch the planning, since it is done 48 hours upfront and due to the fact that the involved parties should be able to get used to the new lock operation policy. It is more desirable to use the general trend of the arrival as an indicator for changing the lock operation policy.

The last part of the recommendation is dedicated to the effects of a lock operation policy. It should be noted that the direction of the trends that are identified are leading, the actual numbers are case specific and can therefore not be translated directly to another case. It is also possible that certain factors which are not present in the port of Amsterdam have an impact on the performance, this may influence the results of this study.

6.5. Future research

This paragraph will discuss the opportunities for expanding this study. This can either be expanding the study or deepening the study. The study can be expanded by embedding this study in a larger whole. Meaning that not only the movement of the vessels through the locks is taken into account, but the movements towards the locks as well. This might be important since there is a chance that dependencies exist between the arriving vessels. For example, if vessels cannot pass each other on the adjacent waterway or if the arrival of a certain vessel causes other vessels to arrive as well. This can occur if a vessel is unloading at a terminal and the cargo is transshipped on smaller vessels. This contributes to the completeness of the study as well as to the possibilities to improve the planning of the vessels. This is possible since the predictability of the arrivals increases. Eventually it might even be possible to include a whole port into the model and include the processes at the terminals in the model as well. A second way of expanding the study is shifting the focus from the long term lock operation policies to short term planning. By using the findings of this study as underlying lock operation policies and creating a tool that can apply those rules in the daily operations. This automatic planning tool would reduce the influence of human behavior on the performance and can increase the efficiency by calculating all possible options instead of trusting someone’s gut feeling.

Deepening the study can be explained as increasing the level of detail and including processes that are not included yet. The first aspect that can be added to the simulation are the pleasure vessels. A reason for doing this is gaining more insight into the process as a whole. As mentioned before, the impact of the pleasure vessels on the system as a whole is not that large, but it might be useful to acquire data from the pleasure vessels in order to calculate the effects of other lock operation policies on the pleasure vessels. This might even give an incentive for the pleasure vessels to start using the possibilities to plan their trip through the locks, if they see the benefits of planning. Another aspect that can be added are more detailed KPIs. The number of lockages now represents the salt exchange and the energy use. These factors can be made more explicit in order to give a better and more detailed overview of the system. This might be
useful to explain the choice for a certain lock operation policy in greater detail and increase the acceptance of the policy. The downside is that it will require a lot of extra research and it would not improve the results of the study. It merely increases the level of detail. Lastly, it is possible to add another process which is now included in a simplistic way. This is the tidal process. Now the tide is just taken into account as a delay for vessels with a large draft. The reason that the tide is taken into account in this way is the fact that the influence of the tide in the port of Amsterdam is not that large, since the locks are located near open sea. Ports with locks that are located more landward might suffer more from the tide, therefore the tidal process might need some improvement. This can be done by adding a gradual scale, where the maximum draft declined gradually and the time it takes to arrive at the locks should be added as well in order to create a more detailed tidal process. By including the elements described above, the model can be used in other ways than it is intended now and the results might be more generally applicable and more detailed.

6.6. Reflection

The process that led to the thesis started in April 2015. The assignment I was planning to do was, although challenging, quite straightforward: investigate how the capacity of locks can be used most efficiently. During the process, it became clear that it was not as straightforward as expected. First of all, the question of how to define the capacity of the locks arose. Nobody seems to have an answer to this question. After visiting both the port of Ghent and the port of Antwerp, it was still unclear how to define it. Even now, at the end of the study, I still have not found a satisfactory answer on this question.

I had the privilege to have five supervisors for my graduation project. On the one hand, this was very useful, since I could get plenty of feedback which would increase the quality of the work. On the other hand, dealing with five people who all want something different out of this study was sometimes hard, but in the end it turn out that the feedback sessions with all supervisors were very helpful. It helped me a lot as well that it was possible to spend two days in the office of the port of Amsterdam and three days in the office of Systems Navigator. This made the communication with the experts easier and quicker, but also more frequent which took a lot of time. During the process itself, it became clear that I was becoming more of an expert myself along the way. Resulting in some nice discussions with the experts at the port of Amsterdam.

In general, I can say that the process I went through turned out to be a good approach for this topic. The first few months were spent on merely the literature search. This literature search led to a good understanding of the system, the possible policies for lock operations and the effects of those policies both in theory and in practice. The remaining time was spent on model building and analyzing the results. During this period I visited the two other ports, which gave me more insight into the processes around locks. It might have been more convenient to have had those meetings earlier in the process, so the literature search could have been focused on the applied lock operation policies. On the other hand, the literature was less influenced by external factors and more independent. In addition to the research itself, the thesis had to be written. Luckily, I started writing the thesis from day 1, as a result the mix between modelling, literature search and writing was fine and there was a good alternation between research and writing.
References

Literature references


**Website and personal communication**


A. Appendix A: Data analysis of arrived vessels in 2014

In this appendix, the data of all vessel movements through the locks during the year 2014 will be analyzed. The data that is used is the raw data from the Data Warehouse, which is used to store all data on vessels for the port of Amsterdam and the pivot tables which are derived from this data. These data is analyzed by means of Spotfire, excel analysis methods and SPSS. The goal is to retrieve the following data in order to be used during the simulation; the lockage time, the arrival distribution, the chance on an unexpected arrival, the difference between ETA and ATA, the sailing time into and out of the chambers, the chance on hazardous cargo and the tidal slots.

1. Filtering data and general information

1.1. Visual inspection

In order to retrieve this data, the dataset of all arrivals in 2014 should be cleaned up. The first step is a visual inspection. First of all the small chamber is deleted from the data since this chamber is only used for boating. The second exclusion has to do with boating as well. The second smallest chamber, the Southern Chamber, is partially used for boating and partially for commercial traffic. This chamber was out of service between the 15th of April and the 15th of June. As a result a lot of boating went through the second biggest chamber, the Middle Chamber. These cases are deleted as well, since they are an exception and are normally handled by the two smallest chambers. Therefore, this data is not reliable. The same switch occurs for small vessels who would have gone through the southern chamber. Therefore, the division of vessels over the chambers is likely to be different than during a normal operations. Beside those choices, there is also some inconsistency in the data. There are some cases which have a negative locking time. Those cases are excluded as well (331). The same is done with extremely large values, so a locking time of more than 10 hours (19). The last vessels that are deleted are the tugboats. Since these vessels are merely a result of the locking process instead of vessels that need to be planned in the schedule, these can be deleted (7742). The rest of the cases that are deleted are the earlier mentioned pleasure boats. Table 34 till Table 36 show the general characteristics of the lockage process. The total amount of vessels in the dataset after the filtering was 29188 divided over 19090 lockage processes.

Table 34 Expected and unexpected arrivals

<table>
<thead>
<tr>
<th>Name of Lock</th>
<th>Expected vessels</th>
<th>Small vessels</th>
<th>Unexpected vessels</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern</td>
<td>4418</td>
<td>964</td>
<td>1741</td>
<td>7123</td>
</tr>
<tr>
<td>Middle</td>
<td>8929</td>
<td>42</td>
<td>998</td>
<td>9969</td>
</tr>
<tr>
<td>Northern</td>
<td>7432</td>
<td>2</td>
<td>4662</td>
<td>12096</td>
</tr>
<tr>
<td>total</td>
<td>20779</td>
<td>1008</td>
<td>7401</td>
<td>29188</td>
</tr>
</tbody>
</table>

Table 35 West going and east going arrivals

<table>
<thead>
<tr>
<th>Name of lock</th>
<th>West going</th>
<th>East going</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern</td>
<td>3653</td>
<td>3470</td>
<td>7123</td>
</tr>
<tr>
<td>Middle</td>
<td>5326</td>
<td>4643</td>
<td>9969</td>
</tr>
<tr>
<td>Northern</td>
<td>5936</td>
<td>6160</td>
<td>12096</td>
</tr>
<tr>
<td>total</td>
<td>14915</td>
<td>14273</td>
<td>29188</td>
</tr>
</tbody>
</table>
Looking at the data it becomes clear that the rules that are applied to schedule the vessels are not only based on size, since 17813 van de 30577 did not went through the minimal sized chamber. Another deviation in the data is the fact that two vessels which, according to the data, do not fit in the Southern Lock, went through this lock. It is assumed that this was a typo, so those cases are taken into account during the study as if they fit in the Southern Lock.

### 1.2. Definitions

In order to make the data useful for further analyses, some definitions have to be made explicit. First of all, if ‘time in’ is earlier than the start of the lockage, the ‘time in’ is set equal to the start time of the lockage. Secondly, the start of the lockage is equal to the time at which the door of the chamber opens. The ‘time in’ is the moment at which the vessel passes the doors of the chamber.

### 2. Lockage time

The locking time should be known per chamber. Since they are all of different sizes, it is likely that the locking times will differ. The locking time is calculated by subtracting the starting time of the lockage from the time the vessels sail out of the lock. The first step in determining the locking time per chamber is checking dependencies. The locking time can be dependent on the dimensions of the vessels, on the number of vessels per lockage and on the chamber. In order to do this, the correlation between these factors and the average locking time is calculated. This is done by means of a correlation analysis. This is done with SPSS. The table below shows the correlations between the locking time and the dimensions of the vessel.

**Table 37 Correlation table lockage time vs. width, draft and length**

<table>
<thead>
<tr>
<th>Lockage time</th>
<th>Lockage time</th>
<th>Width</th>
<th>Draft</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson Correlation</td>
<td>1</td>
<td>.170**</td>
<td>.209**</td>
<td>.096**</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>29188</td>
<td>28062</td>
<td>28062</td>
<td>28062</td>
</tr>
</tbody>
</table>

As can be seen the significance level is lower than 0.05, therefore it can be concluded that there is a correlations between the locking time and the dimensions. The question is however, is it a strong connection. In order to determine the connection, a multiple regression analysis is done. The results are
shown below. The most important value is the $R^2$. This is a value for the percentage of variance that can be explained by the predictors. So, the Length, width and depth of the vessels together explain 4.8% of the variance. So, it can be assumed that the dimensions of the vessels do not influence the lockage time.

Table 38 Relation between dimensions and lockage time

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.209</td>
<td>.044</td>
<td>.044</td>
<td>46.78255</td>
</tr>
<tr>
<td>2</td>
<td>.213</td>
<td>.045</td>
<td>.045</td>
<td>46.74079</td>
</tr>
<tr>
<td>3</td>
<td>.220</td>
<td>.048</td>
<td>.048</td>
<td>46.66743</td>
</tr>
</tbody>
</table>

These claims can be checked visually by looking at the following figures. These show the spread of the lockage time vs the dimensions.

Figure 30 Lockage time vs. width

Figure 31 Lockage time vs. length
The next step is to test whether multiple vessels in the chamber influence the lockage time. Since this predictor has a nominal level, it is impossible to do a correlation or regression analysis. The only way to compare the two groups, one or multiple vessels, is by comparing the means. This can be done by the ANOVA test. This is the ANalysis Of VAriances test. This test checks whether the two average lockage times of the groups can be of the same main group. The results can be found in the table below.

**Table 39 ANOVA table lockage time**

<table>
<thead>
<tr>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups (Combined)</td>
<td>451519.221</td>
<td>1</td>
<td>451519.221</td>
<td>199.247</td>
</tr>
<tr>
<td>Within Groups</td>
<td>66139371.876</td>
<td>29185</td>
<td>2266.133</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>66590891.097</td>
<td>29187</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the significance level is below the 0.05, it can be assumed with 95% certainty that the means of the two groups are different. So it can be concluded that the lockage time is dependent on the amount of vessels in the chamber at the moment of the lockage.

The last step that needs to be taken before it is possible to determine the lockage time, is checking whether the different chambers have different lockage times. Since the level of the predictor is again nominal, the ANOVA test will be executed again. The result can be found in the table below.

**Table 40 ANOVA table lockage time and lock name**

<table>
<thead>
<tr>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups (Combined)</td>
<td>4069558.848</td>
<td>2</td>
<td>2034779.424</td>
<td>949.836</td>
</tr>
<tr>
<td>Within Groups</td>
<td>62521332.249</td>
<td>29185</td>
<td>2142.242</td>
<td></td>
</tr>
</tbody>
</table>
The grouping variable Lock name is a string, so the test for linearity cannot be computed.

The significance level is again lower than 0.05, so it can be concluded that the lockage time is dependent on the chamber. So, since the lockage time is dependent on both multiple vessels in a chamber and the chambers itself, new groups should be constructed with those two factors. This will result in validated lockage times. The results are shown in the table below. These results can be used in the simulation model for the

Table 41 Lockage time per chamber

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Minimal processing time lock (minute)</th>
<th>Average processing time lock (minute)</th>
<th>Maximum processing time lock (minute)</th>
<th>Standard deviation processing time lock (minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern</td>
<td>One vessel</td>
<td>0.04</td>
<td>42.58</td>
<td>578.85</td>
</tr>
<tr>
<td></td>
<td>Multiple vessels</td>
<td>0.01</td>
<td>33.87</td>
<td>595.52</td>
</tr>
<tr>
<td>Middle</td>
<td>One vessel</td>
<td>0.49</td>
<td>54.43</td>
<td>576.38</td>
</tr>
<tr>
<td></td>
<td>Multiple vessels</td>
<td>0.92</td>
<td>51.35</td>
<td>578.50</td>
</tr>
<tr>
<td>Northern</td>
<td>One vessel</td>
<td>0.11</td>
<td>61.27</td>
<td>569.54</td>
</tr>
<tr>
<td></td>
<td>Multiple vessels</td>
<td>0.03</td>
<td>70.13</td>
<td>552.03</td>
</tr>
</tbody>
</table>

3. Arrival distribution
The first step is checking whether the arrivals from the east are equal to the arrivals from the west. The table below shows that the significance level is below the 0.05, therefore it can be concluded that they are not equally distributed over time if the two directions are compared. This can be explained by the fact that vessels can leave the system at other places and the fact that there were most likely some vessels left in the system at the start of 2014.
Table 42 ANOVA table arrival time and direction

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival time *</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>direction</td>
<td>Between Groups</td>
<td>1</td>
<td>518191398137</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Combined)</td>
<td></td>
<td>167.600</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>236927441053</td>
<td>29186</td>
<td>6.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7038800.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2</td>
<td>236979260193</td>
<td>29187</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5176200.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As a result the arrival distribution should be determined for both sides of the locks, since the vessels can enter or exit the port in different ways. It is likely that the arrivals have seasonal influences and day and night influences. Looking at the figure below, it can be assumed that there is a difference between day and night. In order to verify and quantify this, it should be tested in more detail.

The first test that is performed, is checking for correlation between the hour of the day and the number of vessels that arrives. The results can be found in the table below. As can be seen, the significance of the correlation is higher than 0.05, therefore it can be concluded that there is no difference in the amount of vessels that arrives every hour.

Table 43 Correlation table arrivals per hour

<table>
<thead>
<tr>
<th></th>
<th>hour</th>
<th>aantal²</th>
</tr>
</thead>
<tbody>
<tr>
<td>hour Pearson Correlation</td>
<td>1</td>
<td>.356*</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td>.25</td>
</tr>
<tr>
<td>N</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>number Pearson Correlation</td>
<td>.356*</td>
<td>1</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td></td>
<td>.25</td>
</tr>
<tr>
<td>N</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

*. Correlation is significant at the 0.05 level (2-tailed).

Looking at the seasonal influences, the figure below shows that the share of every month to the total amount of vessels is between 8% and 9%. So, it is not likely that the seasons have a big influence on the vessel arrivals. This can be explained by the fact that boating is excluded from the research, this group is likely to arrive more frequent in the summer than during the other seasons. Commercial traffic, is not likely to be influenced by the seasons.
The statement about the seasonal influence can be backed up by the following table. This table shows that the significance of the correlation is higher than 0.05 (0.961), so it can be concluded that there is no seasonal influence on the amount of vessels.

**Table 44 Correlations of seasonal influence**

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Number of vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>month Pearson Correlation</td>
<td>1 -0.016</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.961</td>
</tr>
<tr>
<td>N</td>
<td>12 12</td>
</tr>
<tr>
<td>Number of vessels Pearson Correlation</td>
<td>-0.016 1</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.961</td>
</tr>
<tr>
<td>N</td>
<td>12 12</td>
</tr>
</tbody>
</table>

Therefore the inter arrival rate will be 24/30.86 = 0.8 hr.

The next stochastic external factor is the experience of the shippers. Since the experience of the shippers can lead to a more accurate ETA, it is possible to differentiate the variance in the arrival time in a stochastic way. By doing this, the delay is not directly coupled to the experience of the shipper, but is randomly assigned. The same can be said about the strategic behavior of the vessels. The difference between the ETA and the ATA will be determined by a stochastic distribution. The distribution will have the following characteristics:
Table 45 Delays

<table>
<thead>
<tr>
<th>Numerical value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chance on delay per vessel</strong></td>
<td>7.5%</td>
</tr>
<tr>
<td><strong>Average delay time</strong></td>
<td>22.5 minutes</td>
</tr>
</tbody>
</table>

4. Unexpected arrivals

An unexpected arrival is a vessel which arrives at the locks, but did not communicated his ETA at the requested times. These arrivals will have less priority since they do not fit the predefined procedures. They will be schedule at the first available spot, but it might be the case that there are more consequences. It might for example be possible that the lockage time will be higher, since it is not known upfront what kind of vessel it is and what the cargo is etcetera. In order to test whether the lockage time of unscheduled vessels is different from scheduled vessels, it is tested whether the two means can be derived from the same parent group. This is done by comparing means with the ANOVA test. The result can be find in Table 46 and Table 47.

Table 46 Descriptives unexpected arrivals

<table>
<thead>
<tr>
<th>Lockage type</th>
<th>Mean</th>
<th>N</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled lockage</td>
<td>55.5258</td>
<td>20779</td>
<td>45.35813</td>
</tr>
<tr>
<td>Small vessels</td>
<td>31.5890</td>
<td>1008</td>
<td>38.49458</td>
</tr>
<tr>
<td>Unscheduled lockage</td>
<td>61.0972</td>
<td>7401</td>
<td>53.96896</td>
</tr>
<tr>
<td>Total</td>
<td>56.1119</td>
<td>29188</td>
<td>47.76532</td>
</tr>
</tbody>
</table>

Table 47 ANOVA table unexpected arrivals

<table>
<thead>
<tr>
<th>ANOVA Table</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lockage time * lockage type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>169397.731</td>
<td>1</td>
<td>169397.731</td>
<td>74.233</td>
<td>.000</td>
</tr>
<tr>
<td>Within Groups</td>
<td>64301421.203</td>
<td>28178</td>
<td>2281.973</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>64470818.933</td>
<td>28179</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first thing that can be concluded is that 7401/29188 = 25% of the arrivals is unscheduled. The effect of the unscheduled arrivals on the lockage time can be found in Table 47. Since the significance level is lower than 0.05 it can be concluded that the lockage time between the groups differs. Since the mean of unscheduled arrivals is roughly 5.5 minutes higher, this should be added to the lockage time is a vessel arrives unexpected.
The unintentional behavior of humans should be added in a stochastic way. Both overlooking a vessel and forgetting to send the ETA, can be added in the same way. It can be done by creating vessels which arrive at the locks without notice. This has some consequences; the vessel has to be scheduled in the first available spot and the lockage time will increase. The chance on an unexpected arrival is 25%. This percentage is high, since it includes vessels who depart from port nearby with a short travel time. As a result, 5.5 minutes should be added to the lockage process, due to the unexpected arrival of a vessel.

5. The differentiation between ETA and ATA
The differentiation between the Estimated Time of Arrival and the Actual Time of Arrival is important, since it determines whether a vessel is still allowed to enter the chamber. If the vessel arrives more than 30 minutes after the ETA, it is not allowed to enter the chamber. So, it has to wait till the next available spot. The difference is determined based on 19000 cases in the year 2014. The data of the rest of the vessel arrivals is not available. The table below shows the results of the comparison of the means between the vessels that are on time and the vessels that are delayed. Looking at the second row, it can be concluded that the average delay if a vessel has to wait is 22.5 minutes with a standard deviation of 32 minutes. The percentage that has to wait is $\frac{1393}{18981} \times 100 = 7.5\%$.

*Table 48 Descriptives delayed arrivals*

<table>
<thead>
<tr>
<th>Report type</th>
<th>Mean</th>
<th>N</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>On time</td>
<td>.81</td>
<td>17588</td>
<td>6.90</td>
</tr>
<tr>
<td>Delayed</td>
<td>22.51</td>
<td>1393</td>
<td>32.04</td>
</tr>
<tr>
<td>Total</td>
<td>2.40</td>
<td>18981</td>
<td>12.30</td>
</tr>
</tbody>
</table>

6. The sailing time in and out of the chambers
Although it seems like the sailing time into the chambers is important, it is not. The only way in which the time of arrival at the locks is important, is the differentiation of ETA. Since the sailing time into the chamber is a part of the journey that leads to the arrival time, it is already included into the differentiation of the ETA. The time it takes to sail out of the chamber is not important either, since the lockage time is the time between closing the door and sailing out of the chamber. The time it takes to reach the destination is not relevant for the scope of this research.

7. Hazardous cargo and the tidal slots
Information about those two factors could not be found in the dataset that was available. Additional information should be gathered to get this information, since it is crucial to the results of the simulation study.

The hazardous cargo will be added as a stochastic external factor. This will be done, since it is important to let the vessels with hazardous cargo arrive not in a fixed order or at fixed points in time. This will be done by adding a chance on hazardous cargo to each vessel. This will result in a randomly spread of the hazardous cargo over the arriving vessels. The chance on a hazardous cargo is: ...
The first factor that will be included in a fixed way is the tide. The tide is important, since a major part of the vessels is dependent on the high tide to pass the locks. If this factor was not taken into account at all or as a fixed external factor, the tidal vessels could pass the locks either all the time or never. Since the tide shifts one hours every day, the tidal influences will be included in the following way:

\[
if(0 < t < 6 \text{ or } 12 < t < 18, \text{high tide, low tide})
\]
\[
if(\text{high tide, ships can enter, ships cannot enter})
\]

\[t = \text{hour of the day}\]
B. Appendix B: a detailed description of the arrival process

The general arrival process is described in Appendix 0. But this is just a part of the total arrival process. Since the choices that will be made later on about the different chambers, the need for tugboats and so on, it is necessary to define the characteristics of the arrivals. This includes the categories of arrivals and the dimensions. It is important to use categories of vessels instead of the raw data in order to make it possible to generalize the results and make it scalable. If the raw data was used, it is impossible to increase the number of arrivals or to validate the results.

1. Categories of arrivals

Since the main choice that has to be made is the choice of the chamber, the categories will be related to the chambers. It should be noted that this is done based on the dimensions of the vessel. If a vessel falls within the category of the Southern chamber, it is not necessary that it will pass through the Southern chamber. This vessel can pass through any chamber since it fits in the smallest chamber. An overview can be found in Table 49.

Table 49 Vessel - Lock overview

<table>
<thead>
<tr>
<th>Category:</th>
<th>Can pass through:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern chamber</td>
<td>Northern chamber</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
</tr>
<tr>
<td></td>
<td>Southern chamber</td>
</tr>
<tr>
<td>Middle chamber</td>
<td>Northern chamber</td>
</tr>
<tr>
<td></td>
<td>Middle chamber</td>
</tr>
<tr>
<td>Northern chamber</td>
<td>Northern chamber</td>
</tr>
</tbody>
</table>

The next step is to define the dimensions within the categories. Since those dimensions determine the number of vessels that fit into the lock and determine whether a tugboat or pilot is needed, it is necessary to determine the draft as well.

2. Characteristics of the arrivals

The first check that needs to be done is checking whether the dimensions fit a normal distribution. Table 49 shows the results of the check for normality. As can be seen the significance level is lower than 0.05, so it can be assumed that the Width, Draft and Length do not fit a normal distribution.
Table 50 Normality test vessel characteristics

<table>
<thead>
<tr>
<th>Tests of Normality</th>
<th>Max allowed chamber</th>
<th>Kolmogorov-Smirnov</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Width</td>
<td>Middle</td>
<td>.177</td>
<td>3507</td>
</tr>
<tr>
<td></td>
<td>Northern</td>
<td>.328</td>
<td>3257</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>.119</td>
<td>21298</td>
</tr>
<tr>
<td>Draft</td>
<td>Middle</td>
<td>.085</td>
<td>3507</td>
</tr>
<tr>
<td></td>
<td>Northern</td>
<td>.128</td>
<td>3257</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>.101</td>
<td>21298</td>
</tr>
<tr>
<td>Length</td>
<td>Middle</td>
<td>.135</td>
<td>3507</td>
</tr>
<tr>
<td></td>
<td>Northern</td>
<td>.180</td>
<td>3257</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>.202</td>
<td>21298</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

3. Chamber characteristics

So in order to determine the distribution of the length, width and draft of the vessels, all categories have to be examined individually. The characteristics of the Southern chamber can be found in Table 51.

Table 51 Characteristics of the Southern chamber category

<table>
<thead>
<tr>
<th>Number of vessels</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
<th>Standard deviation</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>22424</td>
<td>5</td>
<td>64.3</td>
<td>119.98</td>
<td>30.81</td>
</tr>
<tr>
<td>Width</td>
<td>2</td>
<td>10.33</td>
<td>17.9</td>
<td>2.71</td>
<td>9.6</td>
</tr>
<tr>
<td>Draft</td>
<td>0</td>
<td>3.49</td>
<td>7.8</td>
<td>1.44</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 52 Characteristics of the Middle chamber category

<table>
<thead>
<tr>
<th>Number of vessels</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
<th>Standard deviation</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>3507</td>
<td>50</td>
<td>133.63</td>
<td>220</td>
<td>24.73</td>
</tr>
<tr>
<td>Width</td>
<td>7.25</td>
<td>19.83</td>
<td>24.8</td>
<td>3.62</td>
<td>20.45</td>
</tr>
<tr>
<td>Draft</td>
<td>0</td>
<td>5.4</td>
<td>9.8</td>
<td>2.15</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Looking at the tables above, it can be concluded that the standard deviations are fairly large. Since the length, width and draft are not independent values and the spread is large, it can be concluded that the vessels which pass through any chamber do not with a mathematical distribution. If a mathematical distribution would be applied, it might be possible that the length of a vessel is shorter than the width.

### 4. Conclusion

First of all, the distribution among the chambers is dependent on the size of the vessel, some vessels have to go through the northern chamber due to dimension limitations. The next step is to see whether the dimensions of the vessels fits any mathematical distribution. After performing a test for normality, it can be concluded that the dimensions do not fit a normal distribution. From paragraph 3 could be concluded that the dimensions do not fit any mathematical distribution. Since it is not possible to properly fit a distribution to the dimensions of the vessels, another options is chosen. The generation of vessels will be done based on a database. Each vessel gets the characteristics of a random vessel from the database assigned. This will result in realistic dimensions for the vessels and a distribution over the different vessel types which is similar to the distribution in the year 2014.
C. Appendix C: Actor analysis

In this appendix the actor analysis will be done. The goal of the actor analysis is to map the goals, power and interests of the different actors. By ordering the actors by power and interest, it becomes clear which actors have interest in the process and have the power to act and should therefore be taken into account during the whole analysis phase. The way in which actors can be taken into account is by adding requirements which represent the interest of the actor is an actor is very powerful or by involving the actor in the decision making process. The reason for doing this upfront is that it is easier to convince opposing actors if they are involved from the beginning and it is easier as well to included wishes and demands of other players into the process if they are involved at an early phase.
### 1. List of Stakeholders

**Table 54 List of stakeholders**

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Goal</th>
<th>interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port of Amsterdam</td>
<td></td>
<td>Increase the accessibility of the port of Amsterdam in order to compete with other port in Western Europe (<a href="http://www.portofamsterdam.nl/Nieuwe-grote-zeesluis">http://www.portofamsterdam.nl/Nieuwe-grote-zeesluis</a>)</td>
<td>The port of Amsterdam wants a management approach which ensures an efficient use of the available infrastructure</td>
</tr>
<tr>
<td>DIVV</td>
<td>Dienst infrastructuur verkeer en vervoer</td>
<td>Develops and improves the infrastructure of the city of Amsterdam (<a href="http://www.a13c.nl/wp-content/uploads/2012/11/DIVV-DEF.pdf">http://www.a13c.nl/wp-content/uploads/2012/11/DIVV-DEF.pdf</a>)</td>
<td>A management approach which ensures the continuity of the traffic flows, both on land as via water</td>
</tr>
<tr>
<td>dRO</td>
<td>Dienst ruimtelijke ordening</td>
<td>dRO want a durable development of the city of Amsterdam (<a href="http://www.amsterdam.nl/gemeente/organisatie/ruimte-economie/ruimte-duurzaamheid/ruimte-duurzaamheid/">http://www.amsterdam.nl/gemeente/organisatie/ruimte-economie/ruimte-duurzaamheid/ruimte-duurzaamheid/</a>)</td>
<td>A durable management approach for the locks</td>
</tr>
<tr>
<td>OGA</td>
<td>Ontwikkelingsbedrijf gemeente Amsterdam</td>
<td>The OGA is responsible for the special planning and development within the municipality of Amsterdam</td>
<td>A durable and efficient layout of the locks</td>
</tr>
<tr>
<td>Transporting companies</td>
<td></td>
<td>Ensuring the continuity of the company and increasing the share of profit</td>
<td>Fast, reliable and cheap transport through the North Sea channel</td>
</tr>
<tr>
<td>Shippers</td>
<td></td>
<td>Ensuring the continuity of the company and increasing the share of profit</td>
<td>Passage through the channel without much hassle.</td>
</tr>
<tr>
<td>Lock operators</td>
<td></td>
<td>Guiding the vessels through the chambers in an easy, but efficient way</td>
<td>An easy set of rules to guide the vessels through the locks</td>
</tr>
<tr>
<td>Ministry of infrastructure and environment (ministry of I&amp;M)</td>
<td></td>
<td>Good connections by road, rail, waterways and through the air, while improving air and water quality (ministerie van infrastructuur en milieu, 2015)</td>
<td>An locking process which does not harm the environment and with a minimal impact on road traffic</td>
</tr>
<tr>
<td><strong>Department of waterways and public works (RWS)</strong></td>
<td>Rijkswaterstaat</td>
<td>Increasing safety, livability and accessibility of the Netherlands (rijkswaterstaat, 2015)</td>
<td>As the owner of the lock, they want to extend the lifetime of the locks with a proper management approach</td>
</tr>
<tr>
<td><strong>Municipality of Amsterdam</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of Amsterdam and ensure the continuity of the municipality</td>
<td>An efficient lock management approach in order to increase the profit for the municipality</td>
</tr>
<tr>
<td><strong>Province of North-Holland</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of the province of North-Holland and ensure the continuity of the province</td>
<td>An efficient lock management approach in order to increase the profit for the province</td>
</tr>
<tr>
<td><strong>Municipality of Velsen</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of Velsen and ensure the continuity of the municipality</td>
<td>An environmentally friendly process for lock management in order to increase the wellbeing of the inhabitants</td>
</tr>
<tr>
<td><strong>Municipality of Ijmuiden</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of Ijmuiden and ensure the continuity of the municipality</td>
<td>An environmentally friendly process for lock management in order to increase the wellbeing of the inhabitants</td>
</tr>
<tr>
<td><strong>Municipality of Beverwijk</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of Beverwijk and ensure the continuity of the municipality</td>
<td>An environmentally friendly process for lock management in order to increase the wellbeing of the inhabitants</td>
</tr>
<tr>
<td><strong>Municipality of Zaandam</strong></td>
<td></td>
<td>Ensure the wellbeing of the inhabitants of Zaandam and ensure the continuity of the municipality</td>
<td>An environmentally friendly process for lock management in order to increase the wellbeing of the inhabitants</td>
</tr>
<tr>
<td><strong>VTS-coordinator</strong></td>
<td>Vessel Traffic services coordinator</td>
<td>The VTS-coordinator is responsible for the vessel and lock scheduling and for the execution of the policies (<a href="http://intranet/haintranet/(1740)-Organisatie/Afdelingen-ampamp-sectoren/(217342)-Divisie-Havenmeester/(217342)-Divisie-Havenmeester-Startpagina/Afdelingen-ampamp-sectoren-Divisie-Havenmeester-Kolom-2/Afdeling-Operatie/Afdeling-Operatie-Afdeling-Operatie.html?highlight=vts">http://intranet/haintranet/(1740)-Organisatie/Afdelingen-ampamp-sectoren/(217342)-Divisie-Havenmeester/(217342)-Divisie-Havenmeester-Startpagina/Afdelingen-ampamp-sectoren-Divisie-Havenmeester-Kolom-2/Afdeling-Operatie/Afdeling-Operatie-Afdeling-Operatie.html?highlight=vts</a>)</td>
<td>A management style which complies with their experience and findings</td>
</tr>
<tr>
<td>Role</td>
<td>Description</td>
<td>Requirements</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Sluismeesters</td>
<td>The locks men are responsible for operating the locks.</td>
<td>They want a management approach which can be executed in an easy way in real-time situations</td>
<td></td>
</tr>
<tr>
<td>Pilots</td>
<td>Guiding vessels through unknown waterways</td>
<td>A clear process which reduces hassle during the guiding process</td>
<td></td>
</tr>
<tr>
<td>Agent</td>
<td>Supporting the vessels as best as possible</td>
<td>A clear process with reliable slots for their vessels</td>
<td></td>
</tr>
<tr>
<td>Mooring teams</td>
<td>They are responsible for the mooring of the vessels in the locks</td>
<td>They do not want measures in place which makes their work more difficult</td>
<td></td>
</tr>
<tr>
<td>Customs</td>
<td>Reduce the smuggling to a minimum</td>
<td>They want the possibility to check vessels on smuggling</td>
<td></td>
</tr>
<tr>
<td>Tugboat</td>
<td>Help vessels steering through unknown waterways</td>
<td>A clear process which reduces hassle during the guiding process</td>
<td></td>
</tr>
<tr>
<td>Terminals at the port of Amsterdam</td>
<td>Ensuring the continuity of the company and increasing the share of profit</td>
<td>A fast and timely process to reduce the fluctuations in arrival times.</td>
<td></td>
</tr>
</tbody>
</table>
2. Power interest diagram

By mapping the stakeholders by their power and interest in the lock managing problem, it becomes possible to divide the stakeholders into different categories. Each of the categories needs to be involved in the process in another way.

![Stakeholder quadrant diagram]

**Figure 34 Stakeholder power-interest grid**

2.1. Meet their needs

The first category can be described as meet their needs. This group of stakeholders has high power, but less interest in the problem. The only stakeholder which belongs to this group is the ministry of infrastructure and environment. They are responsible for the road and waterway connections in the Netherlands, so they are eventually responsible if the capacity of either the road network or the waterway network will decrease. Therefore, they have the power to influence the decision making, but it is not likely that they will use their power. Since it is not about the construction of new infrastructure, it is likely that the interest will be less than if would have been if new infrastructure was constructed.

The way to include this group into the process is by using their demands for this specific project into the requirements of the project. So, the new management style, should not negatively affect the environment and the road traffic.

2.2. Key players

The second category is the key players. All stakeholders within this group have high interest and great power and should therefore be considered during all phases of the project. This group consists of the VTS-coordinators, the lock operators, the RWS and the municipality of Ijmuiden. The VTS-coordinators
are responsible for the planning of the locks and the vessels. They can use their experience to influence the project, therefore they are powerful. They will be interested as well, since the management approach will directly affect their job. The lock operators are responsible for the operational part of the lock management, they have to guide the vessels through the locks. If they are not able or willing to execute the chosen management approach, it is possible that the approach will fail. The lock operators are likely to be willing to influence the project, since it affects their daily work directly. The RWS is the owner of the locks and therefore interested in the use of it. The newly chosen management style can affect the lifetime of the locks and thereby the value of their investment. Since they are the owner of the locks, the RWS will have influence on the operational part of the infrastructure. The municipality of Ijmuiden is owner of the ground around the locks. Since the operations within the locks can seriously affect the wellbeing of the residents of Ijmuiden, it is likely that they are interested in the project. Since the ground is the property of the municipality of Ijmuiden, they have to grant permission for all kinds of operations and are therefore powerful. So all those stakeholders will have the power to influence the process and are willing to use the power since they are interested in the project.

There are several ways of dealing with this group, first of all, it is possible to involve the actors in the decision making process. This is very well possible for the lock operators and the VTS coordinators, since they are directly involved. Considering the simulation model, those two stakeholders can interact with the model in order to improve the theoretical best approach of the simulation model. The other two stakeholders, the RWS and the municipality of Ijmuiden are harder to involve, since they are not concerned with the operational part of the locks, they are mainly interested in the results of the project. The way in which those actors can be involved is by acting within the laws and agreements that are in place.

2.3. The least important stakeholders
This group of stakeholders can be affected by the project, but they do not have the power nor the interest to act upon it. The pilots and tugboats have the interest nor the power, since it will not affect their work in a significant way. They only difference might be the order in which vessels are handled. The customs are only interested in the cargo and not in the movements of the vessels, they do not have any means to influence the process. Although shippers have slightly more interest in the process, since it has an influence on the travel time if the vessels, they are not very interested in the project, since most vessels visit the port of Amsterdam just once or a couple of times and therefore it is not worth it to invest in the management approach. As individual shippers, they do not have the power to influence the process. If they combine forces and work together, they might have a chance, but since most shippers have slightly different interests, it is hard to get support from other shippers. Mooring teams have just one task, they have to facilitate the mooring process of the vessels within the locks. Since they are easily replaceable and there work is not affected by the new process, it is likely that they have interest nor power. The other municipalities, which are listed in table 54, do not have any interest in the project, since it does not affect them. For the same reason they do not have the power to influence the process. The dRO and OGA can only influence and are only interested in the construction of new infrastructure, therefore, they are considered as least important stakeholders.

2.4. Show consideration
The last category which can be identified is the category with stakeholders who need to be shown consideration. These people do not have the power to act upon their interests in the project. By keeping them posted and explaining choices it is possible to keep them satisfied, without including them too much in the process. This category consists of the following stakeholders: Terminals, the province of North-Holland, transporting companies, agents, DIVV and the municipality of Amsterdam. Terminals at the port of Amsterdam and transporting companies are influenced by the lock and the
managing approach, since the locks determine the capacity of the North Sea Channel and thereby the maximum workload of the terminals and transporting companies. The problem is that those companies made agreements about the amount of vessels a year with the port authorities and they are not linked businesswise with the locks in any way. So, their power is limited. The province of North-Holland is mainly interested in the wellbeing of the inhabitants and the continuity of the province. The wellbeing of the inhabitants can be harmed, they have interest in the project, but since it is not their jurisdiction, it will be hard to use their means during the process. Agents are interested in the project, since it might be an opportunity to earn more money. If the order of vessels will be influenced, it might be possible to reduce costs or increase profit. Since it is assumed that they do not have any shares in the lock, they do not have the power to influence the process. The DIVV is concerned with the task to develop the infrastructure of Amsterdam, the locks of Ijmuiden are the jurisdiction of the municipality of Ijmuiden and therefore the DIVV cannot influence the process, but is interested in the outcome. The same can be said about the municipality of Amsterdam, they are interested in the project and will be influenced by it, but they do not have the power to pursue personal goals, since it is not within their jurisdiction.

3. Conclusion
From this appendix can be concluded that there are a lot of stakeholders which should in one way or another be taken into account, since they have either the power to intervene or they have power and interest to intervene. The table below shows which stakeholder should be taken into account and in which way this should be done.

*Table 55 Stakeholder - action table*

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ministry of Infrastructure and environment</td>
<td>Use their demands as requirements in the project</td>
</tr>
<tr>
<td>Shippers</td>
<td>Let them interact with the model in order to improve the efficiency of the best theoretical approach</td>
</tr>
<tr>
<td>VTS-coordinators</td>
<td>Let them interact with the model in order to improve the efficiency of the best theoretical approach</td>
</tr>
<tr>
<td>RWS</td>
<td>Act within the agreements which are agreed upon.</td>
</tr>
<tr>
<td>Lock operators</td>
<td>Let them interact with the model in order to improve the efficiency of the best theoretical approach</td>
</tr>
<tr>
<td>Municipality of Velsen (Ijmuiden)</td>
<td>Act within the law set by the municipality</td>
</tr>
</tbody>
</table>
D. Appendix D: Conceptual model of the port of Amsterdam

This appendix will describe the conceptual model in detail. The first step is to describe the processes. The second step to describe the elements and lastly the timeframe of the system. Describing the processes is useful, since it will become easier to translate the sub-processes into a simulation model. If done properly, the sub-processes can directly be implemented in the model. The exact characteristics of the elements in the system are necessary to determine whether all information in gathered before the process of model building begins.

1. Processes

The processes of the system are documented in an IDEF0 diagram. An IDEF0 diagram is a way of dividing the main process into sub-processes in such a way that all processes and the relations between processes are described. Each process is shown in a box with incoming and outgoing arrows. The outgoing arrows are the output of the process. The incoming arrows from the left are the input of the process, while the incoming arrows from the top represent the information that is needed and the incoming arrows from the bottom represent the needed resources. It should be noted that the information and the resources are not shown in the high level decomposition in order to make the figure understandable. The first figure below shows the main process, where the waiting vessel are transformed into served vessels by guiding the vessels trough the locks. The next step is to divide this process into sub-processes, which will be described in the same way. This division into sub-processes will continue till the level of detail is sufficient.

![Diagram of the system](image)

*Figure 35 IDEF0: The system*

During the first decomposition, the process of guiding vessels through the locks is divided into three processes as can be seen in the following figure. These are still very general processes. Therefore this decomposition can only be used for explaining the system, rather than be useful as an input for the simulation model. The first process is the pre-lock process. This entails everything until the vessels enters the lock. The locking process describes everything that happens in the chamber, while the post-lock process describes the actions that needs to be taken after the vessel leave the lock.

![Diagram of guiding vessels through locks](image)

*Figure 36 IDEF0: Guide vessels through the locks*
Figure 37 IDEF0: Pre-lock process
Figure 38 Unloading part of cargo
Small ships
Physically ready ships
Ship with chamber

A1.3.1
Check load

A1.3.2
Update width & length of ship

A1.3.3
allow lockage with multiple ships

A1.3.4
Check dimensions

A1.3.5
Assign Noordersluis

A1.3.6
Assign Noordersluis or middensluis

A1.3.7
Ship smaller than 48X12X5m

A1.3.8
Assign Noordersluis, middensluis, zuiderluis or kleine sluis

Ship smaller than 120X18X8m

Ship smaller than 225X25X15m

Ship smaller than 400X50X15m

Ship with chamber

Figure 39 Assigning chamber
Figure 40 Planning of Vessels
1.1. Pre-lock process

The pre-lock process can be divided into six sub-processes. The most important thing to notice is that not all vessels need to pass through all processes. Based on the vessel type, some vessels need a tugboat or a pilot. Furthermore, the entering of pilots and attaching tugboats are processes which can be described in great detail, but this is not necessary for this system. So, these processes will be added as a delay which should be taken into account. Both processes take approximately 1.5 hours. The rest of the processes is again divided into sub-processes. The first step is to determine the type of the vessel. This is important to limit the unnecessary use of resources and to exclude invalid chamber assignment later on. As mentioned the next two processes are the entering of a pilot and attaching a tugboat. The next step is to decide whether the draft of the vessel is not too deep. If the draft is more than 14.1 meter, it is not possible to pass the locks, therefore it is necessary to unload a part of the cargo. If this is done, it is possible to assign a chamber and plan the vessel into the schedule.

The first part that is further specified is the unloading of the cargo. This is done because this process can cause a delays in the process and it is crucial to include the lightering of the vessels into the planning of the vessels, since it can take up to 4 hours. The first step is to check whether the draft is more than 14.1 meter. If this is the case, lightering will be necessary. The next step is to start the mooring process. This will be done by using at least one tugboat. The next step is to claim barges which can transport a port of the cargo through the locks. The next step, unloading the vessel and loading the barges, will take approximately 4 hours. Now, the barges and the vessel itself can pass through the locks and continue to their destination.

The second process of the pre-lock process that is described in detail is assigning of a chamber. This is done in two steps, first it will be check whether the vessel transports a hazardous cargo. If this is true, there will be restriction will become active. The next step is to check whether the second vessel arrives within 40 minutes of the first vessel. Lastly, it will be checked whether the second vessel fits into the chamber. This process is important, since it involves the planning of the lock. One chamber can lead to shorter waiting times.

The last step in the pre-lock process is checking the following conditions; the availability of the resources and checking the tidal slots. If one of these conditions is not met, a delay will occur. This will negatively affect the performance of the locks. After claiming a pilot and a tugboat, it is checked at what time the vessel can enter the lock and this slot is claimed by the vessel.

1.2. Locking process and post-locking process

After the pre-lock process is completed, the actual locking process will start. This process contains 10 sub processes. These can be found in Figure 41. In general the process can be described as follows. First it will be checked whether a chamber is ready for a new lockage process, then the vessels will be summoned. Which will be moored in the chamber. The next step is to prepare the vessels for the process. After the door is closed the chamber will either be filled or emptied. Lastly the vessels will be unmoored and they are allowed to exit the chamber.

The post locking process entails the vessels to either exit the port or enter the port and the release of the tugboats and pilots. These last two process are not that complicated and can mainly be seen as a delay and a restriction in the availability of the resources.
Figure 41 Locking process
Figure 42 Post-locking process
E. Appendix E: Characteristics of the model

This appendix gives an overview of all characteristics and parameters of the model which cannot be derived from the data analyses in Appendix A and 0.

1. Allocation of vessel type

The allocation of the vessel type is done based on the length and width of the vessels. If a vessel fits into the Southern chamber it is assigned vessel type 1, if a vessel fits through the middle chamber it is assigned vessel type 2 and if a vessel fits just the northern chamber it is assigned vessel type 3. The maximum dimension of the vessel types is shown in Table 56. It should be noted that it is not possible to encounter vessels which do not belong to any of those categories for two reasons. The first reason is that the vessels which arrive are drawn from the vessel arrivals of 2014. This data does not contain vessels which are larger than 380 meter or wider than 50 meter. Secondly, if vessels would arrive with a length larger than 380 meters or wider than 50, the vessels would not fit into the chamber and are therefore not interesting for this study.

Table 56 Dimensions of the vessel types

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Corresponding chamber</th>
<th>Maximum length</th>
<th>Maximum width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Southern chamber</td>
<td>103 meter</td>
<td>17.50 meter</td>
</tr>
<tr>
<td>2</td>
<td>Middle chamber</td>
<td>200 meter</td>
<td>25 meter</td>
</tr>
<tr>
<td>3</td>
<td>Northern chamber</td>
<td>380 meter</td>
<td>47.6 meter</td>
</tr>
</tbody>
</table>

2. Choice for resources

The next characteristic of the model which cannot be derived from the data analysis is the resource decision. The underlying choices are made based on the tide, dimensions, wind speed, wind direction and the availability of enough and the right engines. Since those factors are not taken into account, the decision whether or not and how much tugboats and pilots are needed are merely based on the dimensions of the vessel. are based on the rules which are used by the central nautical management (centraal Nautisch Beheer) (CNB, 2015). One pilot is needed if the length of a vessel is more than 60 meters. Two pilots are needed if the width is more than 35 meters. These pilots stay on board till the vessel arrives at the berth or the Kruispost.

The dimensions of the vessels and their corresponding need for tugboats is shown in Table 57. A distinction is made between entering and exiting the locks, because while exiting the locks, less tugboats are needed.
The capacity of the tugboats and pilots can be fixed since it is fixed in the real system as well. Since the port of Amsterdam indicated that the only resources that are a restriction on the efficiency of the lock are the tugboats and the pilots, those will be taken into account. The mooring men, locks men and lock operator are assumed to be sufficient and are therefore not taken into account as a resource. The number of tugboats in the model will be: 11. The number of pilots in the model will be: 50. Those numbers correspond with the actual numbers of tugboats and pilots in the port of Amsterdam.
### F. Appendix F: mix of arrivals test

#### Table 58 Scenarios for testing mix of arrivals

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Percentage of southern chamber bounded vessels</th>
<th>Percentage of middle chamber bounded vessels</th>
<th>Percentage of northern chamber bounded vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>75%</td>
<td>25%</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>75%</td>
<td>0%</td>
<td>25%</td>
</tr>
<tr>
<td>4</td>
<td>50%</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>50%</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>6</td>
<td>50%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>7</td>
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</tr>
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<td>0%</td>
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</tr>
</tbody>
</table>