



IMPACT ASSESSMENT MODEL FOR MULTI-LAYER SAFETY

Development and application of a method to assess **interacting interventions** that reduce the damage of storm surges at **container terminals**

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I

Preface

This report is the result of my thesis research as part of the master degree Construction Management and Engineering at the Delft University of Technology. It all started about two years ago, while abroad in the USA, working on a cost-benefit analysis for the designed flood barrier within a multidisciplinary project. Roughly one year later, I started searching for a thesis subject into the field of hydraulic engineering, in the hope of finding a challenging mathematical subject. After a couple conversations with a few professors and companies, the impact of multi-layer safety on container terminals appeared to be the best fit.

After months of hard work, I'm about to finalize my master thesis, which would not have been possible without the valuable input of my graduation committee. First of all, I would like to thank Matthijs, for the interest, high-quality conversations, critical eye and giving me the opportunity to write a thesis within the hydraulic engineering. Rob, thank you for showing me the possibilities of integrating asset management with the subject, providing constructive feedback and being there when I lost the broader picture. Pieter, despite the critical notes, I felt motivated every time I walked out of your room, without you, it would not have been possible to develop such an intensive model in Excel. Kasper, many thanks for the continuous support, where I recognized your sincere interest, and for introducing me to the right people. You were always there to point me in the right direction and providing practical input that brought this thesis to a higher level.

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Many others have contributed to this thesis, either by discussions or expressing confidence. Thank you for assisting me through this process. I especially want to mention Chantel, Niels, Quirine, my parents, and sister. Last, but not least, Melanie, thank you so much for the patience and support during this intense graduation period.

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Summary

When Dutch experts identified several weaknesses of the current flood risk policy, a second Delta Committee was established by the government in 2005. Their main advice was to express the necessity of the realization of stricter safety levels (Delta Committee, 2008), an advice that was implemented into the National Waterplan. To achieve the stricter safety levels, the government is opting for a sustainable flood safety policy by focusing on *multi-layer safety* (Central Dutch Government, 2009). A new strategy consisting of three different layers that widened the scope from flood prevention to flood damage reduction:

1. *Prevention*, the prevention of flooding by the primary dike system;
2. *Spatial planning*, improvement of sustainable spatial planning and partitioning;
3. *Disaster Management*, realizing better coordination among emergency services during a disaster (Kolen and Kok, 2011).

This research builds on the proposition that multi-layer safety is a promising approach assessing the impact of storm surges on the economic damage. After which, the impact is reduced by making use of flood interventions within the multi-layer safety. However, because of the lack of knowledge and the application of the multi-layer safety strategy differs per case, especially when considering relative small cases, there is no method to assess the effect of interacting multi-layer safety interventions. Therefore, it is essential to focus on a specific type of case to cope with this problem. In this present research, the selected types are container terminals, exposed via a case-study. Prior to the case-study, the theorem of multi-layer safety has been transformed into a model and subsequently applied. An important aspect of the model is the identical index, which allows comparison of the impact of interventions originating from different layers. The research objective is to develop a model to assess the economic potential of interacting multi-layer safety interventions that reduce the expected damage of storm surges at container terminals.

To achieve the development of a model to assess multi-layer safety, theories of flood risk management are supplemented by asset management theories. The base is formed through a cost-benefit analysis, which enables us to calculate the economic optimum when only prevention interventions (layer 1) would have been used. Within the cost-benefit analysis, a distinction is made between direct and indirect damage, to determine the repair cost and revenue loss caused by a flood. The direct and indirect damage is subsequently linked to assets and fault events (originating from asset management theories), which enables partitioning of the case and calculate the impact of storm surges on specific assets. Essentially, it shows when the effect of spatial planning and disaster management interventions (layer 2 and 3) needs to be assessed. The fault events are structured into a fault tree, to visualize their relationships and determine the revenue loss in the case of flooding. Lastly, both theories are organized into the decision-making process that led to the formation of the MLS-Model (multi-layer safety model).

The MLS-Model consists of variables and equations, which are structured in such a way that the impact of multi-layer safety can be assessed. This structuring meant that the development of the MLS-Model consisting of an input, simulation and outcome phases resulted in Figure Sum 1, which shows a simplification of the entire operational MLS-Model (Figure 3-13). The blue boxes are the input data, where outcomes of the simulation steps are visualized by white boxes. Linking the outcomes, the blue arrows shape the general simulation process, whereas the green arrows show the effect of interventions. The MLS-Model was developed in the program Excel, which performed the simulations.

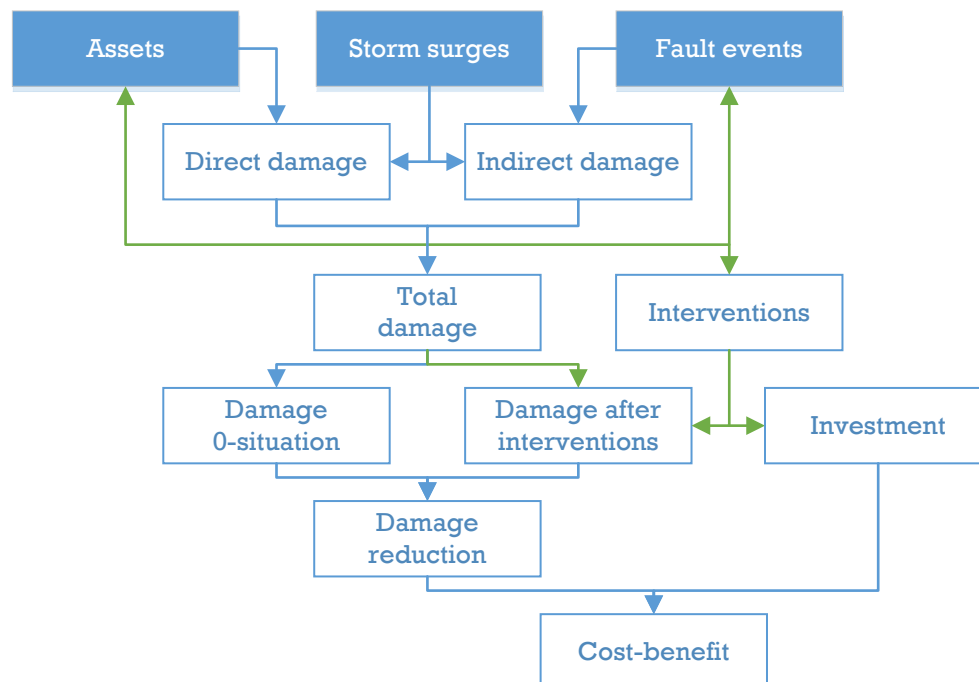


Figure Sum 1: Simplified operational MLS-Model

To show its proof of concept, the MLS-Model is applied at a case-study. Due to confidentiality reasons, the name of the case-study location cannot be mentioned. The case considers a Caribbean transshipment container terminal situated in a bay and has a concession period of 30 years. As transshipment hub, the main function of the port is to transship containers from one vessel to the other, whereby the containers will be stacked on the terminal in the meantime. Only a small amount of the containers are transported landward. To be able to perform the transshipment process, the terminal needs to be accessible and internal operation must be stable. These functions form the base of the fault tree of the container terminal. Underlying fault events are linked to involved assets, whereby the terminal system is schematized. The defined system generates an average yearly revenue of \$ 273 M, established via the volume of container traffic earnings, a factor which is increasing throughout the concession period.

In order to use the described terminal system as input data for the MLS-Model, the impact of storm surges (cause) on assets and fault events (consequence) and their interrelationships are found. Firstly, a prediction is made on the storm surges and their probability of occurrence for the upcoming 30 years, wherein different storm surge data sets are studied and the influence of climate change is involved. The values of the terminal assets are estimated, taking the depreciation into account. Relationships between the inundation height and assets have subsequently been established and visualized in damage functions. The same process is performed on the relationships between the inundation height and fault events, which are called the capacity loss functions. Lastly, the occurring downtimes of fault events through floods are established. All these variables are estimations based on several sources and made under the supervision of specialists.

By using the established input data in the MLS-Model, the simulation process of the case-study is started. The total expected economic damage during the 30 year concession period through storm surges appeared to be \$ 284.4 M, based on results of the simulation. This outcome shows the damage in case the most likely storm surges will occur during the upcoming 30 years and no interventions are applied (0-situation). The MLS-Model is able to calculate the effect of interventions on the expected damage, by adding interventions to the simulation process. Via an economic optimization, the extent in which the intervention should be constructed has been found. Resulting scores imply to what extent the intervention should be applied to maximize the cost-benefit analysis. The monetized cost-benefit analysis is the expected savings during the concession period and can be calculated by the expected storm surge damage minus the investment needed to construct the intervention. The process to find the most cost-beneficial intervention combination is started by simulating all interventions individually, after which the effect of promising combinations have been calculated. Resulting in an expected cost-benefit of \$ 109.1 M in 30 years, realized via a combination of layer 2 and 3 interventions.

In this research, the focus was on the question: what is the impact of interacting multi-layer safety interventions on the expected economic damage caused by storm surges at container terminals? The answer to this question is formed by extracting conclusions from an application of a developed method on a case-study. By deriving the most important relationships between forcing (storm surge) and economic damage (flood damage) a model has been developed that is able to assess interacting multi-layer safety interventions. Realizing prevention interventions (layer 1) to reduce the expected economic damage within the case-study appeared too costly. Spatial planning (layer 2) appears to be the most cost-beneficial intervention layer as it is able to reduce a significant amount of the expected damage for a relatively low investment. Though a small investment is needed to realize the disaster management interventions (layer 3), they will have a relatively low impact on the damage reduction. Using a multi-layer safety solution is especially profitable when interventions are combined that affect relating fault events, an outcome that can be explained by the extreme increase in indirect damage reduction. In case one relative input fault event occurs, the output fault event takes place. However, when both input fault events are prevented the output fault event will not appear. This results in an extremely favorable multi-layer safety solution.

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IV Abbreviations

Abbreviation	Definition
CBA	Cost benefit analysis
Ch.	Chapter
COWCLIP	Coordinated Ocean Wave Climate Project
EAD	Expected annual damage
FMEA	Failure mode and effects analysis
FTA	Fault tree analysis
IPCC	Intergovernmental Panel on Climate Change
k	Thousand
Layer 1	Prevention interventions
Layer 2	Spatial planning interventions
Layer 3	Disaster management interventions
M	Million
m	Meter
MLS	Multi-layer safety
MLS-Model	Multi-layer safety model
MQ	Research main question
MSL	Mean sea level
MSLR	Mean sea level rise
P.	Paragraph
SQ	Research sub question
TEU	Twenty-foot equivalent unit
TOS	Terminal operating system
UPS	Uninterruptible power supply

V

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1 Introduction

1.1 Introduction to the subject

As far as the practice of flood risk management around the globe, the Dutch became well known for their expertise in this field. For instance in Southeast Asia, experts from the Netherlands have been working to shore up defenses from the Mekong delta to Jakarta (Delaunay, 2015). In Jakarta, a masterplan for the upcoming thirty years was elaborated by a Dutch consortium to protect the city against floods (Netherlands Water Partnership, 2014). Another example, after the devastating flood in New Orleans, due to hurricane Katrina, the American newspapers wrote “time to bring the Dutch” (Steketee, 2013), and the Dutch came. Several Dutch engineering companies have worked over the years on the creation and practical realization of the flood protection system for the city (Higgins, 2012).

The flood risk management policy of the Netherlands became important because it is essential for the country to protect itself from the huge threats of flooding by the sea and rivers. The Rhine, Meuse and Scheldt, all major continental rivers, flow from Germany and Belgium via the Dutch delta to the North Sea (Figure 1-1). The flood threats of the sea and rivers, in combination with the fact that large parts of the Netherlands lie below sea level, makes the country extremely vulnerable to flooding, as visualized in a map of the flood-prone area in Figure 1-2. Without flood protection measures, 60% of the Netherlands would frequently flood (Central Dutch Government, 2015b).



Figure 1-1: Key river and canal networks of northwest Europe (Hamilton, T. M., 2013)

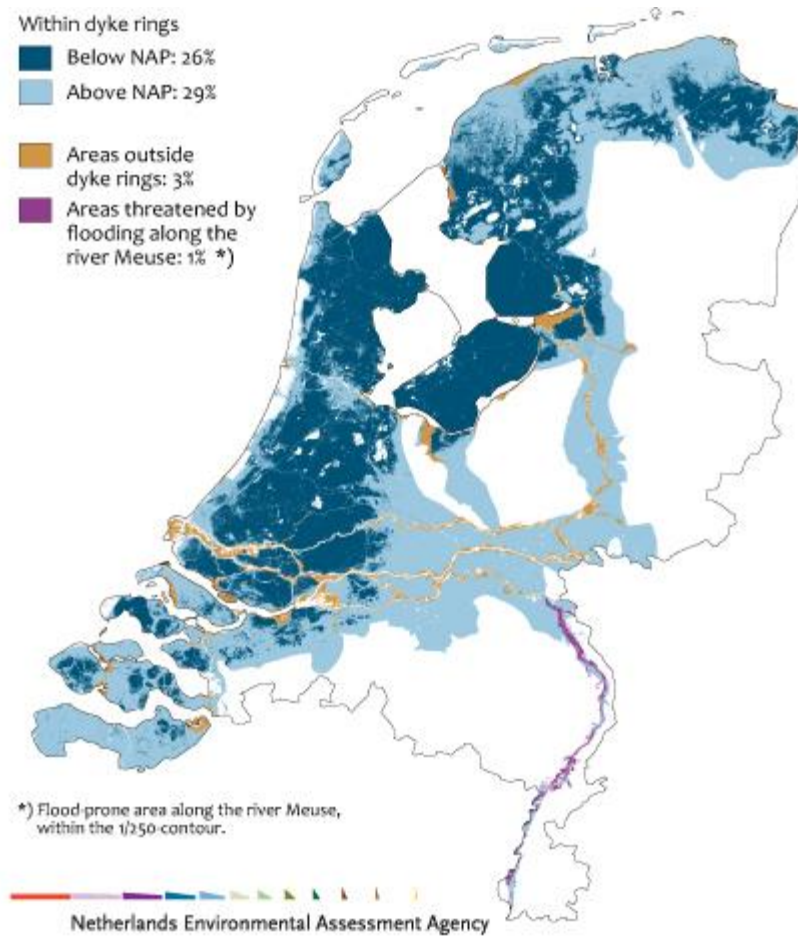


Figure 1-2: Flood prone area of the Netherlands (PBL Netherlands Environmental, 2015)

In 1953 an event occurred that changed the Dutch perspective forever. A large area of the southwestern part of the Netherlands was flooded by the North Sea. This event resulted in the deaths of more than 1800 people and caused economic damage in the order of 10% of the gross domestic product (Gerritsen, 2005). The disaster led to the formulation of an administrative body, the *Delta Committee*, an important change in the Dutch flood risk policy. The objective of the Delta Committee was to protect the country against flooding by investigating the possibilities of a new flood risk safety approach. Up until 1953, the height of the dikes had been determined to withhold the highest occurring water level. The method changed to a *cost-benefit analysis (CBA)*, the method calculates the *safety level* via an *economic optimization*. A safety level is the probability of flooding, e.g., a safety level of 1/100 years means that the area will flood once every 100 years on average. The economic optimization is indicated through the lowest outcome, which could be found by summing the expected losses through *damage* of a flood with the *investments* in improving the flood defenses (Van Dantzig, 1956). The method became the foundation for the new safety approach of the Dutch flood risk policy and still forms the basis of modern safety level calculations. Economic optimizing is applied in more disciplines, as well as in *asset management*, e.g., at IBM. As continuing on this example, being the largest consultancy firm focused on asset management, an asset management framework created to manage assets and allow organizations to better optimize and align their asset investment (Campbell, 2011). Assets are items or standards owned by a person or organization that contain certain values.

In the following years, advice from the Delta Committee was executed and flood protection measures at the coast and rivers were realized. In particular, the realization of the *Delta Works* attracts attention from abroad. The Delta Works are a cluster of flood protection measures to protect the land within the Dutch delta. The measures consist of storm surge barriers, dams, sluices, locks, dikes and levees. The worldwide recognition was confirmed when the Delta Works was selected as one of the seven wonders of the modern world (Smith, 2015).



Figure 1-3: MLS: emergency, spatial and prevention (Kolen and Kok, 2011)

As visualized in Figure 1-3, MLS consists of three layers:

1. *Prevention*, the prevention of flooding by the primary dike system;
2. *Spatial planning*, improvement of sustainable spatial planning and partitioning;
3. *Disaster Management*, realizing better coordination among emergency services during a disaster (Kolen and Kok, 2011).

In the latest National Water Plan, wherein the guidelines, principles and direction of the national water policy are described for 2016 up until 2021, a new insight is given to achieve the safety levels. Prevention interventions (layer 1) remain a crucial factor in realizing the safety levels. Examples of prevention applications are dikes, dunes, flood barriers and river widening. However, in specific situations (e.g. when dike reinforcement is very expensive or socially radical), *smart combinations* could assist in achieving the required safety level. Smart combinations give the opportunity for spatial planning and disaster management interventions (layer 2 and 3) to interact with layer 1, to accomplish a more effective solution. When smart combinations are applied, case specific agreements about the roles, responsibilities and financing are made. In order to clarify the investments in layer 2 and 3, the resulting cost reduction for layer 1 needs to be comparable with at least the required investment (Central Dutch Government, 2015b).

Throughout the decades after the installation of the Delta Committee, Dutch experts identified several weaknesses of the current flood risk policy. The Dutch government acknowledged these weaknesses and was aware of the need for improvement (Tsimopoulou, 2015). Therefore, a second Delta Committee was established by the Dutch government in 2005. The main advice of the committee was to express the necessity to realize stricter safety levels. However, further research was needed to detect the most efficient methods to accomplish these stricter safety levels (Delta Committee, 2008). The advice was approved by the government and became incorporated into the National Water Plan. To achieve the stricter safety levels, the government is opting for a sustainable flood safety policy by focusing on *multi-layer safety*, abbreviation: MLS (Central Dutch Government, 2009).

1.2 Problem definition

With the growing flooding threat, it can be assumed that the need for solutions that reduce the impact of floods, like MLS, will only increase. The threat of flooding is an enormous global problem and is growing due to the *rising sea level* and *land subsidence*, which means that floods will occur in nearly every coastal city sooner or later. The global mean absolute sea level rise is currently around 3 mm/year and is expected to be in the range of 3-10 mm/year until 2100, according to the IPCC scenarios (Slangen et al, 2011). In addition, to the sea level rise, the observed subsidence rates are in the range of 6-100 mm/year in coastal megacities and the projections up until 2025 show similar rates (Deltares, 2015). Cities with these features are called *sinking coastal cities*. This recurring problem, even if essential flood protection measures are executed, is the case for numerous sinking cities. The impact of the problem on a few of the sinking coastal cities is shown in Figure 1-4. Not only for coastal areas, which are most vulnerable, is the flooding threat a problem. Think of areas near rivers or lakes, or simply low lying surfaces, where major damage will occur if flood prevention measures fail. Thereby, flooding problems do not only take place through large storm surges, frequently minor flood damage can be devastating. Examples that can result in minor flood damage are high water levels, rainfalls, river discharges or hurricanes.

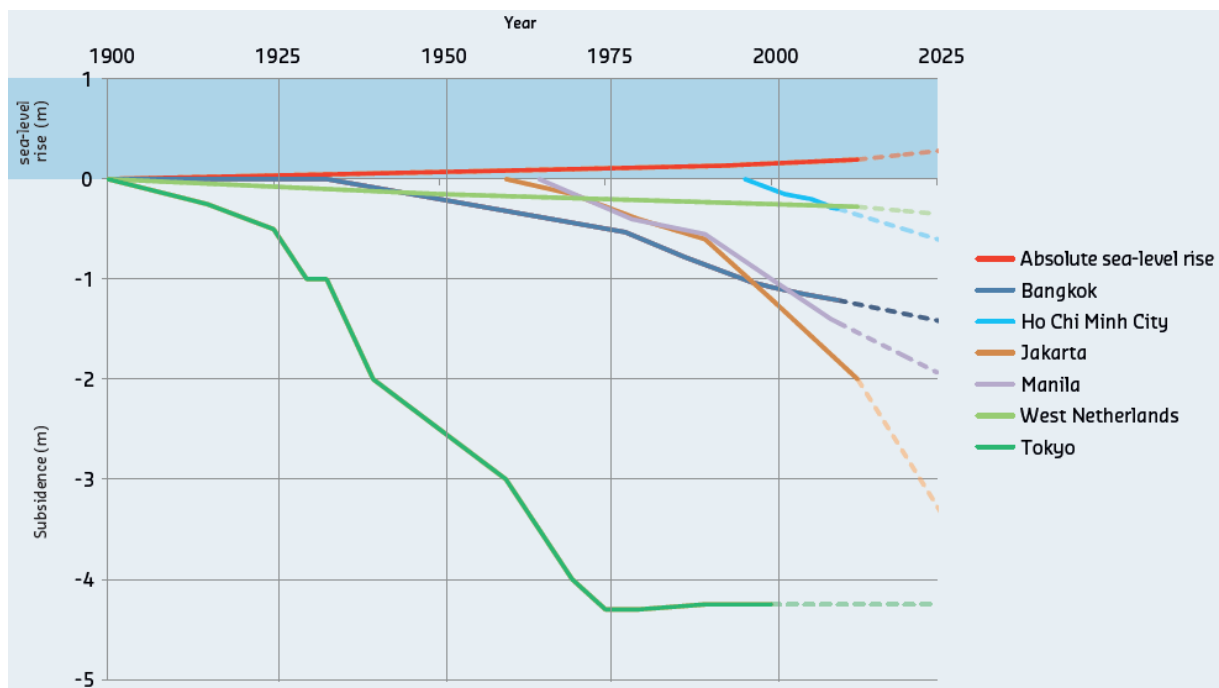


Figure 1-4: Global sea level rise and average land subsidence (Deltares, 2015)

MLS is one of the solutions to cope with the threat of flooding, however, there is no known acknowledged method to test the impact of MLS. This is because each application of MLS is different and there is a lack of knowledge in this field. Different in terms of the interventions that are possible to apply and the interactions between them, which are case specific. Certain intervention combinations are promising with applications for cases, however, this does not mean that applying the same interventions in other cases like residential areas lead to the same interactions between the interventions. *Promising interactions* could occur by applying multiple interventions, e.g., when an evacuation plan and flood proof roads are realized, these interventions reinforce each other. Another aspect is the *lack of knowledge* in the MLS field. There is limited knowledge about the resulting impact when MLS is applied because it is a relatively new phenomenon. To cope with this, the Dutch government has the intention to gain more knowledge and experience through the upcoming years by monitoring pilot projects. By applying prevention, spatial planning and disaster management interventions, information will be collected about the interactions, capabilities and effectiveness of intervention combinations as an alternative for dike reinforcements and river-widening interventions (Central Dutch Government, 2015a). In 2013, the government initiated three pilot projects, located in Dordrecht, Marken and the IJssel-Vechtdelta, which will be active for the upcoming years (Central Dutch Government, 2013).

To increase the likelihood in successfully implementing MLS, assigning norms to each layer could have a positive impact. But it becomes even more interesting if all layers have one *overarching norm*.

Scope

This research builds on the proposition that MLS can potentially be a promising solution for any case threatened by flooding. But, due to the application diversity and the need of an identical index, this research delimits the scope and zooms in according the following demarcations.

- **Area:** *container terminals*, because MLS seems an especially interesting solution for cases that contain a lot of value and are vulnerable to flooding, two typical aspects of container terminals.
- **Cause:** *storm surges*, in case the container terminal is positioned in a bay, it is assumed that storm surges are the decisive cause for the occurring damage. The reasoning behind this assumption is that the waves will be minimized, whereby wave run-up is neglected. A storm surge is an abnormal rise of water generated by a storm, which is measured via the difference between the regular water tide and the storm tide. To predict the occurring storm surges for the future a forecast is designed based on the past and climate change, leading to the expected storm surges.
- **Solution:** *MLS*, consisting of a combination of interacting interventions.
- **Timespan:** *concession period*, the time a client wishes to optimize the benefit. In this research the container terminal is hired out by the client to a port operator for a period of 30 years.
- **Impact:** *economic damage*, divided in repair costs (direct) and revenue loss (indirect). The impact of the expected storm surges on container terminals are expressed in the economic damage occurring throughout the concession period. The impact of MLS is measured via the difference between the economic damage occurring at the 0-situation compared with the improved situation.
- **Index:** *dollars*, the economic damage is expressed in dollars.

To realize this overarching norm, an identical index for all layers needs to be used. This enables the possibility to compare the impact of each intervention regardless the layer. An identical index can be achieved by changing the focus of the Dutch flood risk policy from *flood protection* to *flood damage reduction*. Flood protection contains only prevention interventions (layer 1), where flood damage reduction contains prevention, spatial planning and disaster management interventions (layers 1, 2 and 3). However, a certain base level of prevention is advisable (elaborated in Paragraph 1.1). By changing the focus to risk reduction the usage of layer 1 becomes less crucial and positive results can be achieved by applying layer 2 and 3, because all layers influence the overarching norm (Kolen et al., 2010). The flood risk reduction application could subsequently be integrated with the calculation method to define the economic optimum (originally applied on flood protection), in this research expressed via the expected economic damage, whereby an economic optimum is calculated for multiple layers, the need for such a study has already been expressed in the Netherlands (Tsimopoulou, 2015).

Given the problems and scope of this research, the problem definition is specified as follows:

Problem definition

There is no method to assess the interactions between multi-layer safety interventions that reduce the expected economic damage of storm surges at container terminals.

1.3 Research objective

The objective of this research is to gain insight into the functioning of MLS interventions. This report focusses especially on the promising interactions between combined applied MLS interventions. Due to the lack of knowledge and diversity of MLS, a specific case-study is chosen within the scope to realize one in-depth application of MLS. With this application, the functioning and potential of promising interactions are elaborated and conclusions are formed on container terminals in general. Therefore, the formulation of the objective is as follows:

Research objective

To develop a model to assess the economic potential of interacting multi-layer safety interventions that reduce the expected damage of storm surges at container terminals.

The case-study considers a container terminal situated in a bay. The impact of MLS interventions will be measured via the reduction on the expected economic damage caused by storm surges. Therefore, a new impact assessment model is developed to map the exposed flood risk and possible consequences in case a flood occurs. Using the flood risk and consequence map the model is able to simulate a variety of interventions, individually or applied in combination, to determine their expected impact on the storm surge damage. In this way, the economic potential of promising interacting interventions will be calculated and can be assessed for a specific case. Within this research, the developed model is subsequently applied to one container terminal in the Caribbean to show its proof of concept (as described in Chapter 4).

1.4 Research questions

In order to achieve the research objective (Paragraph 1.3), the following main research question will be answered throughout this research:

Main research question

What is the impact of interacting multi-layer safety interventions on the expected economic damage caused by storm surges at container terminals?

The main research question is broken down into four sub questions. By answering the sub questions, an answer to the main research question will be found. The sub research questions are:

Sub research question 1

What structure of variables and equations enables the model to assess the impact of multi-layer safety?

Sub research question 2

Which typical assets and fault events can be identified at container terminals?

Sub research question 3

What are the decisive assets and fault events on the expected direct and indirect damage?

Sub research question 4

Which combination of interventions results in the maximum cost-benefit analysis for the case-study?

1.5 Research methodology

To be able to answer the research questions a research framework is designed based on Verschuren et al. (2010). This means that each Chapter will be concluded with a sub conclusion to answer the relative sub research question, which question relates to which Chapter can be seen via the abbreviations Ch. (Chapter) and SQ (sub research questions), as presented in Figure 1-5. The framework is divided into six phases. Firstly, the theory is studied during the first phase of the research process (Ch. 2), containing flood risk management, decision making and asset management. With the input from the theory, it is possible to develop the structure of the calculations and relationships between the variables, which is the second phase (Ch. 3). During the next phase a case is described (Ch. 4). Fourthly, out of the input from the model design and case description, the needed data to execute the calculations is established in the Chapter variables (Ch. 5). By using the established data on the developed model, in combination with the separate or combined applied interventions, multiple simulations are performed during phase five (Ch. 6). The final phase consists of the conclusions, discussion and recommendations for further research (Ch. 7).

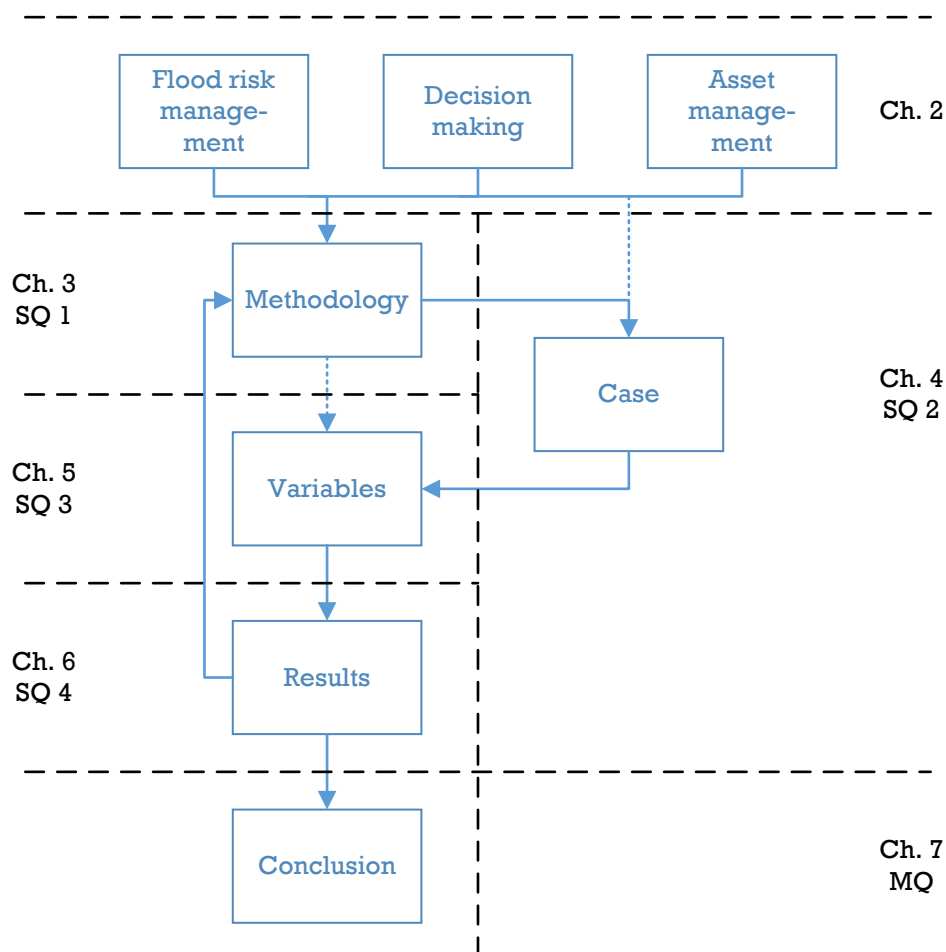


Figure 1-5: Research framework (based on Verschuren et al., 2010)

2

Theory

In this research theories from three different work fields are applied to develop an impact assessment model for MLS. The work fields flood risk management, asset management and decision making are elaborated in this Chapter. In the last Paragraph, the connection between the theories is created, as well as the formation of the method.

2.1 Flood risk management

The Dutch flood risk method in finding the economic optimum as safety level has been applied numerous times domestically and abroad (e.g. in Japan (Jonkman et al, 2005) and Vietnam (Mai et al, 2008)). The essence and objective of the method are always similar, however, some steps are added or applied more extensive depending upon the case and chosen method. Nevertheless, there are essential steps that are used in practically every application in determining the optimal safety level. These steps were introduced by the Delta Committee (1960) and explained step by step through Voorendt (2015), which will form the base of describing the method. This was substantiated by two recent applications of the method on the Dutch province South Holland (Jonkman et al., 2008b) and the American city New Orleans (Jonkman et al., 2008a). The steps are:

1. Research on the past;
2. Research on the future;
3. Cost-benefit analysis (Voorendt, 2015).

Firstly, the *current situation* of the case area is analyzed, wherein one starts to create a flood map of the area. This is done by mapping the current ground levels and simulating different floods. With the design of the flood map, a clear overview is created of which parts of the area will flood when a certain water level occurs. Hereafter, the water levels reached are studied and the relationship between return periods and water levels could be determined, visualized on a graph with the x-axis as the return period in years and the y-axis as the water level in meters (Jonkman et al., 2008a). The return period stands for the years it will take on average until the same water level occurs.

Secondly, a study is made to estimate the *future situation* of the area and its flood scenarios, which shall be concluded via a new flood map and a new graph of the return periods and associated water levels. The following effects will be included within the future situation: climate change (i.e. sea level rise, river discharge, high waters and storms), land subsidence, and growth in values of assets of the area (Jonkman et al., 2008b).

Thirdly, a *cost-benefit analysis* (CBA) is executed to calculate the economic optimum of the safety level. The economic optimization is indicated through the lowest outcome, which could be found by summing the expected losses through damage of storm surges with the investments in improving the flood defenses (Van Dantzig, 1956). An example of a CBA outcome is visualized in Figure 2-1. The total flood damage outcome is often divided in direct and indirect damage. Direct damage is the repair cost on properties and infrastructure. Indirect damage is the loss of services not touched by water (Jonkman et al., 2004). The concept of finding the damage and investments, caused by a flood or prevention against a flood, is to calculate the outcome in euros of several flooding probabilities. Calculating one specific storm surge is done by multiplying the value with the damage factor (Equation 2-1).

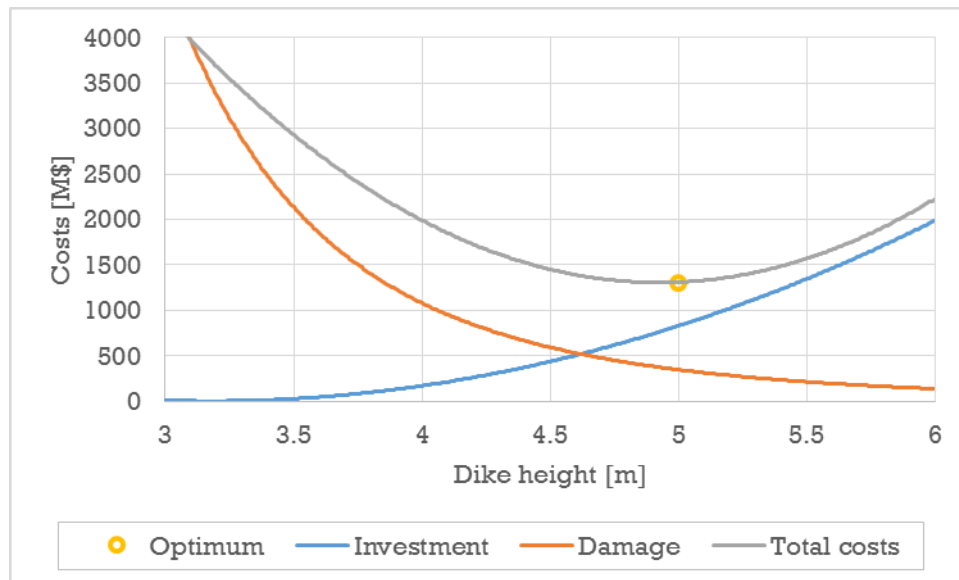


Figure 2-1: Principle of economic optimization (Jonkman et al., 2009)

$$D_{RP} = V * f(D_{RL})$$

Equation 2-1: Flood damage

D_{RP}	[\$]	Flood damage for one storm
V	[\$]	Value of a component
$f(D_{RL})$	[-]	Flood damage factor of one storm

A damage factor is one single point of a damage function, which indicates to what extent the component is damaged according to a given flood or inundation height. Damage functions are applied in mapping the risk and consequences of floods. An example of a damage function is shown in Figure 2-2, other applications of damage function can also be found in FEMA (2013), Jonkman et al. (2008b) Klijn et al. (2007), Kok et al. (2004), and Tebodin (2000).

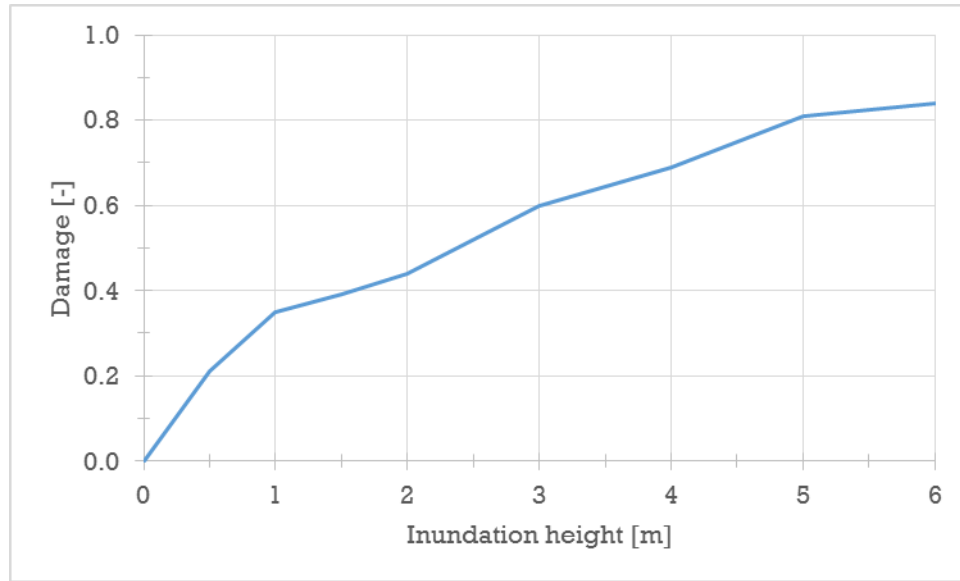


Figure 2-2: Damage functions wood industry (Tebodin, 2000)

When the flood damage, caused by that storm, is multiplied by the probability of storm occurrence the expected flood damage could be found Equation 2-2.

$$ED = D_{RP} * P_{RP}$$

Equation 2-2: Expected damage

ED(s)	[\$]	Expected flood damage for one storm
P _{RP}	[-]	Flood probability

In case that specific storm surge does not occur today but in the future, the variables (discount rate and economic growth) need to be added to the equation (Equation 2-3), where it is assumed that the flood damage grows at the same rate as the predicted economic growth (Hallegatte, 2006).

$$ED(y) = D_{RP} * P_{RP} * (1 + g)^y * \left(\frac{1}{1 + \delta} \right)^y$$

Equation 2-3: Present expected damage (Stoeten, 2013)

ED(y)	[\$]	Expected flood damage for one year
g	[-]	Growth rate
d	[-]	Discount rate

Flood damage determined over an entire year leads to the *expected annual damage* (EAD). It is the most frequently used index showing the impact of flooding (Arnell, 1989). The index is applied by the US Army Corps of Engineers (USACE, 2016), but also in England and Wales (Hall et al., 2004) and Germany (TU Hamburg, 2016). By multiplying the integral of the flood damage with delta possibilities, overall potential floods, the EAD is found (Equation 2-5). The needed delta probability can be found by determining the difference between the probability of a return period and the one after (Equation 2-4).

$$\Delta P_{RP} = \frac{1}{RP - 1} - \frac{1}{RP} = P_{RP-1} - P_{RP}$$

Equation 2-4: Delta probability (TU Hamburg, 2016)

ΔP _{RP}	[-]	Delta probability
RP	[years]	Return period

$$EAD(t) = (1 + g)^t * \left(\frac{1}{1 + \delta} \right)^t * \int_{RP=1}^{\infty} D_{RP} * \Delta P_{RP} = \sum_{RP=1}^{\infty} \frac{D_{RP-1} + D_{RP}}{2} * \Delta P_{RP}$$

Equation 2-5: Annual damage (TU Hamburg, 2016)

EAD(t)	[\$]	Expected annual flood damage
--------	------	------------------------------

2.2 Asset management

In 1960 the aerospace industry developed a design method called *FMEA*. Due to the safety requirements and reliability demands from the industry, FMEA originates. It represents a documented and powerful methodology for engineers to present a formalized and structural manner by using their experience and subjective thinking (Seyed-Hosseini et al., 2006). FMEA is the abbreviation for failure mode and effects analysis and is intended for risk management decisions to provide information (Pillay and Wang, 2003). Nowadays, FMEA is applied in numerous businesses (e.g. in the following industries: electromechanical, computer, semiconductor, medical device and automotive (Stamatis, 2003)). Several variations of the original application of FMEA have been developed over the years (Pillay and Wang, 2003). However, all applications have the same objective, which is to identify the potential failure modes, their causes and effects on the system performance. This has been achieved via a systematic procedure for the analysis of the system (Sayareh and Ahouei, 2013).

The realization and outcome of FMEA differ per application. However, several typical steps to apply FMEA are identified, based on 'modified FMEA using approximate reasoning' (Pillay and Wang, 2003) and 'FMEA for reducing the delays of cargo handling of operations in marine bulk terminals' (Sayareh and Ahouei, 2013) and are as follows:

1. Define the system;
2. Define the functions of the system;
3. Determine the relationships between the functions;
4. Identify the potential failure modes;
5. Identify the causes of the failures;
6. Categorize the severity of the failures on the functions;
7. Categorize the probability of the failures on the functions;
8. Calculate the risks.

One of the methods to visualize the relationships between functions (step 3) is a *functional breakdown structure*. A functional breakdown structure is a technique to partition a system into a hierarchical collection of functions (Brouwer, 2015). The underlying functions causing the failure of an overlying function could readily be determined (assisting step 4 and 5). A categorization of the probability and severity (step 6 and 7) is converted into a ranking system (Table 2-1), designed by AIAG (1995). By multiplying the ranked probability with the severity, the total risk of a particular failure relative to a particular function is calculated (step 8) (Mabrouki et al., 2013).

Table 2-1: Probability and severity criteria and scores (AIAG, 1995)

Probability		Ranking	Severity	Ranking
Very high	≥ 1 in 2	10	Hazardous without warning	10
	1 in 3	9	Hazardous with warning	9
High	1 in 8	8	Very high	8
	1 in 20	7	High	7
Moderate	1 in 80	6	Moderate	6
	1 in 400	5	Low	5
	1 in 2,000	4	Very low	4
Low	1 in 15,000	3	Minor	3
	1 in 150,000	2	Very minor	2
Remote	1 in 1,500,000	1	None	1

Specifying a fault event and its cause(s) for the system could be done via an *FTA* (fault tree analysis). After the specification stage, the system's operation and environment are analyzed to find all dependable occurrences in which the fault event could take place. A fault event is an undesired occurrence. Reviewing the fault events and indicating their relationships in a graphic structure leads to a fault event tree (Schüller et al., 2005).

To execute an FTA, the following tasks have to be performed:

Qualitative analysis:

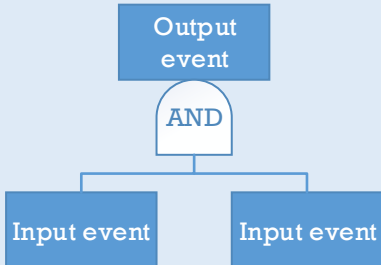
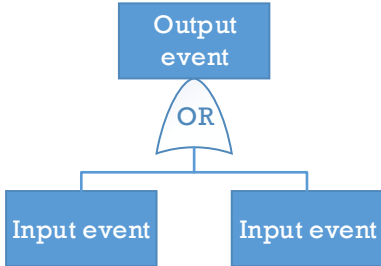
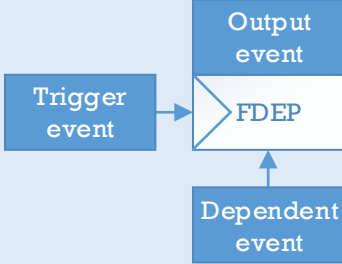
- System familiarization;
- Definition of the top event and construction of the fault tree;
- Determination of the minimal cut-sets;

Quantitative analysis:

- Collecting all relevant failure, repair, test and maintenance data;
- Quantification of the minimal cut-sets;
- Evaluation of the results (Schüller et al., 2005).

An overview of the fault events and gates is given in Table 2-2, essential to be able to design a fault tree. The stated symbols form the base of each fault tree, despite the last symbol. The FDEP gate is a recently developed symbol within the fault event tree analysis applications and is rarely applied. However, it is sometimes needed if a trigger event causes the dependent and output event to occur. Examples of the FDEP gate are elaborated in Delic et al. (2015), Boudali et al. (2010), and Merle et al. (2010).

Table 2-2: Fault event symbols

Symbol	Description
	<i>Fault event:</i> Undesired occurrence.
	<i>Basic event:</i> No further development is required because the appropriate limit of the specification has been reached.
	<i>Transfer:</i> The tree is developed further at the occurrence of the corresponding transfer symbol.
	<i>And gate:</i> The output event only occurs if all input events occur.
	<i>Or gate:</i> The output event occurs if one or more input events occur.
	<i>The function dependency (FDEP) gate:</i> In case the trigger event occurs, all dependent events and the output event will occur.

2.3 Decision making

The definition of making a decision is a choice that has consciously been made before fulfilling the relative action (Heijnen and Bots, 2015). The process to find the economic optimal combination of flood damage reduction interventions is, therefore, a derivation process towards a single decision. Decision making is scientifically executed via a decision analysis, whereby a process specified decision problem is substantially solved. According to Keeney (1982), who divided the decision analysis down into the steps shown in Figure 2-3, this is the first step in the process.

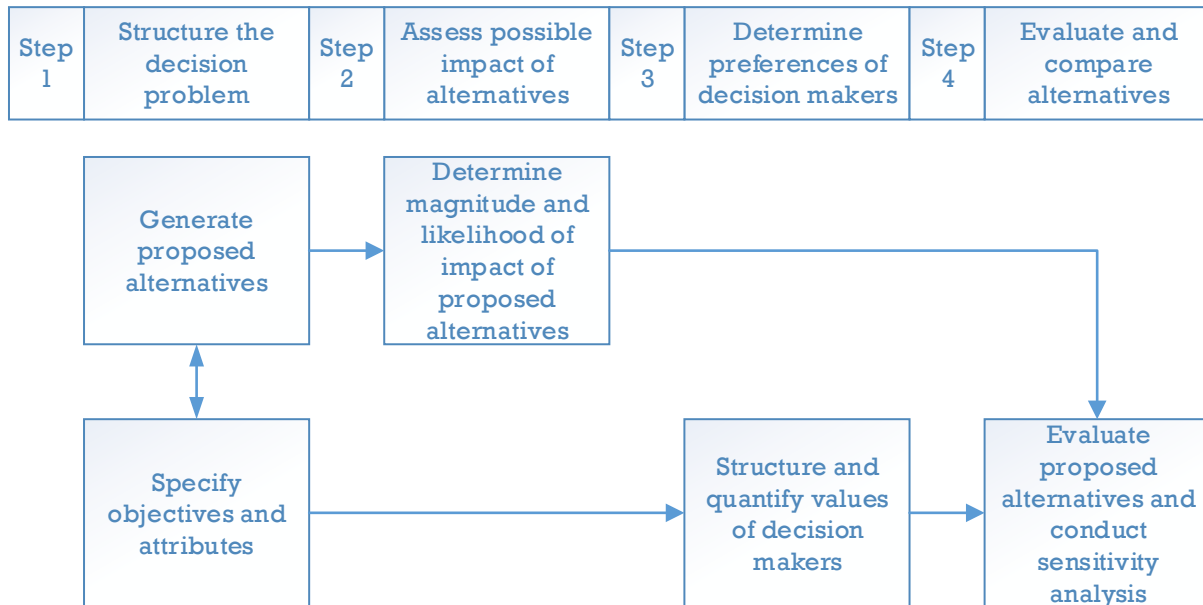


Figure 2-3: Schematic representation of the steps of decision analysis (Keeney, 1982)

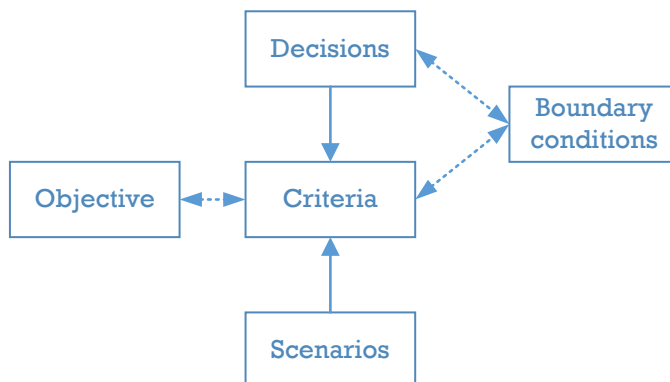


Figure 2-4: Generic conceptual model of a decision problem (Beroggi and Wallace, 1998)

Structuring the decision problem results in a calculation prescription that solves the problem. One way to illustrate the decision problem is via a conceptual model (Figure 2-4), where (1) decision makers have an evaluation function and objective, (2) practices, criteria and scenarios consist of variables, and (3) boundary conditions could influence the decision-making process.

One of the methods to develop a conceptual model into an impact assessment model is a model design cycle. The entire method is divided into six stages, starting by (1) sketching the situation of the decision at stage one. In stage two, the (2) structure of the decision problem will be formed. During stage three the (3) mathematical notation is made. Constructing the (4) computational model with a software tool follows. At stage five, the constructed model will be used to (5) calculate the optimal solution, taking the different scenarios into account. During the last stage, the (6) practical meaning of the outcomes is studied (Heijnen and Bots, 2015).

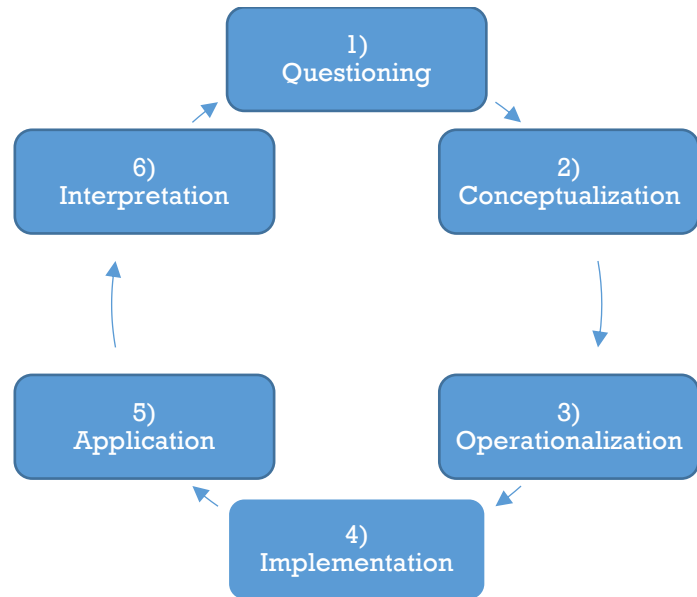


Figure 2-5: Model design cycle (Heijen and Bots, 2015)

2.4 Conclusion

Theories used within this research originate from flood risk management, decision making and asset management. Using only flood risk management theories are not sufficient because spatial planning and disaster management interventions (layer 2 and 3 of MLS) affect not the entire area. These interventions only affect a selected part of overall, an effect that cannot be determined within the flood risk management theories. Therefore, to assess the storm surge impact on selective parts of the area, asset management theories are included, whereby a division between direct and indirect damage (flood risk management) corresponding to damage on assets and capacity losses (asset management) is made. In order to determine the impact of partial interventions, which is the case when layers 2 or 3 are used, the capacity losses need to be related to the partitioning process. The partitioning process in this research is fulfilled by dividing the case in assets. Thereafter fault events are linked to relative assets, which enables us to calculate the indirect damage when partial interventions are applied. Structuring the equations and relating the variables via a model design cycle results in an impact assessment model (Figure 2-6), named MLS-Model in this report.

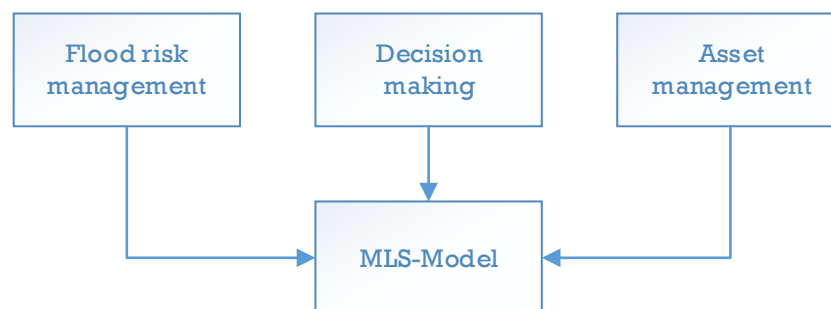
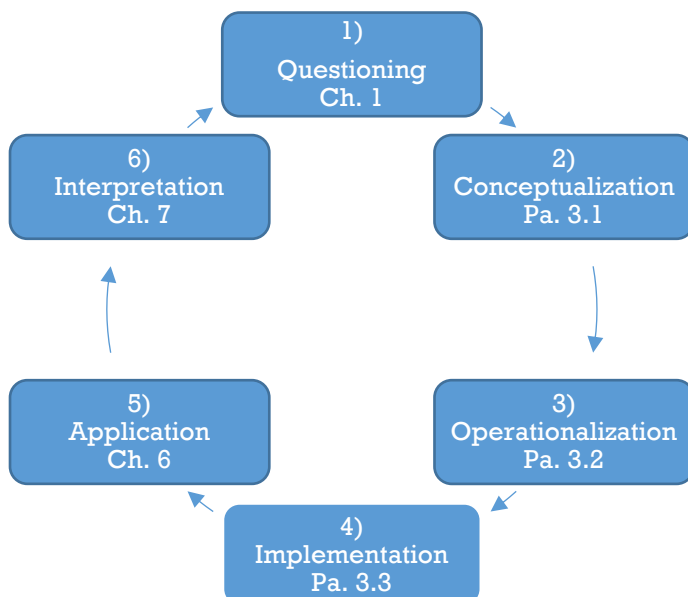


Figure 2-6: Formation of the MLS-Model

3 Methodology



To develop a model that is able to assess the economic impact of storm surges at container terminals the model design cycle is used. In Figure 3-1, the design steps are distributed over the Chapters (Ch.) and Paragraphs (Pa.). The first step of the model design cycle is fulfilled by (1) defining the research questions (Paragraph 1.4), followed by the (2) conceptualization, (3) operationalization and (4) implementation of the model, these steps are described in this Chapter. The last two steps, (5) application and (6) interpretation will be elaborated in the Chapters 6 and 7.

Figure 3-1: Model design cycle distributed over the Chapters

3.1 Conceptualization

Based on Beroggi and Wallace (1998) the research questions are transformed into a conceptual model as visualized in Figure 3-2. Due to future storm surges an economic damage will occur at the container terminal. The storm surges consist of a broad scope of scenarios expressed via inundation heights and relative probabilities. To reduce the resulting damage, the impact of different intervention options needs to be determined in order to make the right decision. Integrating the cause (storm surges) and solution (intervention options) leads to a damage reduction coupled with a needed investment to realize the intervention, whereby the objective is to maximize the damage reduction coupled with a minimal investment, which is equal to maximize the cost-benefit. One of the two criteria contains an identical, which enables the MLS-Model to compare the impact of interventions from different layers and determine their integrated impact. To not blindly simulate every intervention option, the damage reduction needs to be at least equal to the investment. A crucial boundary condition is that interventions will only affect the case area, to create a feasible simulation process.

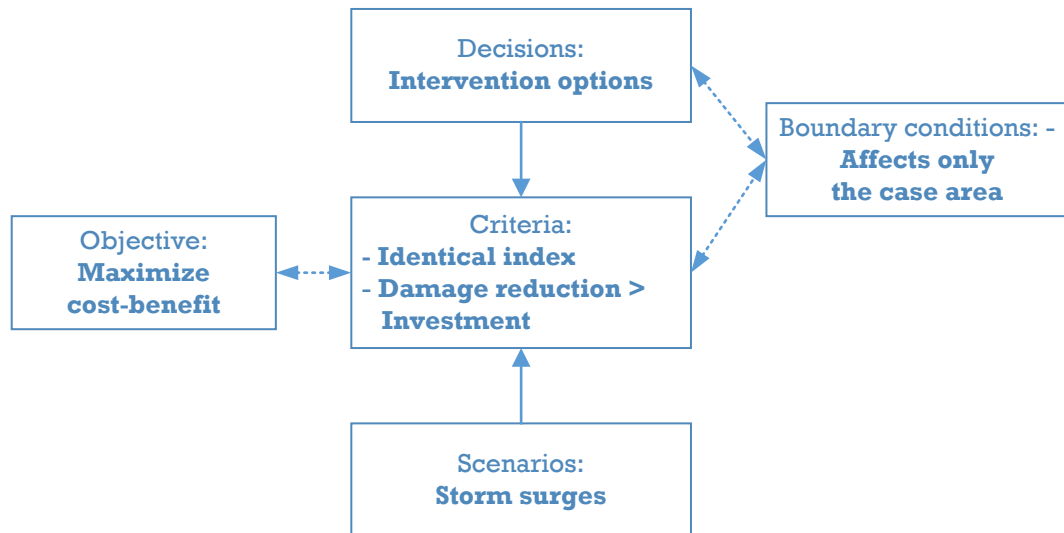


Figure 3-2: Conceptual MLS-Model

3.2 Operationalization

The operationalization of the conceptual model is realized by transforming the established relationships to variables (Paragraph 2.3), whereby the index and equations of these variables are established during this process. The purpose of the MLS-Model is to indicate the flood risk of a container terminal, calculate the resulting economic impact, and simulate the potential of the solutions (Paragraph 1.3). In this report, the flood risk of assets and fault events (Paragraph 2.2) will be assessed within a case-study. Direct damage (repair costs) on each asset and indirect damage (revenue losses) on each fault event need to be determined to establish the impact of flooding. In order to reduce the risk and impact of flooding, simulations are made to predict the potential of multiple solutions (Paragraph 2.4). The results of these simulations are compared to advise which combination of solutions is optimal to apply. Therefore, the MLS-Model could be divided into three phases (as shown in Figure 3-3), where the blue colored box means that data needs to be implemented and the white boxes are simulation outcomes. This distinction in blue (data) and white (simulation) colors is used throughout the whole Chapter.

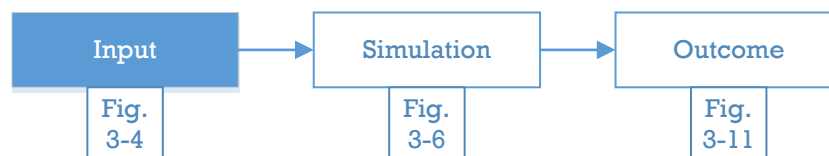


Figure 3-3: Operationalization sections

3.2.1 Input

In the first phase of the MLS-Model, different data is needed in order to be able to execute the simulations. A visualization of this phase is shown in Figure 3-4, where the used equations to calculate the relative variable are indicated by “eq”. The needed input data is divided into three categories:

- Storm surges
- Values
- Factors

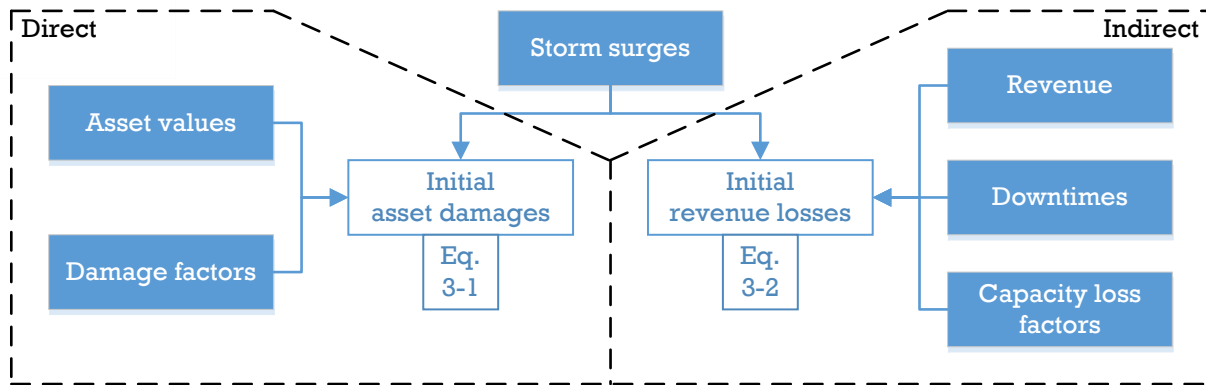


Figure 3-4: Operational MLS-Model input section

Storm surges

Due to the fact that the case is situated in a bay, the waves are minimized, causing the estimation that the height of the *storm surges* is decisive (as established in Paragraph 1.3). A storm surge is an abnormal rise of water generated by a storm, measured in the difference between the regular water tide and the storm tide. Via occurred storm surges in the past, a forecast could be made which storm surges are possible to occur and what the probability of occurrence is. An illustration is given in Figure 3-5, showing the inundation height of a storm that occurs once a year, once every two years, and so in. Leading to a set of data, whereas the magnitude of the storm increases, the relative inundation height becomes higher, the probability reduces, and return period rises.

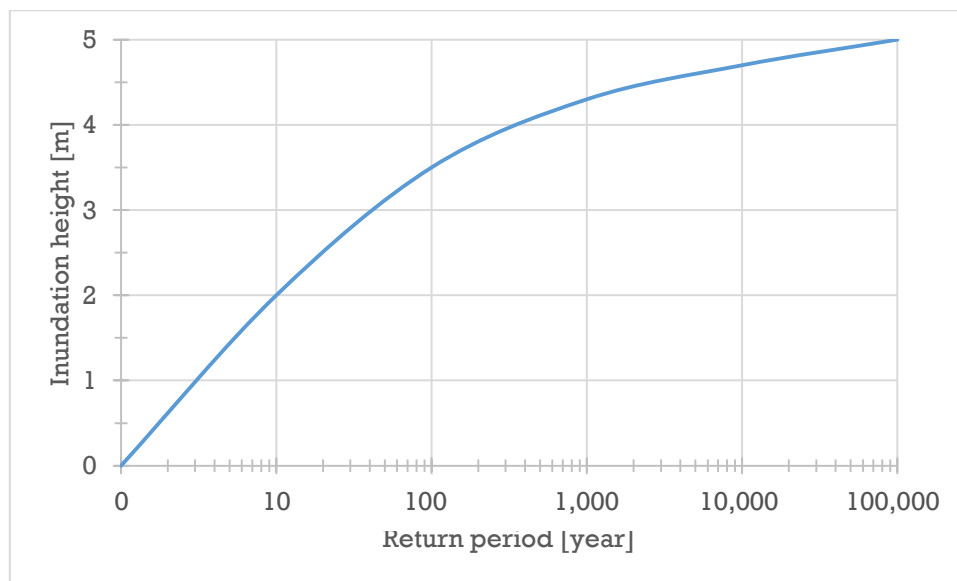


Figure 3-5: Inundation height per return period illustration example

Values

On the direct side of the input section, the values consist of the variable asset values, where the indirect side are the variable downtimes. Assets or groups of assets could consist of several components, where the summation of values of these different components results in the total asset value expressed in dollars. Downtimes of fault events are expressed in months and stand for the period a certain fault event lasts. Another value that needs to be known is the revenue, expressed in dollars, this enables the application to calculate the revenue loss through occurring fault events.

Factors

The inputs of factors are relative to a specific inundation height. This means that larger storm surges lead to larger the impacts, which corresponds to larger damage- or capacity loss factors. By graphing different inundation heights and their relative factor, a function is realized as illustrated in Figure 2-2. The illustration example shows a damage function to determine the direct damage, a principle that could also be used to determine the indirect damage via a capacity loss function.

3.2.2 Simulation

The second phase consist of the calculation simulations (Figure 3-6), which form the link between the input data and the outcome. Hereby a distinction between the direct and indirect damage shall be made. Both will follow the same steps to calculate the total damage, consisting of:

- Initial
- Annual
- Concession
- Total

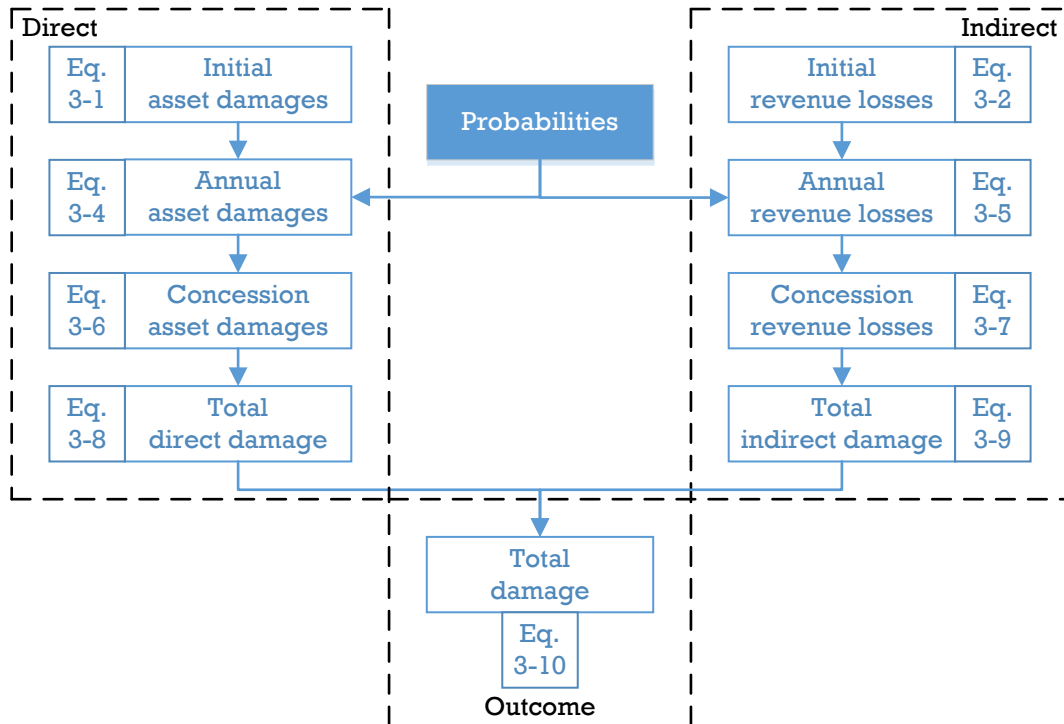


Figure 3-6: Operational MLS-Model simulations section

Initial

With the input data, the initial asset damage and revenue losses could be calculated. In this step, the probability of a storm is excluded. The initial asset damage is the occurring damage in case a particular storm occurs. The initial asset damage of a particular storm could be calculated by multiplying the asset value with the damage factor (Equation 3-1). An illustration of one specific storm, with a relative return period of 1,000 years is shown in Figure 3-7.



Figure 3-7: Storm asset damage illustration example

$$D_{a;y;RP} = V_a * f_a(D_{y;RL})$$

Equation 3-1: Initial asset damage

$D_{a;y;RP}$	[\$]	Asset damage for one storm
V_a	[\$]	Asset value
$f_a(D_{y;RL})$	[-]	Asset damage factor for one storm

Calculating the initial revenue loss is more complex because each storm could lead to the failure of several events. Not to forget the interaction between the different fault events. Therefore, the MLS-Model needs to be able to determine all capacity loss factors for each fault event and the effect on the interactions between them. This is realized in finding the highest capacity loss factor. In case the system is entirely out of order the capacity factor will be 1.0, as is the case in this example to illustrate the functioning. Next, the MLS-Model must be able to detect the second highest capacity loss factor, in case the downtime is higher than the downtime of the highest capacity loss factor, to establish for what time the system is partly not functioning. In case the downtime is lower than the downtime of the highest capacity loss factor, this fault event does not influence the total revenue loss, due to the fault event will be repaired and fully operational before the fault event with the highest factor is back online. These steps need to be executed for each fault event to calculate the total capacity loss and corresponding downtime. The impact of fault event triggers and the interrelationships between the fault events must not be forgotten. A trigger that stays inactivated can prevent an upper fault event from occurring, something that counts also for the other way around. This can be determined by using a fault tree (Paragraph 2.2). An example of this process is illustrated in Figure 3-8, to show the functioning. The highest capacity loss (factor 1) fault event has a relatively short downtime, followed by relatively longer downtimes of the second (factor 0.6) and third (factor 0.3) highest capacity losses. From this example could be concluded that the system is fully offline in the beginning, after which the capacity loss drops and a part of the container terminal become operational. By multiplying the revenue with the fault event downtimes and the capacity loss factors the resulting initial revenue loss caused by a particular storm is calculated (Equation 3-2).

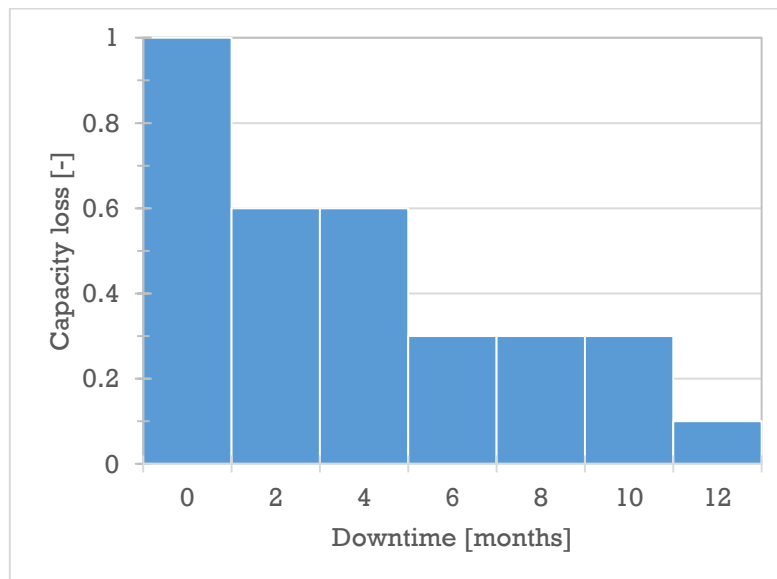


Figure 3-8: Storm revenue loss capacity illustration example

$$RL_{y;RP} = R_y * \sum_{DT=0}^{DT_{max}} MAX(f_{fe}(CL_{y;RP})) * DT_{fe}$$

Equation 3-2: Initial revenue loss

$RL_{y;RP}$	[\$]	Revenue loss for one storm
DT	[month]	Downtime
DT_{max}	[month]	Maximum downtime
R_y	[\$/month]	Monthly revenue for one year
$f_{fe}(CL_{y;RP})$	[factor]	Fault event capacity loss factor one storm
DT_{fe}	[month]	Fault event downtime

Annual

By calculating the damage on assets of all particular storms that occur during a specific a year, and interact this with the probabilities these storms occur, the expected asset damage through that storm in the selected year is determined. By summing the expected damage of all possible storms the expected annual asset damage could be calculated (Equation 3-3). The same counts for the revenue loss (Equation 3-4). This principle is visualized in Figure 3-9, where the multiplication between the initial flood damage is shown through the blue colored column parts.

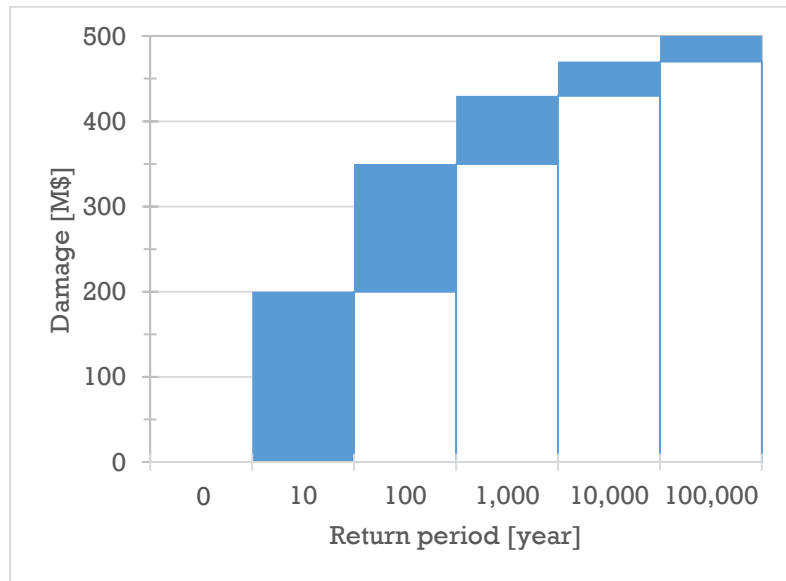


Figure 3-9: Annual asset damage or revenue loss illustration example

$$EAD_{a;y} = (1 + g)^y * \left(\frac{1}{1 + \delta} \right)^y * \sum_{RP=1}^{\infty} \frac{D_{a;y;RP-1} + D_{a;y;RP}}{2} * \Delta P_{RP}$$

Equation 3-3: Annual asset damage

$EAD_{a;y}$	[\$]	Expected annual asset damage
g	[-]	Growth rate
δ	[-]	Discount rate

$$ARL_y = (1 + g)^t * \left(\frac{1}{1 + \delta} \right)^t * \sum_{RP=1}^{\infty} \frac{RL_{y;RP-1} + RL_{y;RP}}{2} * \Delta P_{RP}$$

Equation 3-4: Annual revenue loss

$EARL_y$	[\$]	Expected annual revenue loss
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Concession

Executing the annual calculations for every year in the concession period and summing these results leads to the total concession damage.

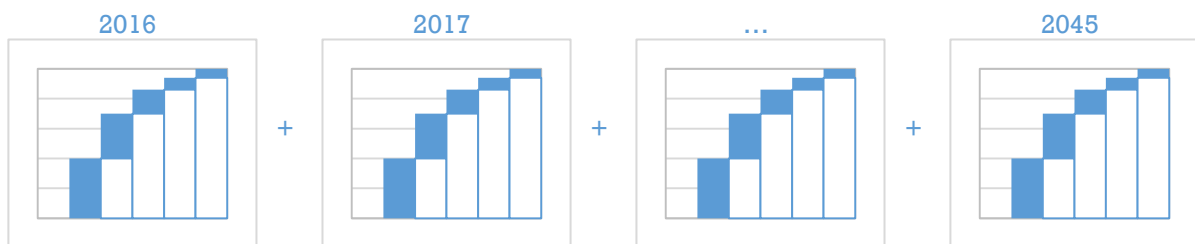


Figure 3-10: Concession asset damage or revenue loss illustration example

$$D_a = \sum_{y=2016}^{2045} AD_{a;y}$$

Equation 3-5: Concession asset damage

D_a [\$] Asset damage over the concession period

$$RL = \sum_{y=2016}^{2045} ARL_y$$

Equation 3-6: Concession revenue loss

RL [\$] Revenue loss over the concession period

Total

When the concession damage of all assets is determined, the summation of this damage leads to the total direct damage (Equation 3-7). The total indirect damage is already found as earlier explained in this Paragraph. Therefore, the revenue loss over the concession period is equal to the total indirect damage (Equation 3-8). When summing the total direct and indirect damage, the total damage is found (Equation 3-9).

$$D_d = \sum_{a=1}^{all} D_a$$

Equation 3-7: Total direct damage

D_d [\$] Total direct damage

$$D_i = RL$$

Equation 3-8: Total indirect damage

D_i [\$] Total indirect damage

$$D_t = D_d + D_i$$

Equation 3-9: Total damage

D_t [\$] Total damage

3.2.3 Outcome

In the third and last phase of the MLS-Model the outcomes originating from the simulations will be established (Figure 3-11). They are divided in an outcome and intervention section if integrated will lead to the impact of interventions on the system and corresponding CBA. All-embracing, the steps are as follows:

- 0-situation
- Interventions
- Cost-benefit analysis

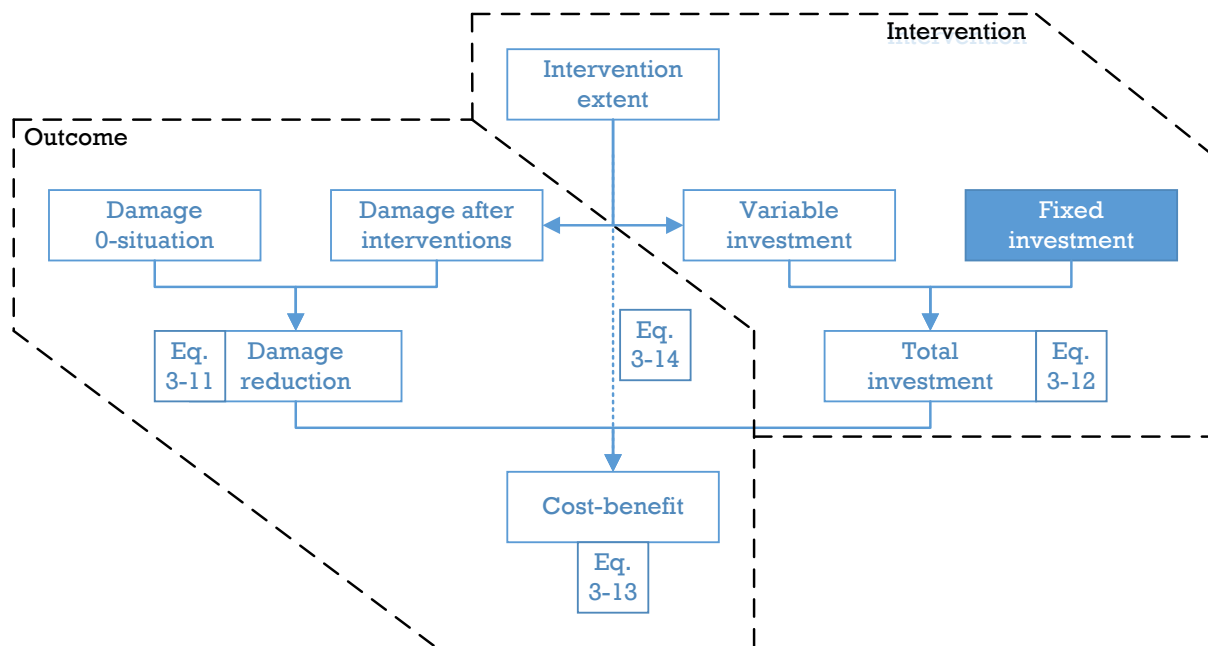


Figure 3-11: Operational MLS-Model outcomes section

0-situation

In case no interventions were added to the system, the expected total damage on the 0-situation is simulated through the MLS-Model (Equation 3-9). This outcome shall comprise the expected total damage throughout the entire concession period when the expected storm surges will occur. The expected storm surges are equal to the storm surges that will averagely occur.

Interventions

When interventions were added to the system, the expected total damage after interventions will be simulated via the MLS-Model. By adding interventions, the input data will adjust according to the statistics of the interventions (e.g. if a certain asset is protected to a certain height, small storm surges will not result in initial asset damage, whereby the annual, concession and total asset damage curve will change). Leading to a reduced expected damage compared to the 0-situation. The difference in damage between the 0-situation and the situation after interventions corresponds to the realized damage reduction (Equation 3-10).

$$D_r = D_0 - D_{ai}$$

Equation 3-10: Damage reduction

D_r	[\$]	Damage reduction
D_0	[\$]	Total damage at 0-situation
D_{ai}	[\$]	Total damage after intervention

The other side of the bracket contains the investments (Figure 3-11) needed to make the interventions possible. The investments are divided in a fixed and a variable cost price, summing both leads to the total intervention investment (Equation 3-11). The fixed cost price does not depend on the extent of the intervention, whereas the variable investment does (e.g. when the cost of removing pavement in order to increase the surface level will not change (fixed), where the sand needed for the increase relies fully on the height of the new surface level (variable)).

$$I_t = I_f + I_v$$

Equation 3-11: Intervention investment

I_t	[\$]	Total intervention investment
I_f	[\$]	Fixed intervention investment
I_v	[\$]	Variable intervention investment

Cost-benefit analysis

The final outcome of the simulations is the damage reduction integrated with the investment (Equation 3-12). An optimization is possible within this interaction because both elements (damage reduction and investment) do rely on the simulated extent of interventions. In general, the larger the extent, the more damage reduction, the higher the investment. Thereby, the most cost-beneficial intervention extent directly leads to the maximum CBA (Equation 3-13). An important final step in optimizing the CBA and relative interventions extent.

$$B = D_r - I_t$$

Equation 3-12: Cost-benefit

B [\$] Cost-benefit

$$\text{MAX}(B) = B_{mbp}$$

Equation 3-13: Maximum cost-benefit

B_{mbp} [\$] Most cost-beneficial intervention extent

3.3 Implementation

Now the operational model is established, the right software needs to be chosen to create the impact assessment model. In this research, excel is used to implement the operationalized model. In order to fulfill this process, the operational model is transformed into 65 excel sheets. The excel sheets are divided into the following groups:

- Data sheets (7)
- Direct damage sheets (17)
- Indirect damage sheets (17)
- Intervention sheets (23)
- Optimization sheet (1)

Structuring the sheets in excel realizes the following Figure 3-12. The data sheets, containing the needed variables to fulfill the simulations, lead to the direct and indirect damage sheets. By using the damage sheets, the 0-situation can be calculated showing the economic damage at the container terminal when no interventions are applied. The economic damage is realized through the expected storm surges throughout the concession period. Implementing the intervention sheets within the calculation process enables the opportunity to assess the impact of interventions. Optimizing the intervention extent via the optimization sheet results in the most cost-beneficial way to apply the intervention. By repeating this process, the impact on the economic damage of several different intervention options can be calculated. In the end, the most cost-beneficial intervention application is found by comparing the different outcomes with each other. An extended description of the excel sheets is elaborated in Appendix A.

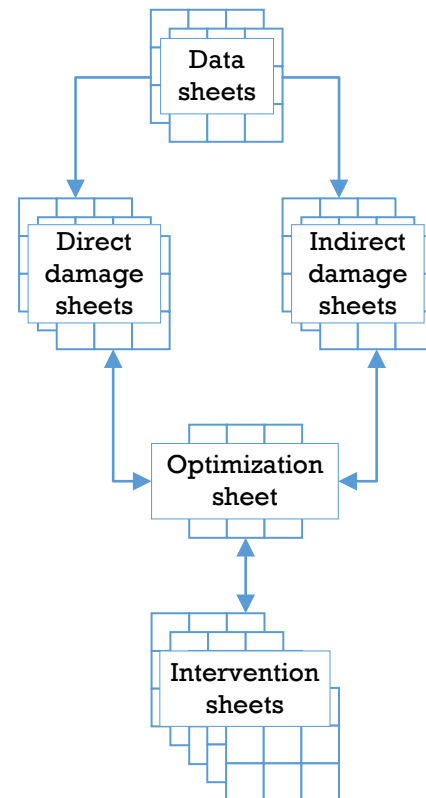


Figure 3-12: Implemented MLS-Model

3.4 Conclusion

Combining the sections input, simulation and outcome lead to the operationalization of the entire MLS-Model (Figure 3-13), where the additional added green lines illustrate the influence of the flood interventions. The selected interventions, applied to a certain extent, can have a positive impact on the input damage factors, downtimes and capacity loss factors, due to these impacts, the expected damage of the improved situation is be reduced. On the other hand, the investment costs needed to realize the interventions are also affected by the application of interventions. Selecting the right interventions and applying them in the right extent will maximize the cost-benefit. Via this structure of variables and equations, the MLS-Model is able to assess the impact of MLS.

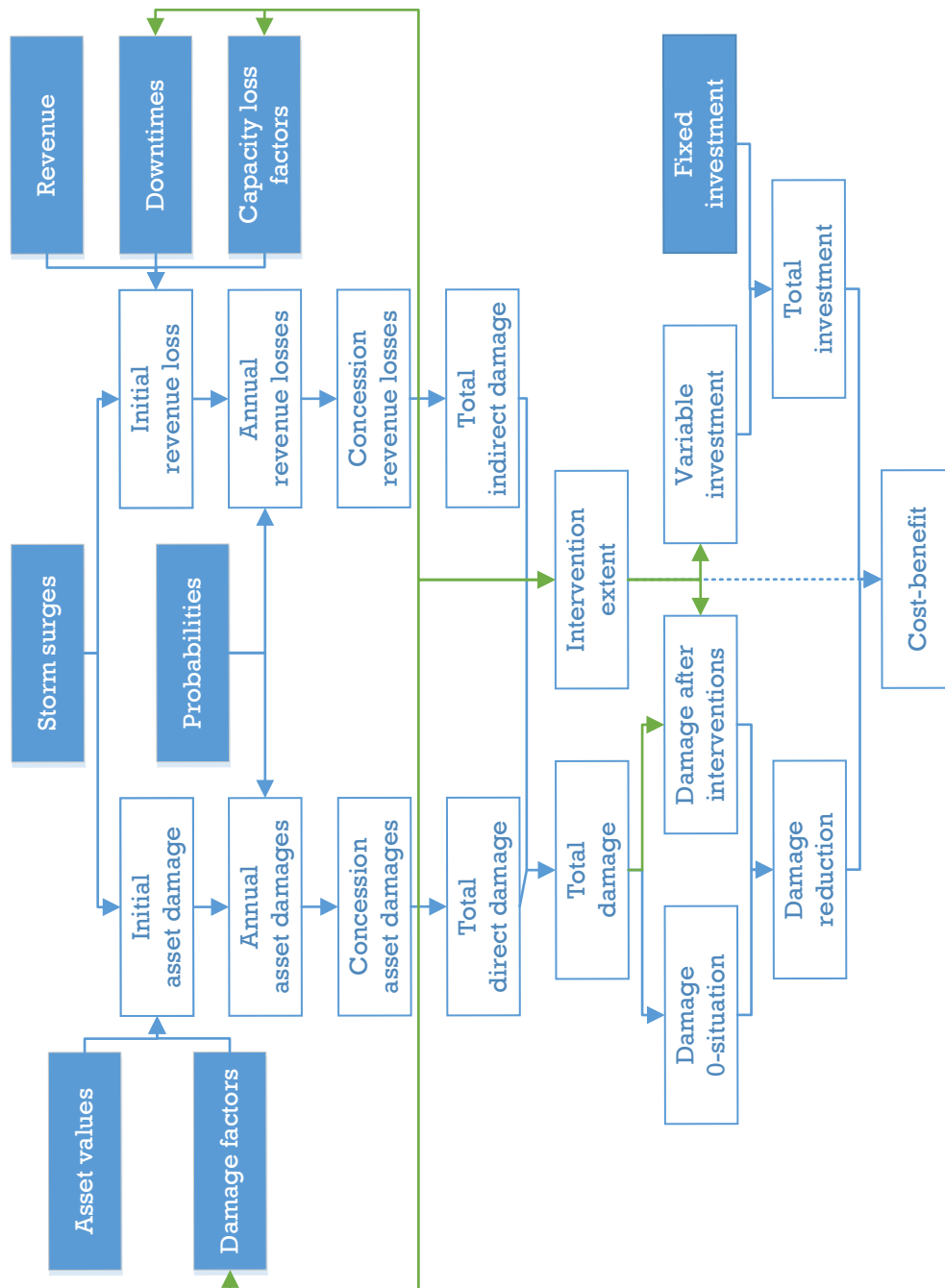


Figure 3-13: Operational MLS-Model

4 Case

4.1 Location

On the coast of the Caribbean is the selected case located (Figure 4-1). The Caribbean area is known for its hurricanes and, the resulting, everlasting flood threat. Especially on the coastline, where big storm surges sporadic occur. On such a flood threat location is the case studied in this report located, limited protected against waves in a sizeable harbor bay (Figure 4-2). For confidentiality reasons the exact location shall not be mentioned, and will the drawings and images relative to the case be altered. However, the drawings and images look similar to the case and give a good impression of the actual situation.



Figure 4-1: The Caribbean marked on a world map

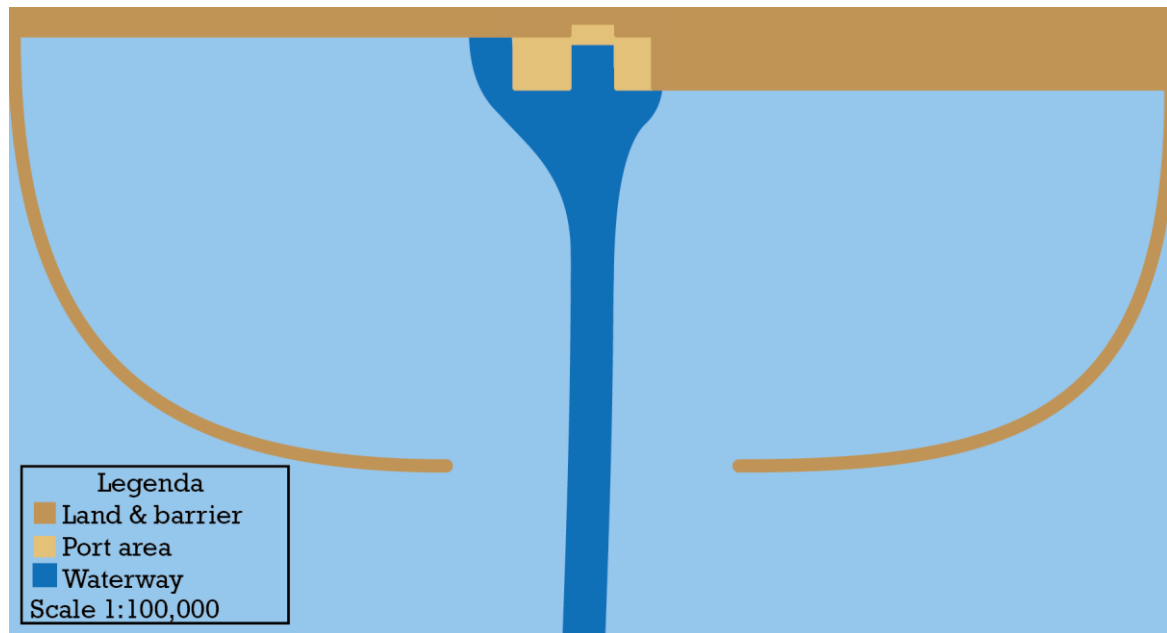


Figure 4-2: Impression bay area (Kelderman, 2016)

4.2 Accessibility

When a major storm hits the container terminal and surrounded area, resulting in a disaster from which the area can hardly recover, due to the inaccessibility of the area. In these circumstances, ports and transport infrastructure are considered critical infrastructure for the survival of the population (Arcadis, 2016). This means that the government aims to get points, which could receive or distribute relief supplies (i.e. the case-study container terminal), quickly back online and accessible. The selected case is a container terminal, with an average surface height of +2,4 m MSL. From the entrance of the harbor bay until the terminal docks is a *waterway* realized (Figure 4-2). In this section, the bay is deeper dredged (until at least 18 meters) than the rest of the harbor bay allowing large container vessels to reach the terminal. The actual depth of the waterway is regularly checked by a harbor owned survey vessel to scout the sedimentation accretion. In case accretion of sedimentation takes place until such an amount that the waterway needs to be dredged, a dredging vessel must be hired to solve this problem. A storm surge is an example of a cause than can result in accretion. The municipality is responsible for hiring a dredging vessel. If it takes too long before the municipality restores the depth of the waterway, the terminal has the opportunity to hire a dredging company and claim the bill at the municipality. In order to know until what waterway depth the terminal stays accessible, the attaining container vessels need to be mapped. Knowing their scantling depth allows us to calculate the moment dredging is needed. An overview of the active vessels in the container transport industry is shown in Figure 4-3, where the vessels Panamax up until new Panamax (types B1, B2, C and D) attaining the case terminal. Figure 4-4 shows the capacity expressed in thousands TEU and frequencies per week of these vessels. The 20-foot container referred to as a twenty-foot equivalent unit (TEU), became the standard reference in the container industry to indicate the cargo volume and vessel capacity (World Shipping Council, 2016). Apart from 20-foot (6.09 m) containers, the container terminal stacks another commonly used 40-foot (12.18 m) container.

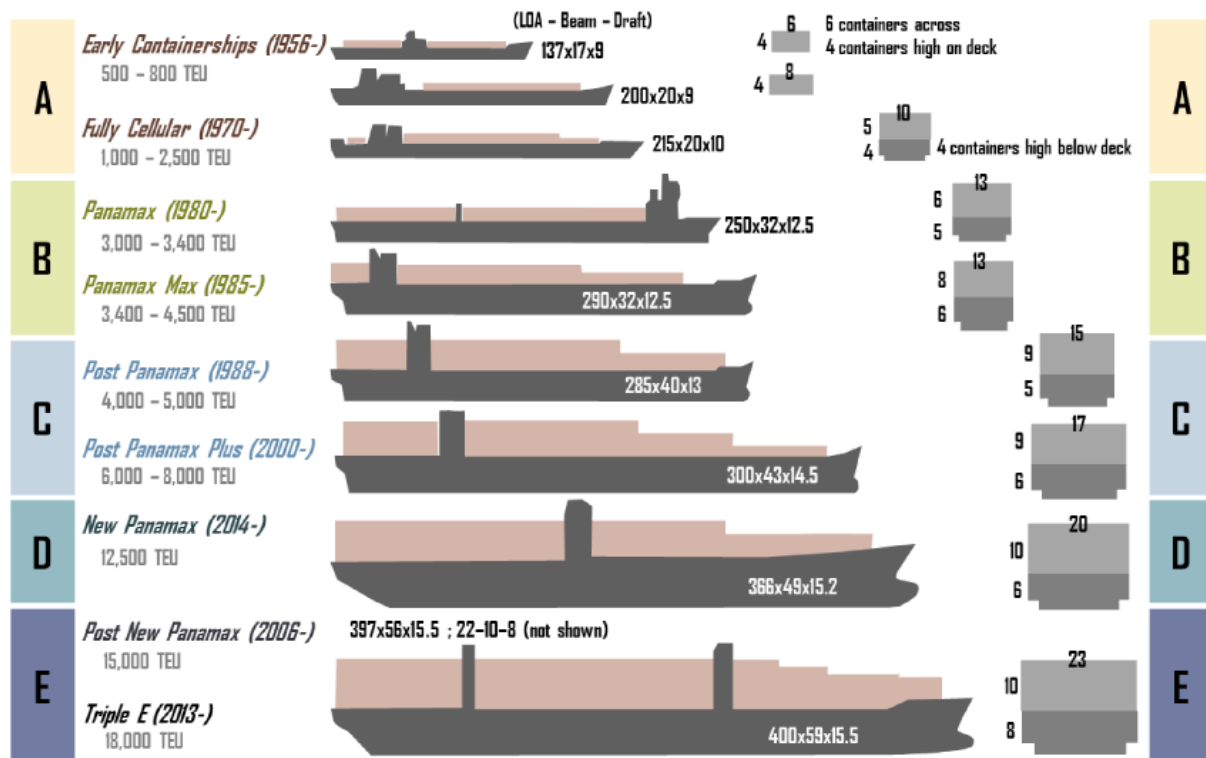


Figure 4-3: Container vessels (Martín Soberón, 2012)

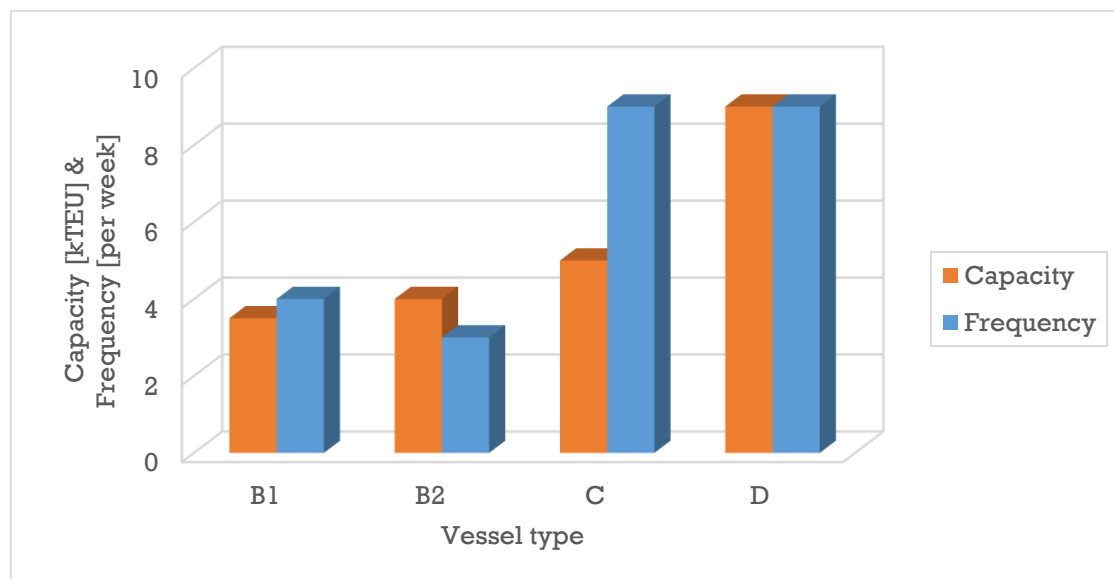


Figure 4-4: Vessel sizes and frequencies (based on Confidential, 2016a)

Another transportation method is via land, where an access road is used to attain the terminal. The access road is a hurricane proof asphalted highway with several lanes that form the connection between the terminal and road network of the country (Confidential, 2016a). Via the exit gate (arrow pointed away from the terminal) of the terminal the access road could be reached, whereas the entrance gate (arrow pointed into the terminal) serves the other direction, as could be seen in Figure 4-12. As a transshipment hub, the main function of the port is to transship containers from one vessel to the other, whereby the containers most of the time will be temporarily stored on the terminal. Only 11% of the containers are imported and exported by land via the access road by trucks, as could be seen in Figure 4-5, where the yearly container traffic is divided by container type (Confidential, 2016a).

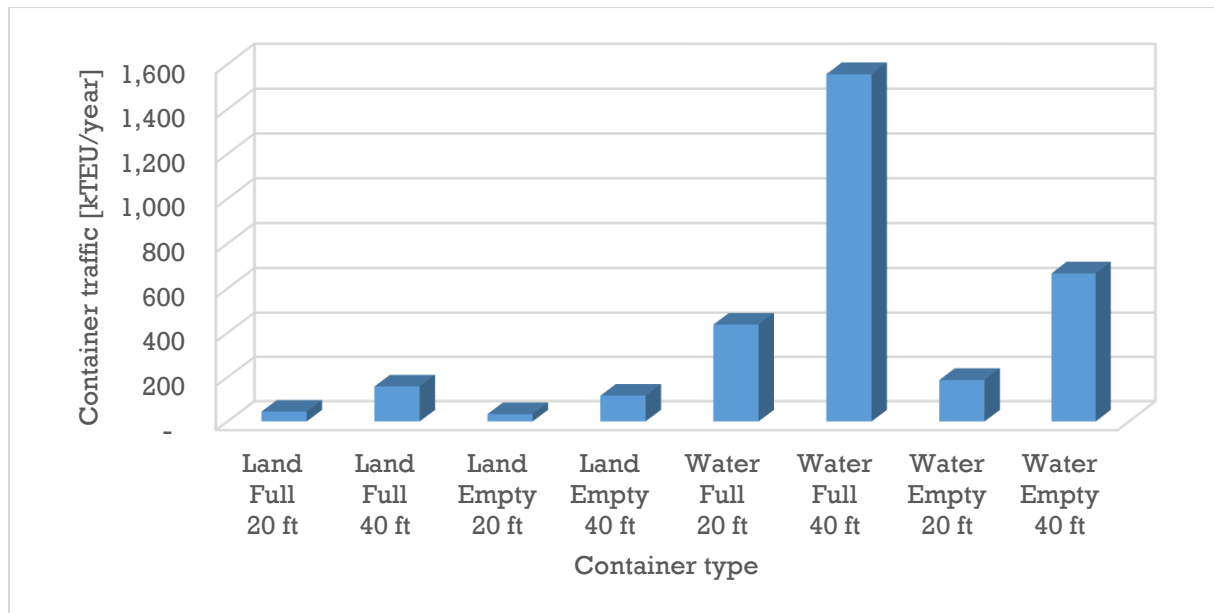


Figure 4-5: Container traffic (based on Confidential, 2016a)

4.3 Process and assets

As could be viewed in Figure 4-12, the container terminal is divided into three sections: Terminal A, B and C. Both terminal A and B have a single dock of 500 meters, where terminal C consists of a double dock. The docks are *quay walls* (Figure 4-6), which are based on a heavy foundation. On top of the quay walls, the containers cranes move sideways via a crane rails. *Revetment* (Figure 4-7) is placed on places that are attached to the water and no quay wall is situated. To enter the container terminal, men has to pass the entrance building.

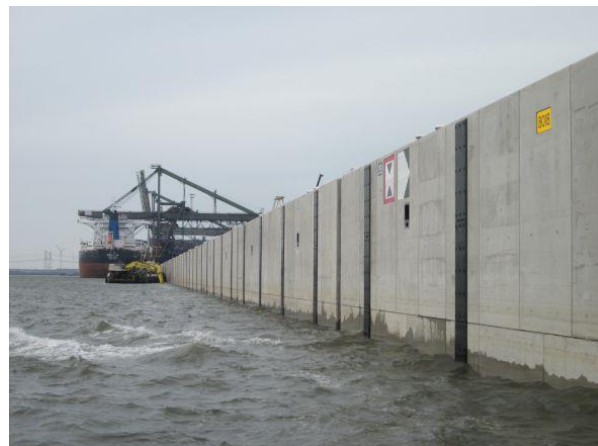


Figure 4-6: Impression quay walls (Volker Stevin, 2016)



Figure 4-7: Impression revetment (Cummins and Cederberg, 2016)

Closely behind the entrance building is the operation building (Figure 4-8) situated, where the controlling process via the terminal operating system (TOS) takes place. The TOS is to assist in managing the container terminal and keep track of the flow of containers throughout the terminal (The Tioga Group et al., 2012). Data of the TOS is saved on the data server located in the operation building, in addition, there is a *backup data server* located uphill away from the flooding threat, which is daily updated in case the data server on the terminal will fail.



Figure 4-8: Impression operation building (South Africa, 2016)

Apart from the entrance and operation building, there are several other buildings situated in the *control area* (e.g. the conference building, to hold meetings, or the roofed space, serving shelter when it rains, for having a meal or take a break). The *maintenance area* consists of a maintenance hangar (Figure 4-9 and Figure 4-10), a terminal fuel facility



Figure 4-9: Impression maintenance hangar outside (Congo Terminal, 2016)

(Figure 4-11), and several warehouses, used as storage buildings. In the hangar is the flexible equipment (straddle carriers, reach stackers and terminal trucks) maintained. The terminal *fuel facility* provides the fuel for the fuel needed assets, as the flexible equipment and generators. Closely located near the petrol station the fuel is stored in two silos.



Figure 4-10: Impression maintenance hangar inside (Briggeman, 2016)



Figure 4-11: Impression terminal fuel facility (Kosan Crisplant, 2016)

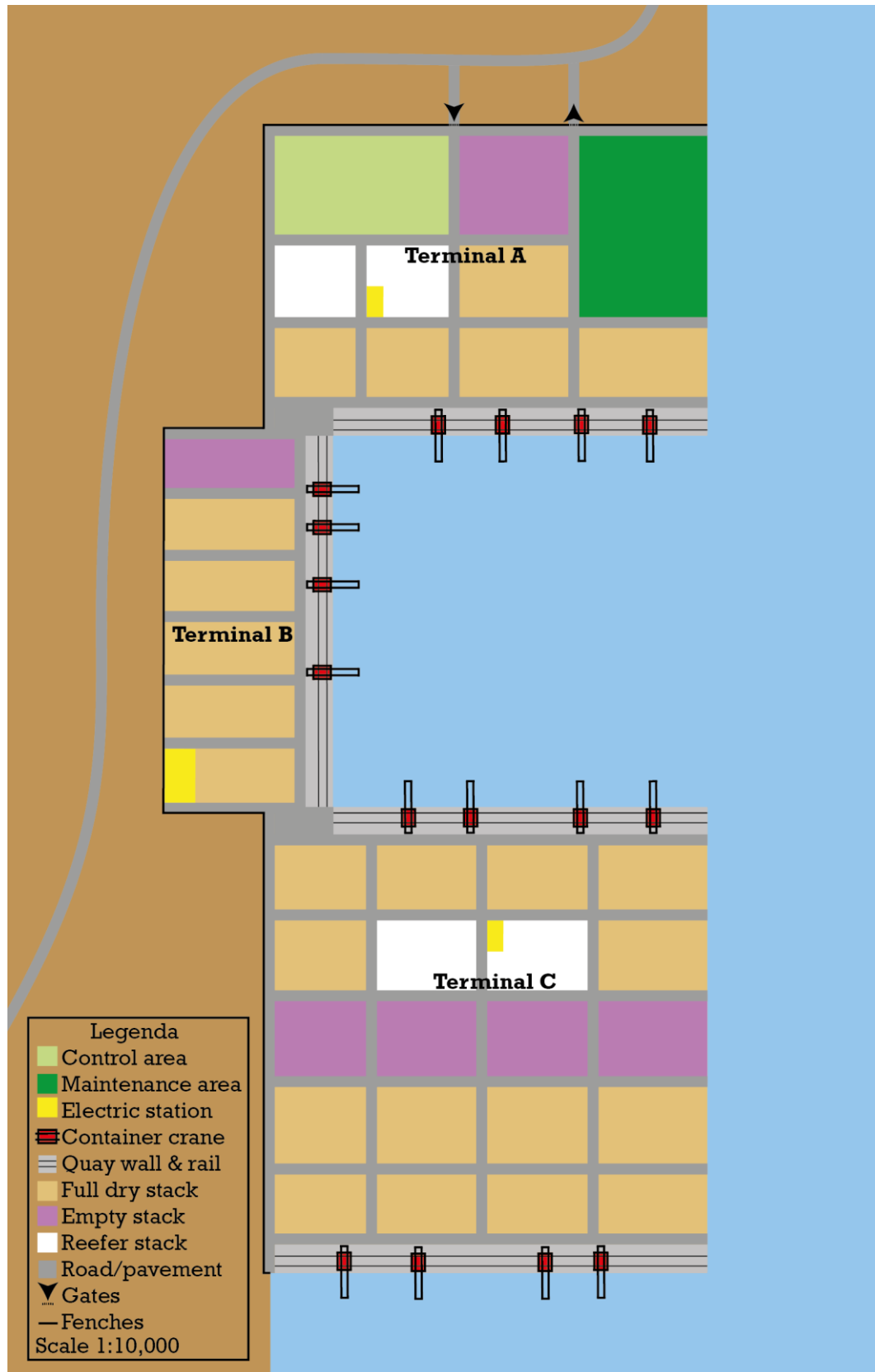


Figure 4-12: Impression container terminal overview (Kelderman, 2016)

Via two *external power stations* the container terminal receives electricity, meaning that in case one of them gets out of order the terminal is able to stay operational. From the power stations, electricity lines are attached to electric poles and come together in the *electric mainstation* (Figure 4-13) of the container terminal. From there the electricity is divided throughout the container terminal via electric cables and *electric substations* (Figure 4-14). Numerous electric cables and data wiring are situated under the *pavement* (Figure 4-15), to facilitate power to electric assets, as container cranes, reefers and the TOS.



Figure 4-13: Impression electric mainstation (CameliaTWU, 2008)



Figure 4-14: Impression electric substation (Smest, 2016)



Figure 4-15: Impression pavements (QES, 2016)



Figure 4-16: Impression generator (Dutch power generators, 2016)

There are two electric substations on container terminal, located at Terminal A and C (Figure 4-12). Meaning that terminal B is electrically facilitated by the mainstation and the remaining areas via the substations. In addition, the port has several diesel *generators* (Figure 4-16) spread over the terminal, in case the general electric supply fails the generators can be used as backup power. However, there is a limit the power a generator can deliver. Certain assets simply need too much electricity, as is, i.e., the case with container cranes. As an extra backup for the main data server an uninterruptible power supply (UPS) is situated in the control area.



Figure 4-17: Impression reefers (Alconet, 2016)



Figure 4-18: Impression empty container stack (Safety4sea, 2016)

A shipping container is a single rigid, sealed, reusable metal box in which merchandise is shipped by vessel (Hinkelman, 2005). Apart from the container size, 20 or 40 foot, a distinction could be made between full and empty containers. Another division is the dry and refrigerated containers. The reefer (Figure 4-17) is a controlled temperature refrigerated shipping container (Hinkelman, 2005). While containing cargo, the reefer needs to be connected to electricity at all times. This is because the reefer contains cargo, where refrigeration is essential, the most common cargo of reefers consist of bananas, citrus, deciduous, exotics, fish and seafood, meat and poultry, and dairy (Dekker, 2014). Therefore, the reefers stacks are situated close to the electric facilities (Figure 4-2). Without cargo, the reefers will be, like dry



Figure 4-19: Impression full dry container stack (Bloomberg, 2012)

containers, stacked closely to each other on the *empty stacks* (Figure 4-18). The third stack type, which covers the most area of the container terminal, are the *full dry containers* (Figure 4-19). How many ground slots are available per stack, expressed in thousands 20 ft. containers are shown in Table 4-1. The average stack height throughout the terminal is one and a half container for the full stacks and four containers for the empty stack. A division in dwell times between the full and empty containers is shown in Figure 4-20. Hereby a distinction between the land and water transportation is made.

Table 4-1: Container ground slots (Confidential, 2016a)

Terminal	Stack [kTEU GS]			Total
	Full Dry	Empty	Reefer	
Terminal A	2.8	1.1	0.4	4.3
Terminal B	2.7	0.8	-	3.5
Terminal C	6.6	3.6	0.5	10.8
Total	12.2	5.4	0.9	18.5

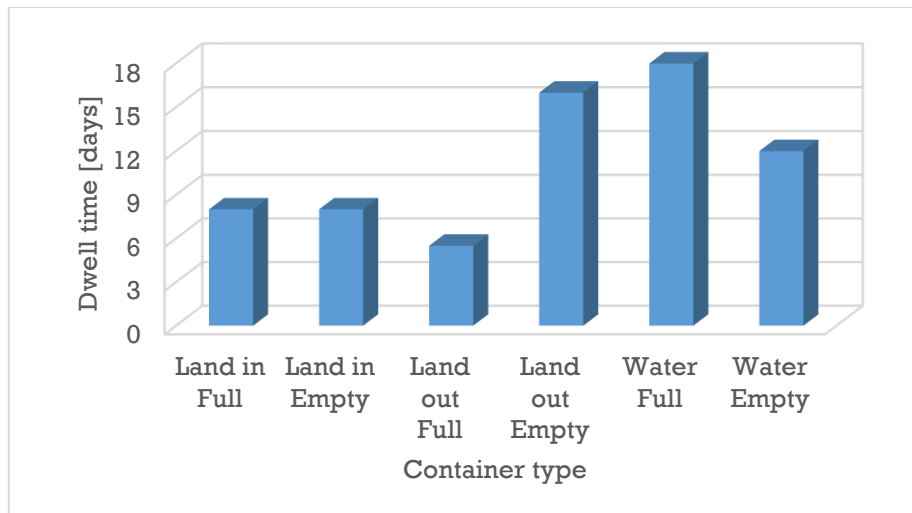


Figure 4-20: Container dwell times (based on Confidential, 2016a)

The general process that takes place on the terminal is the transshipment of containers (Figure 4-21). This process starts when a container vessel, with or without cargo, arrives in the container terminal and docks on one of the berths. In the container terminal four container cranes (Figure 4-22), on each berth, stand ready to load or unload the vessel. In the case of unloading, each container will be lifted by one of the cranes and moved from the vessel to the quay.

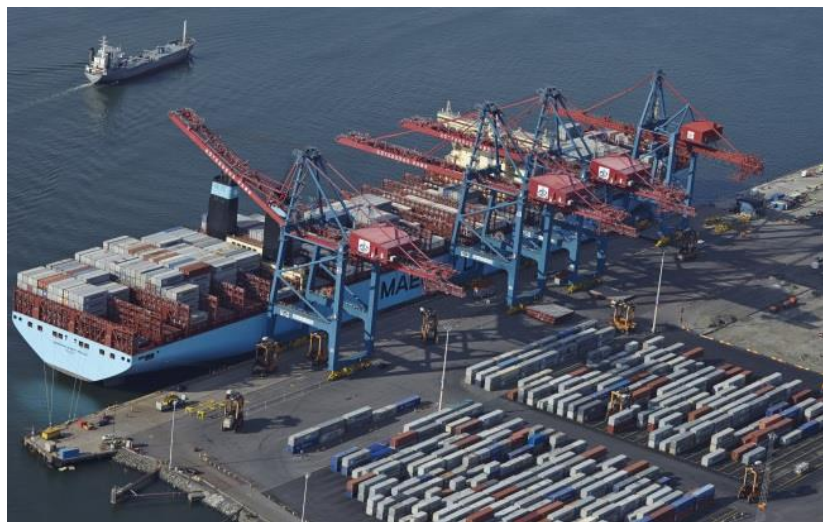


Figure 4-21: Impression container transshipment process (My news desk, 2016)

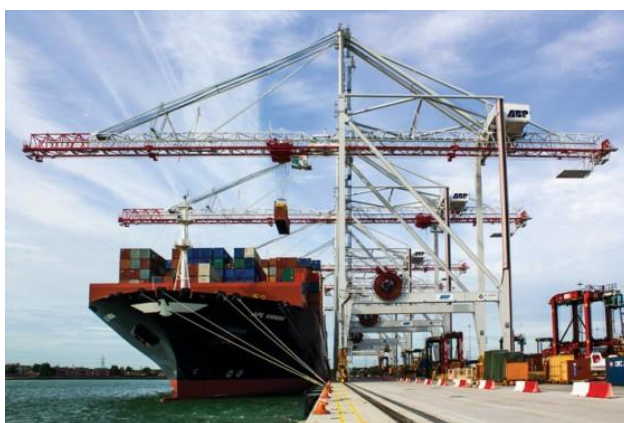


Figure 4-22: Impression container cranes (Liebherr, 2016)

When the vessels are loaded, the movement takes place in the opposite direction. Continuing with the description of the unloading process, *straddle carriers* (Figure 4-23) transfer the containers from the berth to the terminal. This can mean that the containers are directly transported to the stack area or, in case terminal trucks are involved, to a dropping point. The faster *terminal trucks* (Figure 4-25) with multi-trailers are used to deal with longer distances throughout the container terminal. These terminal trucks transport several containers at the same time from one dropping point to the other. At the dropping points, straddle

carriers stand ready to transfer the containers to the initiated stack area. Straddle carriers could stack containers up to three high, whereas *reach stackers* (Figure 4-24) could stack empty containers up to five. Another benefit of reach stackers is that they need less space to place or remove containers because straddle carriers need to drive over a container in order to lift and transfer them. Therefore, several reach stackers drive around the container terminal to maneuver empty containers, because they are not able to pick up full containers.



Figure 4-23: Impression straddle carrier (Deviant Art, 2016)



Figure 4-24: Impression reach stacker (PLS, 2016)



Figure 4-25: Impression terminal truck (The President Post, 2016)

An overview of the process of the container terminal is overviewed in a fault tree. The left-side of the fault tree is shown in Figure 4-26, the right-side in Figure 4-27, combined they form the complete fault tree. The fault tree is based on Schüller et al., 2005, which is elaborated in Paragraph 2.2. On top of the tree could no *transshipment* be found, meaning that in case the fault event took place there will be no transshipment. Since the main function of a transshipment hub is to transship containers, the entire capacity of the terminal will be lost when this fault event occurs. The fault event *no transshipment* could be activating when one of the following fault events take place: *operation fails* or *terminal not accessible*. In case the fault events, *waterway or access road not passable*, occur, the terminal becomes inaccessible for container vessels and trucks, meaning that there will be no transshipment. Operation fails stand for the internal terminal process that fails, which will happen if the *TOS* or *ground transport* fails. The TOS basically needs a *data server* and *electricity*, which could be provided by the *electric stations*, *UPS* or *generators*. The ground transport needs the *container cranes*, *straddle carriers*, *reach stackers*, and *terminal trucks* to function.

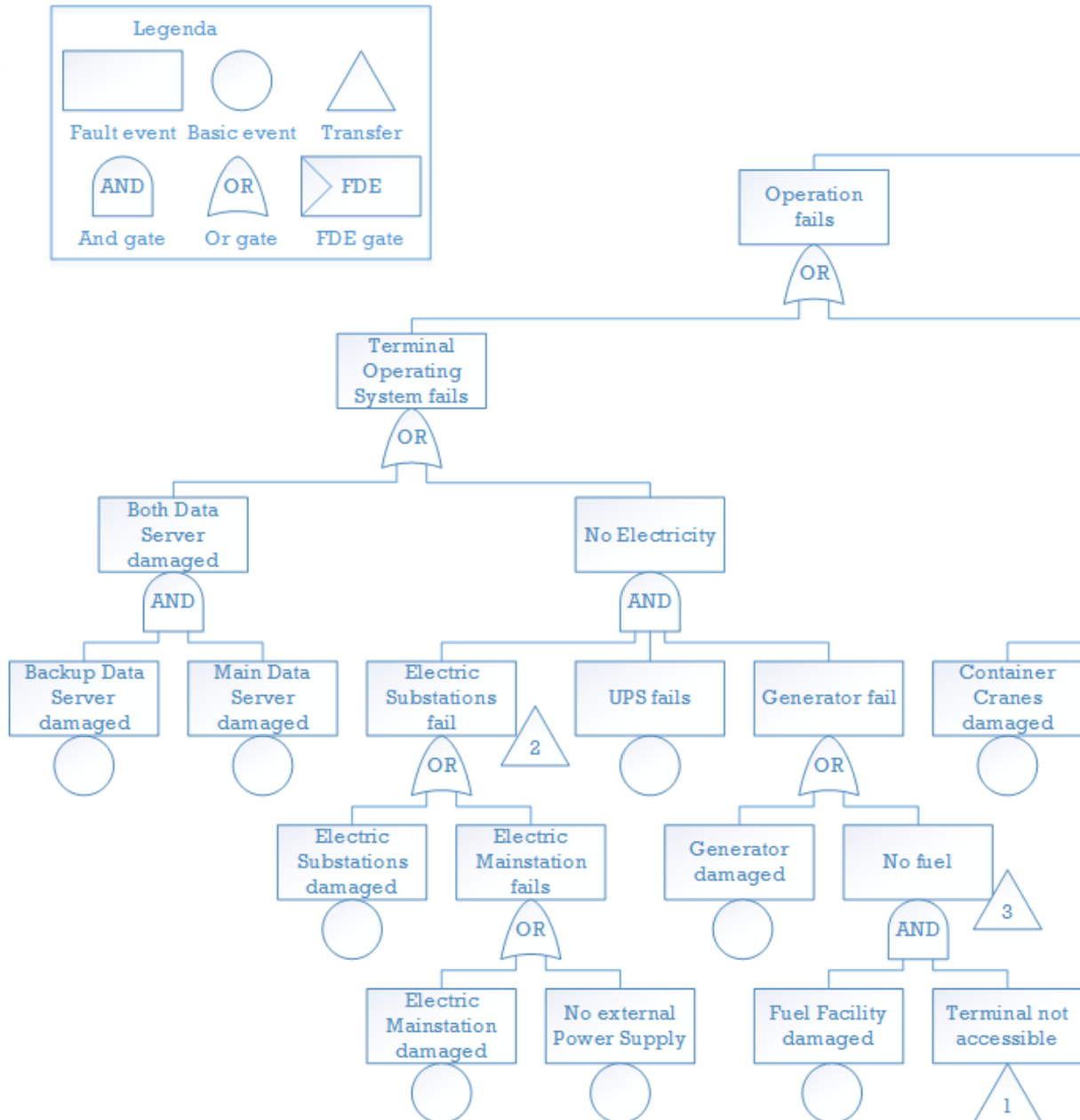


Figure 4-26: Left-side of the fault tree of the container terminal (based on Schüller et al., 2005)

4.4 Traffic increase

The revenue and amount of certain assets will increase, due to the prediction that the container traffic will increase throughout the concession period (Figure 4-28). The specific increases are shown in Table 4-2. In this report the halfway situation will be described (e.g. on the container traffic division (Figure 4-5) or asset value structures (Paragraph 5.2)).

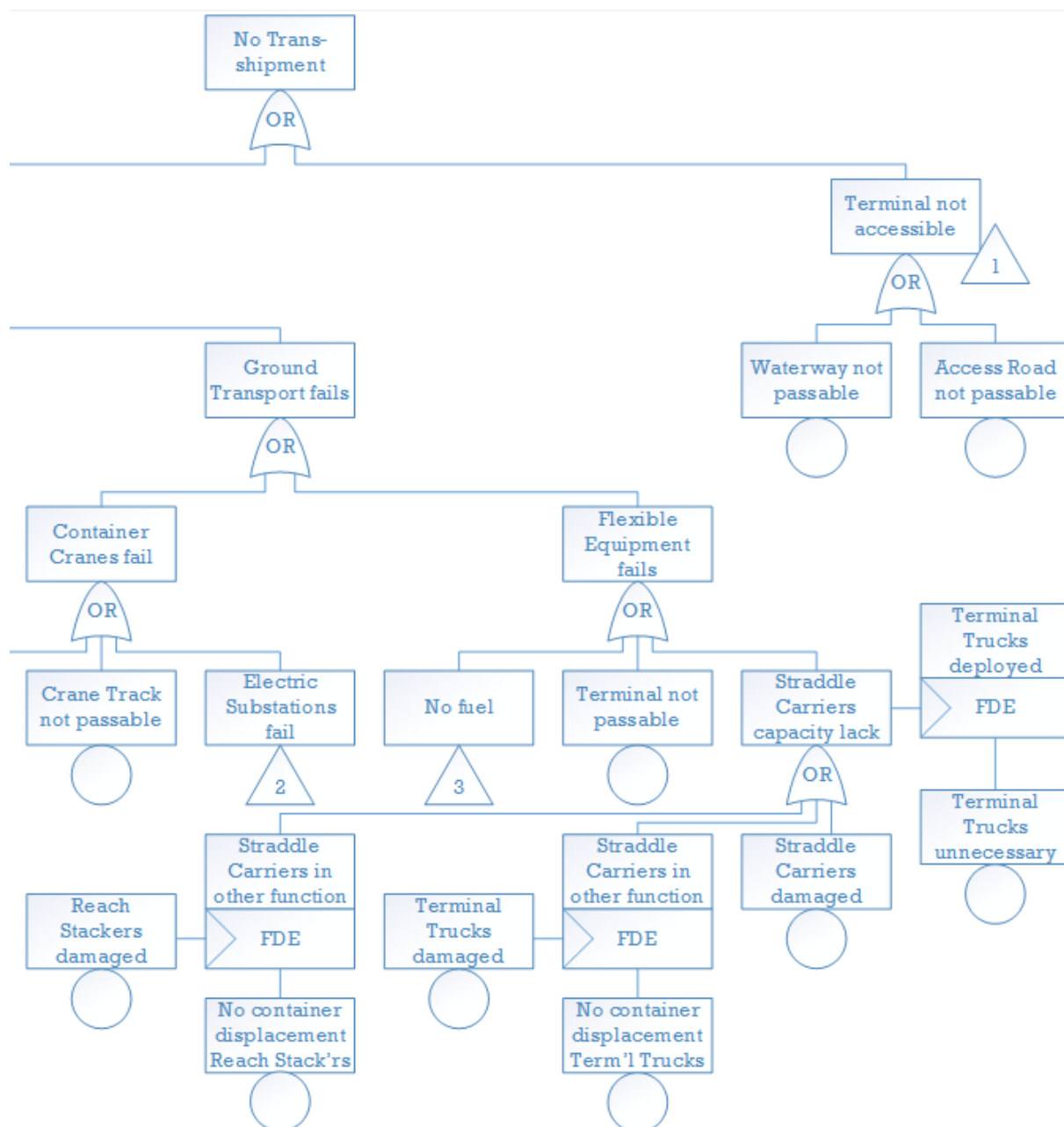


Figure 4-27: Right-side of the fault tree of the container terminal (based on Schüller et al., 2005)

Table 4-2: Increase throughout the concession

Component		2016	Halfway	2045
General increase [%]		87.5%	100.0%	112.5%
Container traffic [MTEU]		2.80	3.20	3.60
Revenue [M\$/year]		239	273	307
Ground transport [units]	Container cranes	14	16	18
	Straddle carriers	55	62	70
	Reach stackers	16	18	21
	Terminal trucks	22	25	29
Container stacked [kTEU]	Full dry	16.0	18.3	20.6
	Empty	18.9	21.6	24.4
	Reefers	1.2	1.4	1.6
Cables [k\$/ha]		43.75	50.00	56.25

That the situation halfway is described does not mean that the increase throughout the concession will not be included in the simulation process. The inclusion is expressed, apart from the predicted sea level rise through the years, via the increase in terminal revenue and asset value increase. Thereby the discount rate and economic growth of the country for the upcoming thirty years needs to be involved. Both discount and growth rate are assumed on 2%, based on IMF, 2016, Confidential, 2016b and Confidential, 2016c.

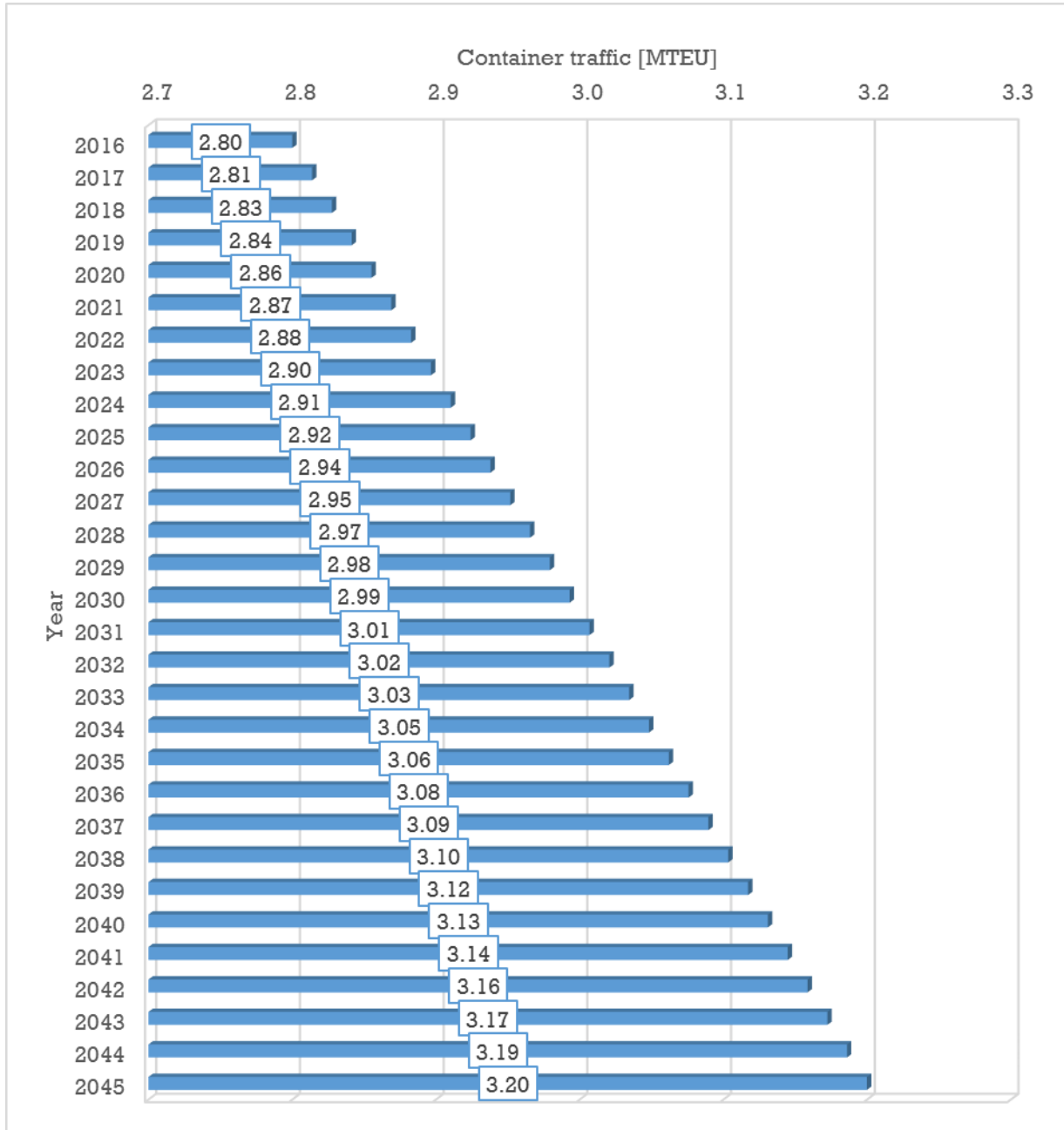


Figure 4-28: Annual container traffic

4.5 Conclusion

The following typical assets and fault events were identified for container terminals, based on the mapped case-study. The fault events are visualized via the upper part of the fault tree (Figure 4-29), whereas the assets are divided into groups, which are:

- Operations areas (control and maintenance);
- Electrical (mainstation, substations and generators);
- Ground transport (container cranes, straddle carriers, reach stackers and terminal trucks);
- Containers (full dry, empty and reefers);
- Fundamental (pavements, quay walls, foundation, revetment and others);
- External (backup data server, power supply, waterway, access road).

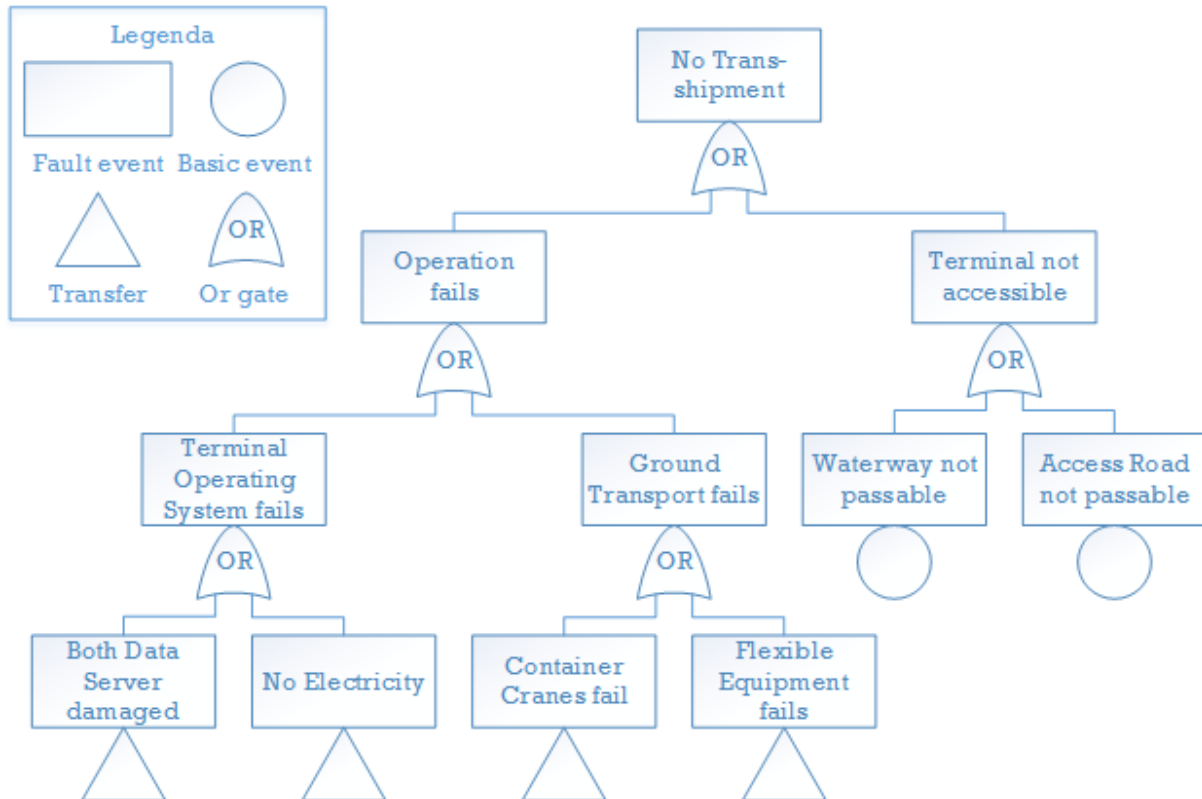


Figure 4-29: Simplified container terminal fault tree (based on Schüller et al., 2005)

5 Variables

As explained, it is necessary to partition the container terminal in order to assess the impact of MLS (Paragraph 2.4). This means that the economic impact of storm surges needs to be established for every part of the case. In this case-study, the partitioning is fulfilled by dividing the container terminal in assets and defining their values, downtimes, damage and capacity loss functions. Together with the storm surges and relative probabilities, these variables are the input data of the MLS-Model (Paragraph 3.2). In establishing the values of these variables an extensive process is fulfilled, because the specific data needed to be extracted from several sources, after which estimations are made under the supervision of specialists. The entire procedure is described in Appendix A, Appendix B and Appendix C. The procedure of the decisive variables is written in this Chapter, concluded by an overview of the results in Paragraph 5.4.

5.1 Storm surges

In order to determine the storm surge, data an extensive process is performed. It starts with (1) comparing different data sets to determine which data sets is most reliable and reasonable to occur. (2) Several fits are, thereafter, added to this data set to estimate the inundation heights for a broader range of return periods. Subsequently, the (3) projected changes on wave height and frequency are studied, after which the impact of climate change, in the form of (4) sea level rise and (5) land subsidence, is included. The entire process is elaborated in Appendix B. These findings in combination with the surface level of the container terminal (Paragraph 4.2), lead to Equation 5-1 and Figure 5-1. In this figure the established inundation height on the research case is shown in beginning of the concession (2016) and the end of the concession (2045). The increase of inundation height over the years is clearly visualized.

$$h_i = h_s + h_{slr} + h_{ls} - h_{sl}$$

Equation 5-1: Inundation height

h_i	[m]	Inundation height
h_s	[m]	Storm surge height
h_{slr}	[m]	Height of sea level rise
h_{ls}	[m]	Height of land subsidence
h_{sl}	[m]	Surface level height

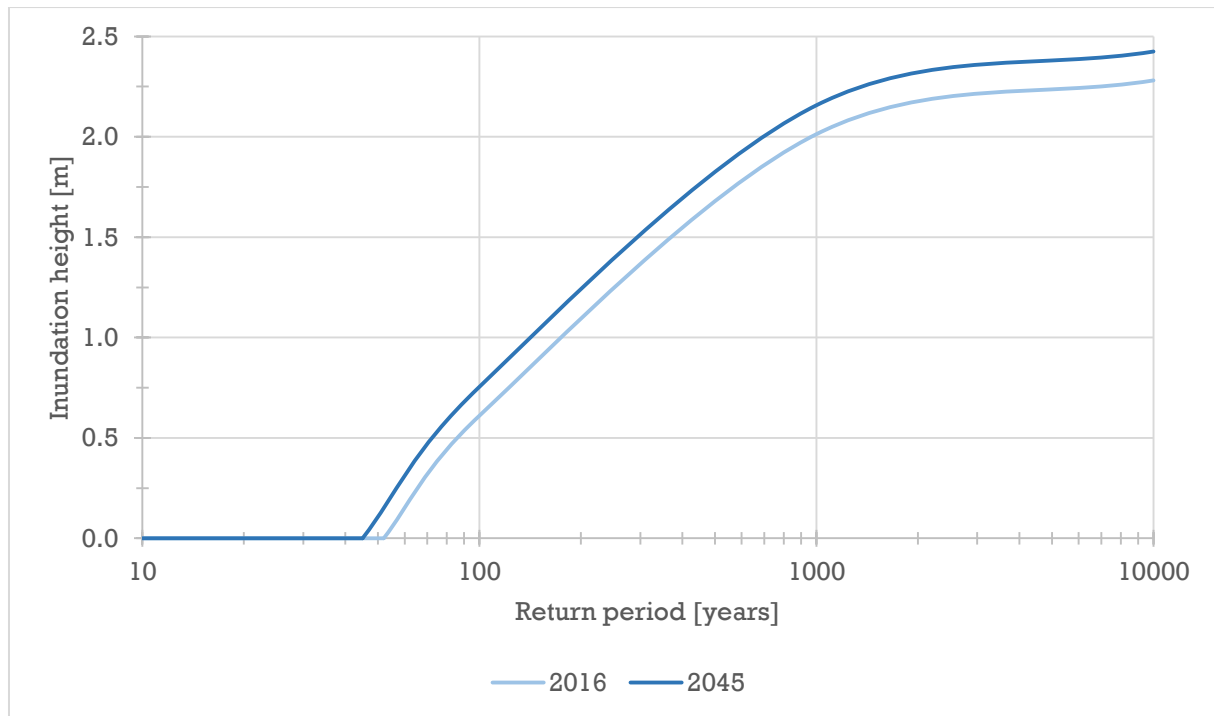


Figure 5-1: Established inundation height on the research case

5.2 Assets

To calculate the direct damage in detail, the values and damage functions of each asset need to be determined (as explained in Paragraph 3.2.1). This is a difficult process, due to the asset values are confidential and such specific damage functions are rarely. Damage functions are normally designed for larger areas, such as a damage function for the entire container terminal. However, using a function for the entire terminal the result becomes less accurate and limits the simulation to assess the impact of MLS. This is because of the fact that certain interventions within MLS affect only specific assets. 17 values and damage functions, relative to 17 assets, are established within this case-study. A description of the assets is given in Paragraph 4.2. The values are estimated by dividing the assets into different components and linking a price to each component. The damage functions show until what extent the asset is damaged according to a range of inundation heights. After establishing all values and functions, the conclusion is made that the containers are the most impactful group of assets, because of their average damage functions and extreme high asset values. The containers are responsible for 91% of the expected direct damage throughout the concession period. The values and functions estimation of the container group will be estimated in this Paragraph since this asset group appeared decisive. An extensive description of the establishing process of all assets can be found in Appendix C.

Full dry containers, empty containers and reefers are the asset group named containers. Combining the data of (1) ground slots, (2) stack height, (3) dwell times and (4) 20 to 40 feet container size ratio a complete picture of transshipment and containers stacks is created. This enables us to calculate the asset value of each container type. Integrating this realized data with the (5) depreciation and adding the (6) cargo values to the full dry containers and reefers leads to the final value structure (Table 5-1).

Table 5-1: Value structure containers

Container type	Full dry	Empty	Reefer	Total
Terminal A [M\$]	156.0	8.7	25.8	190.5
Terminal B [M\$]	150.1	6.2	-	156.3
Terminal C [M\$]	364.8	29.7	33.5	428.0
Total [M\$]:	670.8	44.6	59.3	774.8

The damage functions of the full dry, empty and reefer containers are established, based on a study of Kumagai (2013). There is begun with the (1) interaction between the mass of containers and inundation heights, after which the damage function of (2) empty containers are found, followed by the determination of the (3) cargo damage functions of different stack heights. Integrating the damage functions of containers and cargo with each other, taking into account the transshipment and container stacks, the damage functions are found. The damage functions consist of the full dry containers (Figure 5-2), empty containers (Figure 5-3) and reefers (Figure 5-4). An extensive description of the process resulting in the values and damage functions of the containers can be found in Appendix C.4.

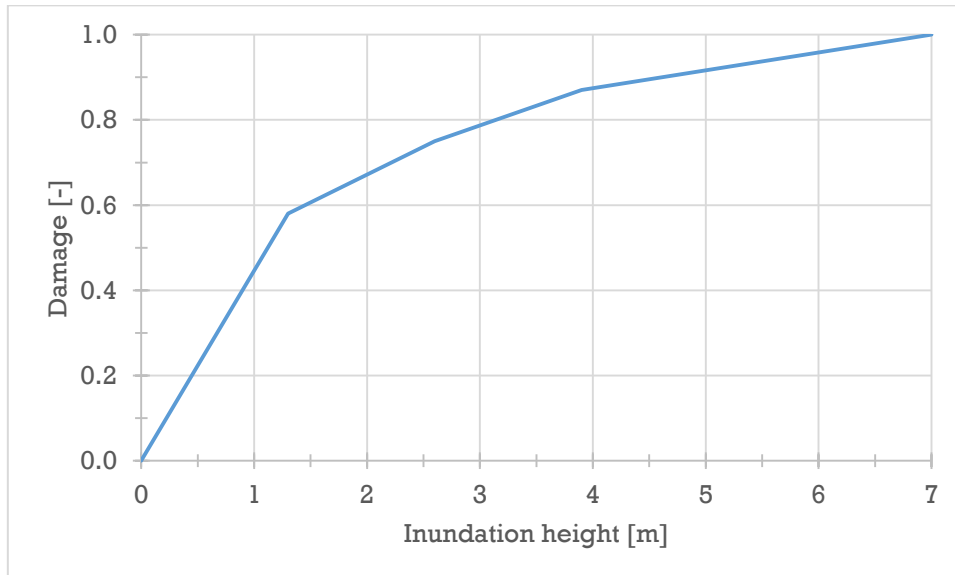


Figure 5-2: Damage function full dry containers

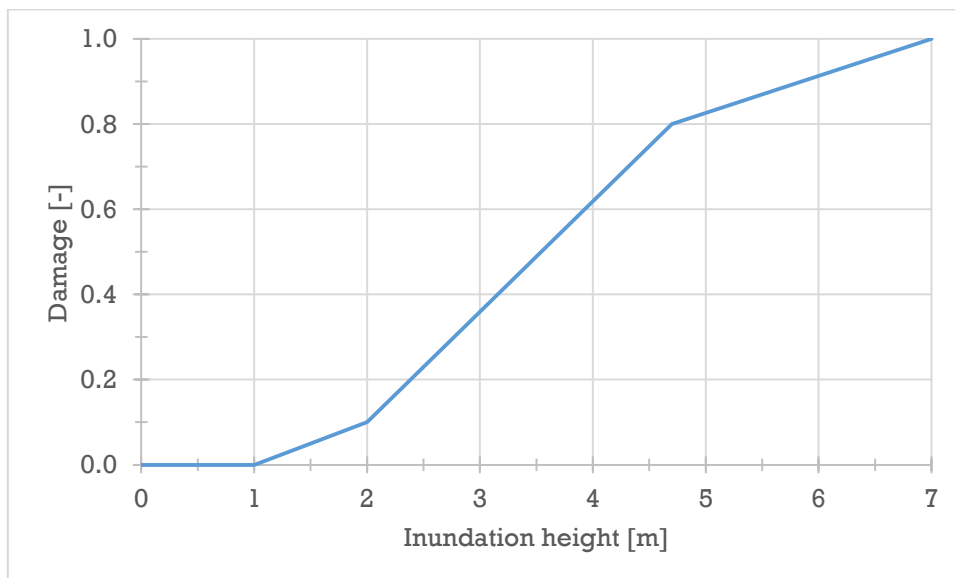


Figure 5-3: Damage function empty containers

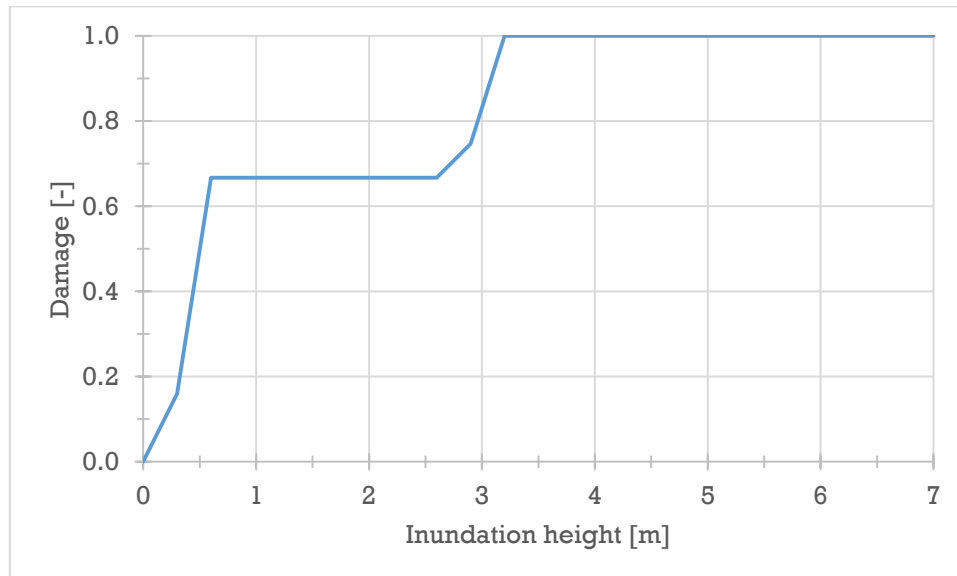


Figure 5-4: Damage function reefers

5.3 Fault events

Indirect damage can be calculated by knowing the relative variables (i.e. revenue, downtimes and capacity loss functions), as explained in Paragraph 3.2.1. The revenue of the container terminal increases during the concession period, the exact numbers are given in Paragraph 4.4. The other two variables (i.e. downtimes and capacity loss functions) can be divided according to fault events. Relationships between the fault events occurring at the container terminal are structured in a fault tree (Figure 4-26 shows the original fault tree). By linking the different assets to fault events, the capacity losses can be found, which will occur due to the failing assets. Therefore, the direct and indirect damage can be calculated when a specific asset becomes out of order. In order to determine the indirect damage, the downtimes and capacity loss functions of each fault event need to be estimated. This process is comprehensively described in 0. Knowing the amount of capacity loss on each fault event, the entire capacity loss of the container terminal could be determined by making use of the fault tree. In order to do this, the fault events need to be linked to assets causing the relative fault event, a process that leads to Figure 5-5 and Figure 5-6. The fault tree is can be seen as one, however, because of illustration reasons spread over two pages. Capacity loss functions show until what extent the fault event and relative asset has lost capacity given a certain inundation height. The downtimes are established by distinguishing the following phases: inspect, construct, transport and install. During the (1) inspection phase the precise damage will be estimated, which components need to be replaced and ordered to get the electric mainstation fully back online. In the next phase, the (2) replacements need to be constructed in the factory of the supplier, subsequently, the (3) new components will be transported to the container terminal. Lastly, the (4) components are build and installed on location. After establishing all needed variables, and running the simulation, the electric mainstation, straddle carriers and waterway turned out to be decisive. Therefore, the downtimes and functions of these assets are briefly elaborated in this Paragraph. An extensive elaboration of the process of all fault events and their relative assets is shown in Appendix D.



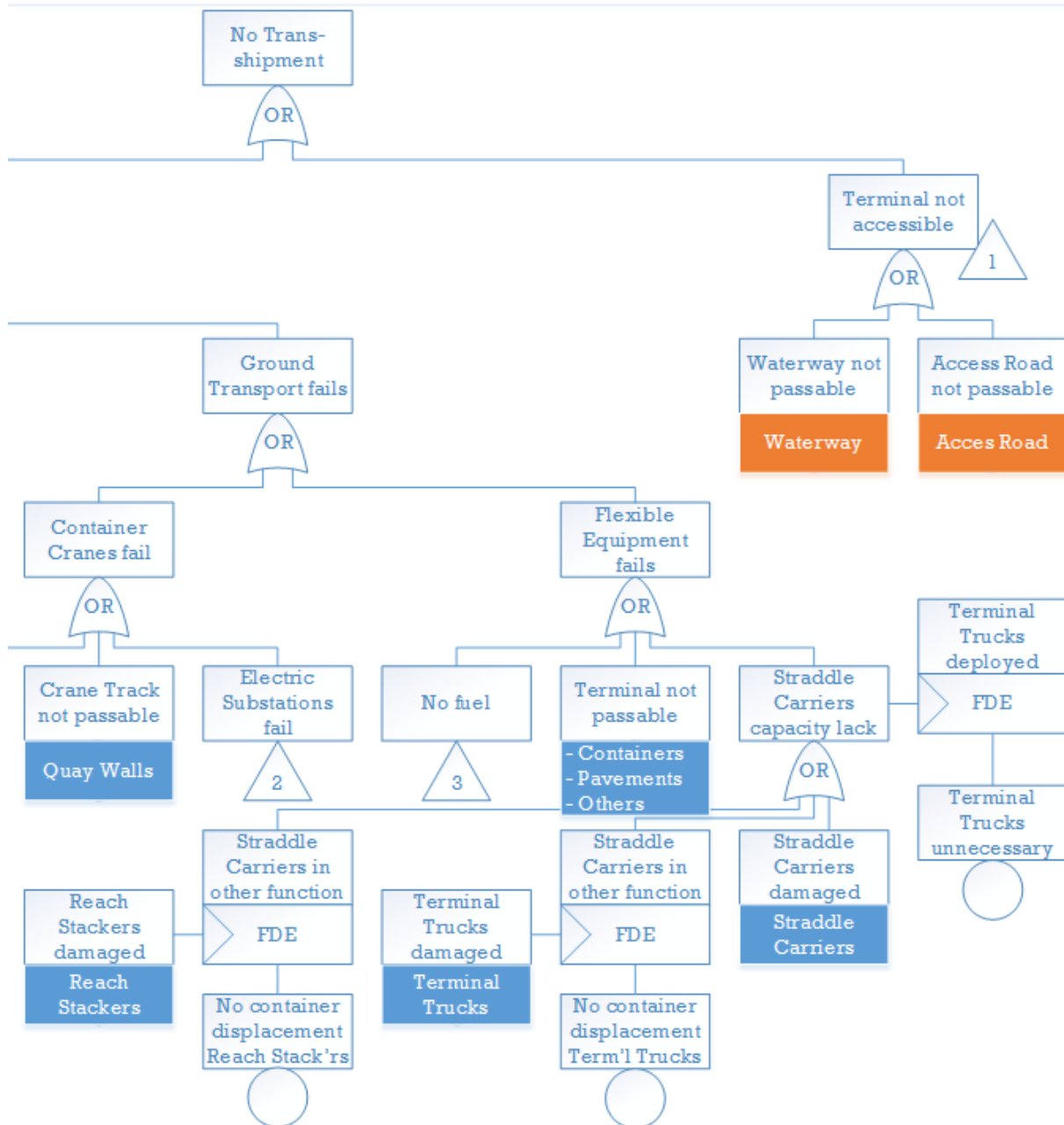


Figure 5-6: Right-side of the fault tree assets added (based on Schüller et al., 2005)

Electric mainstation

Table 5-2: Downtime structure electric mainstation

Section	Downtime [months]
Inspect	1.00
Construct	2.00
Transport ^[1]	0.50
Install	1.00
Total:	4.50

Without electricity, the entire container terminal will not function, as can be concluded out of the fault tree. The essential electrical component appears to be the mainstation, facilitating the terminal B directly and Terminal A and C via the electrical substations. Therefore, the capacity loss function is similar to the damage function, as shown in Figure 5-7. The resulting downtime when the electric mainstation becomes fully out of order is four and a half month (Table 5-2). This estimation follows from an intensive construction phase, because of the exclusive components of the electric mainstation. The inspection and installation will be relatively short, just as the transportation of the components to the terminal, which are originating from the United States.

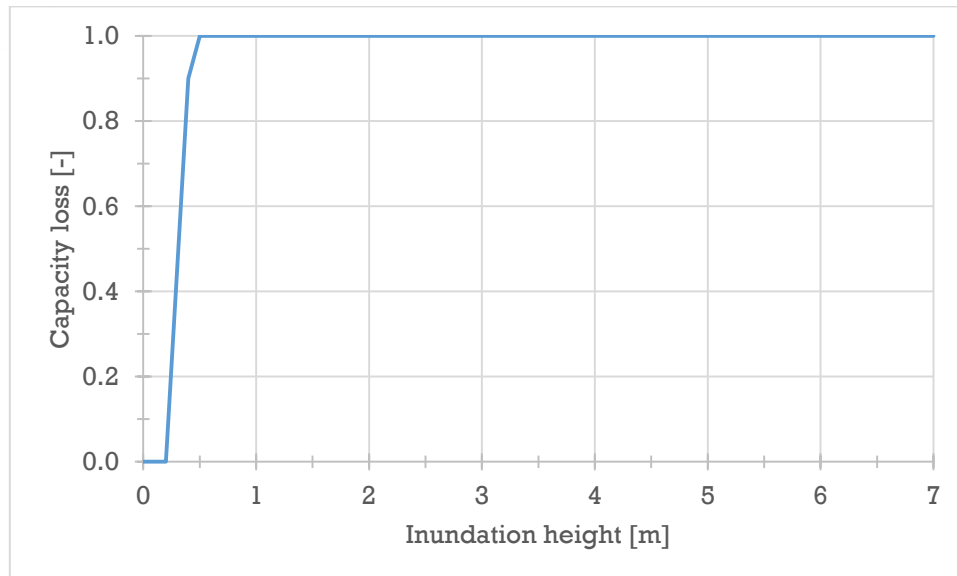


Figure 5-7: Capacity loss function electric mainstation

Straddle carriers

Both container crane and straddle carrier are crucial in the ground transportation process. Without the cranes, the containers cannot be loaded or unloaded from the vessels to the terminal. The straddle carriers account for the movement of full containers since they are the only flexible equipment capable of lifting a heavy container (as explained in Paragraph 4.3). Therefore, the indication is made that the straddle carriers can replace the reach stackers or terminal trucks, but it does not work the other way around. As illustrated via the function dependency gates in the fault tree (Figure 5-5). The downtimes of the container cranes (18 months) and straddle carriers (19.50 months) are comparable. However, the capacity loss function of the straddle carriers is quite steeper, which makes this asset critical in the transport process, as extensively elaborated in Appendix D.3.

Table 5-3: Downtime structure straddle carriers

Section	Downtime [months]
Inspect	1.50
Construct ^{[3][4]}	17.00
Transport ^{[1][3][4]}	1.00
Install	-
Total:	19.50

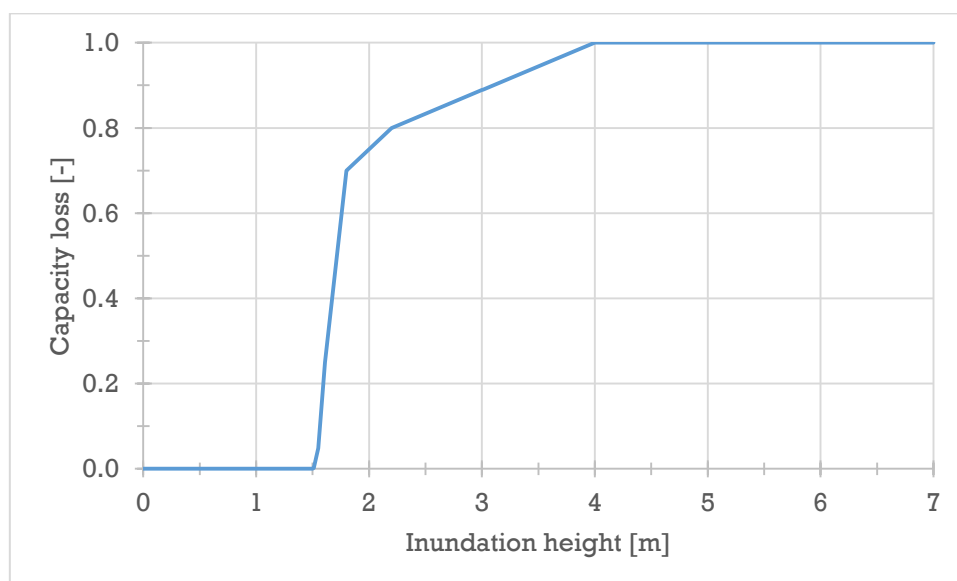


Figure 5-8: Capacity loss function straddle carriers

Due to the relationships between the flexible ground transport relative fault events (i.e. the asset straddle carriers, reach stackers and terminal trucks), as explained in 4.3 and visualized in Figure 5-5, an integrated equation needs to be used in order to calculate the integrated capacity loss (Equation 5-2). An extensive explanation how this equation is formed states in Appendix D.3.2, just as the method to find the relative variables.

$$CL_{flex} = CL_{scrs} - CL_{tt}$$

Equation 5-2: Capacity loss flexible equipment

CL_{flex}	[factor]	Capacity loss by flexible equipment
CL_{scrs}	[factor]	Capacity loss by straddle carriers and reach stackers combined
CL_{tt}	[factor]	Capacity loss by terminal trucks

Waterway

Table 5-4: Downtime structure waterway

Section	Downtime [months]
Inspect	0.50
Construct	-
Transport	3.00
Install	0.50
Total:	4.00

Shortly after a storm, the sediment accretion to the watery way can be identified, due to the availability of a survey vessel, which investigates the sediment that needs to be removed through dredging (as elaborated in Paragraph 4.2). After the survey, a determination can be made if dredging is necessary, in case it does, dredging companies could be informed. The time it takes between informing and arriving of a dredging vessel is another point of uncertainty, as it can reach up to several months. After arrival of the dredging vessel, the sediment will be

removed, whereby the time it takes to dredge the sediment has a direct relationship with the amount of sediment accretion. However, it appeared that removing sediment considers a relatively short period (Table 5-4). The capacity loss function is based on the relationship of vessels attaining the container terminal and the relative scantling draft, resulting in the function shown in Figure 5-9. This process is extensively described in Appendix D.6.

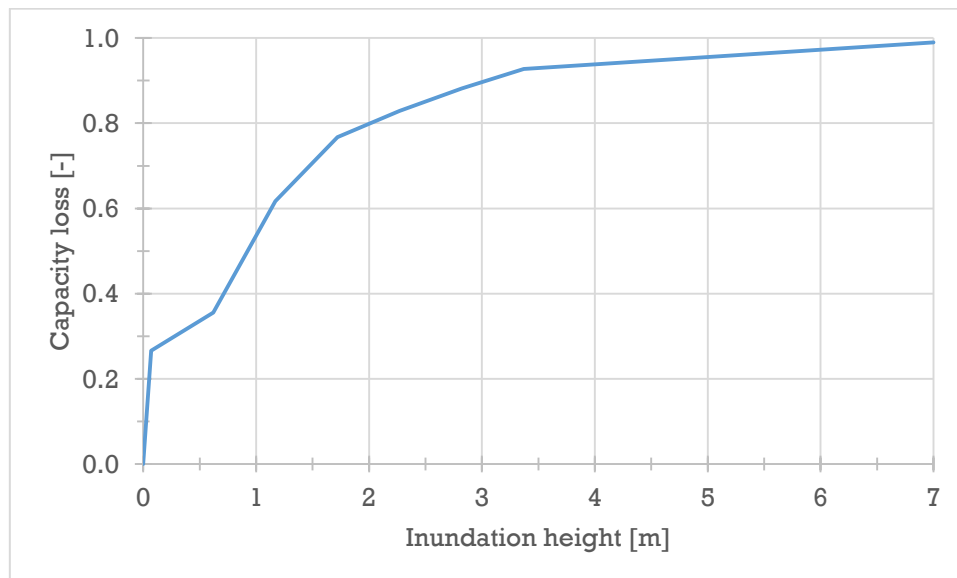


Figure 5-9: Capacity loss function waterway

5.4 Conclusion

An overview of the assets and their corresponding values, damage functions, downtimes and capacity loss functions can be seen in Table 5-5, Table 5-6 and Table 5-7, due to illustration reasons the tables are divided into three pages. The x-axis on both graphs shows the inundation height expressed in meters, where the damage- or capacity loss factor states on the y-axis. These graphs are minimized versions, however, identical to the graphs in Appendix C and Appendix D. In case the asset is decisive for the direct damage, the value and damage function are marked yellow, whereas the downtime and capacity loss function are marked yellow when the fault event is decisive for the indirect damage.

Table 5-5: Overview of assets and fault events variables (1/3)

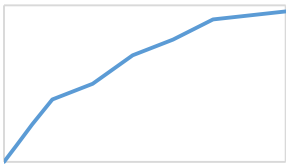
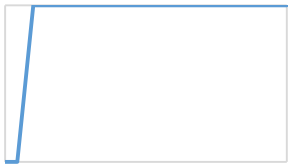
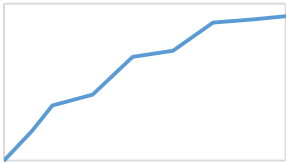
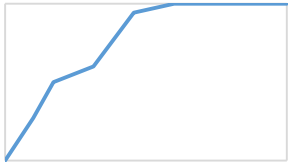
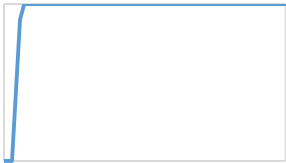
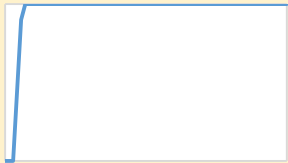
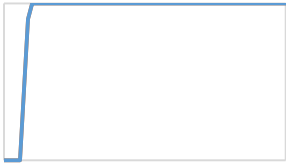
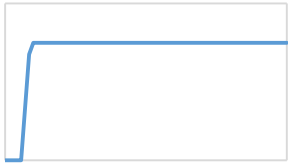
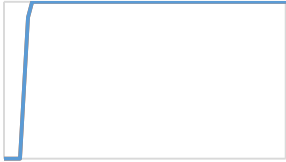
Asset	Value [M\$]	Damage function	Downtime [months]	Capacity loss function
Internal				
Control area	6.10		2.00	
Maintenance area	3.06		7.00	
Electric mainstation	3.00		4.50	
Electric substations	2.50		3.50	
Generators	2.75		N/A	
Container cranes	64.00		18.00	

Table 5-6: Overview of assets and fault events variables (2/3)

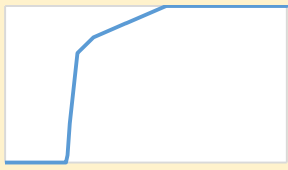
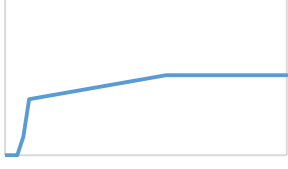
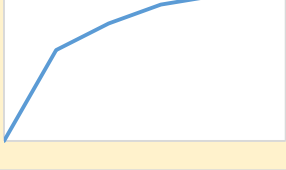
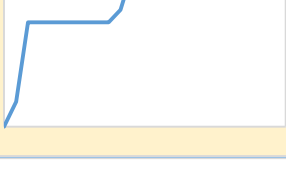
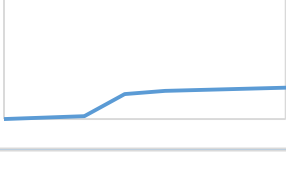
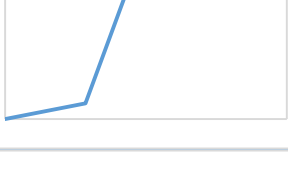
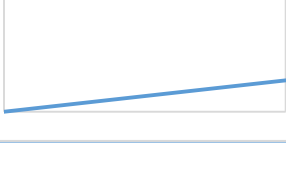
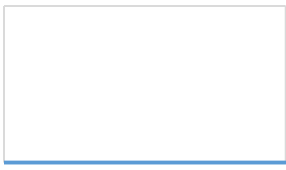
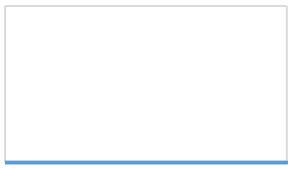
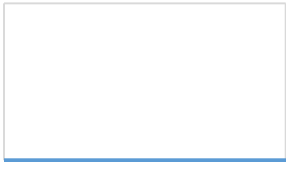
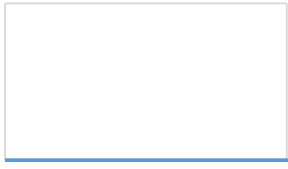
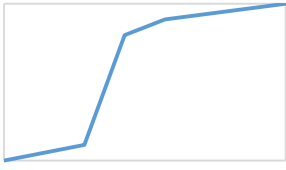
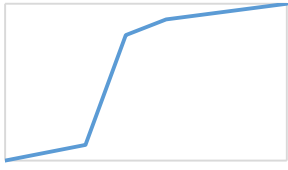
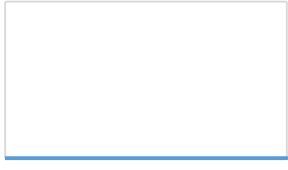
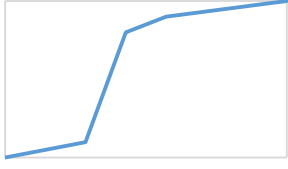
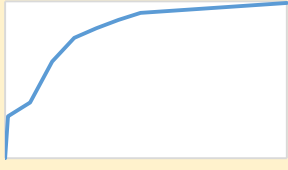
Asset	Value [M\$]	Damage function	Downtime [months]	Capacity loss function
Straddle carriers	27.90		19.50	
Reach stackers	4.05		11.50	
Terminal trucks	1.65		7.50	
Full dry containers	670.89		1.50	
Empty containers	44.60		1.50	
Reefers	59.34		1.50	
Pavements	38.25		4.00	
Quay walls	105.30		11.00	

Table 5-7: Overview of assets and fault events variables (3/3)

Asset	Value [M\$]	Damage function	Downtime [months]	Capacity loss function
Foundation	212.00		N/A	
Revetment	12.00		N/A	
Others	9.75		0.50	
External				
Backup data server	N/A	N/A	N/A	
Power supply	N/A	N/A	1.00	
Waterway	N/A	N/A	0.50	
Access road	N/A	N/A	0.75	

6

Results

Now the simulation method is developed (Chapter 3) and variables are defined (Chapter 5), the MLS-Model is ready to be applied within the case-study (Chapter 4). Before the last variables are described, in the form of intervention options, the 0-situation of the container terminal will be simulated in Paragraph 6.1. By doing this, the expected economic damage when no interventions are realized is calculated, needed to indicate the risk and impact of floods. Thereafter, in Paragraph 6.2, the interventions are formulated and applied within the case-study. In the application process is the optimal extent of the interventions simulated, by which to most cost-beneficial result is achieved. Comparing these results with the 0-situation, the impact of these individually applied interventions is assessed. The process of applying combinations of interventions on the container terminal is subsequently elaborated in Paragraph 6.3. Just as the individual applied interventions, an optimization took place to determine what extent each individual intervention needs to be realized. However, in this case, the optimization is to achieve the most cost-beneficial interaction. Both individual and combined intervention application form the fifth step of the model design cycle (Paragraph 2.3). In Paragraph 6.4 is a sensitivity analysis executed to examine the sensitivity of the model itself and intervention impacts. This Chapter is concluded by an impact assessment of the most cost-beneficial intervention option in Paragraph 6.5.

6.1 0-situation

The 0-situation considers the economic impact of the expected storm surges throughout the concession period on the container terminal, in case no interventions were realized. A broad range of numbers can be generated, due to the partitioning process, whereby the expected impact of storm surge impact on each individual asset is determined. As shown in Figure 6-1, which shows until what extent the asset is expected to be damaged expressed in percentages. The order of assets is the same as the previous paragraph's and starts with the operational areas, followed by the electrical assets, ground transport, containers, fundamental, and external assets. The asset electric mainstation suffers the most from the storm surges, expressed in an expected damage equal to 44% of the asset value. The highest absolute damage occurs at the full dry containers, where 20% is equal to \$ 138.8 M damage. The annual and total expected direct and indirect damage are shown in Figure 6-2, expressed in million dollars. Resulting in expected flood damage throughout the concession period of \$ 284.4 M. The flood damage is divided in a direct damage equal to \$ 4.5 M and indirect damage of \$3.2 M in 2016, after which several variables will change during the concession period, e.g., the amount of assets and terminal revenue (as described in 4.4). Increasing to a maximum of \$ 6.7 M and \$ 4.8 M at the end of the concession (2045).

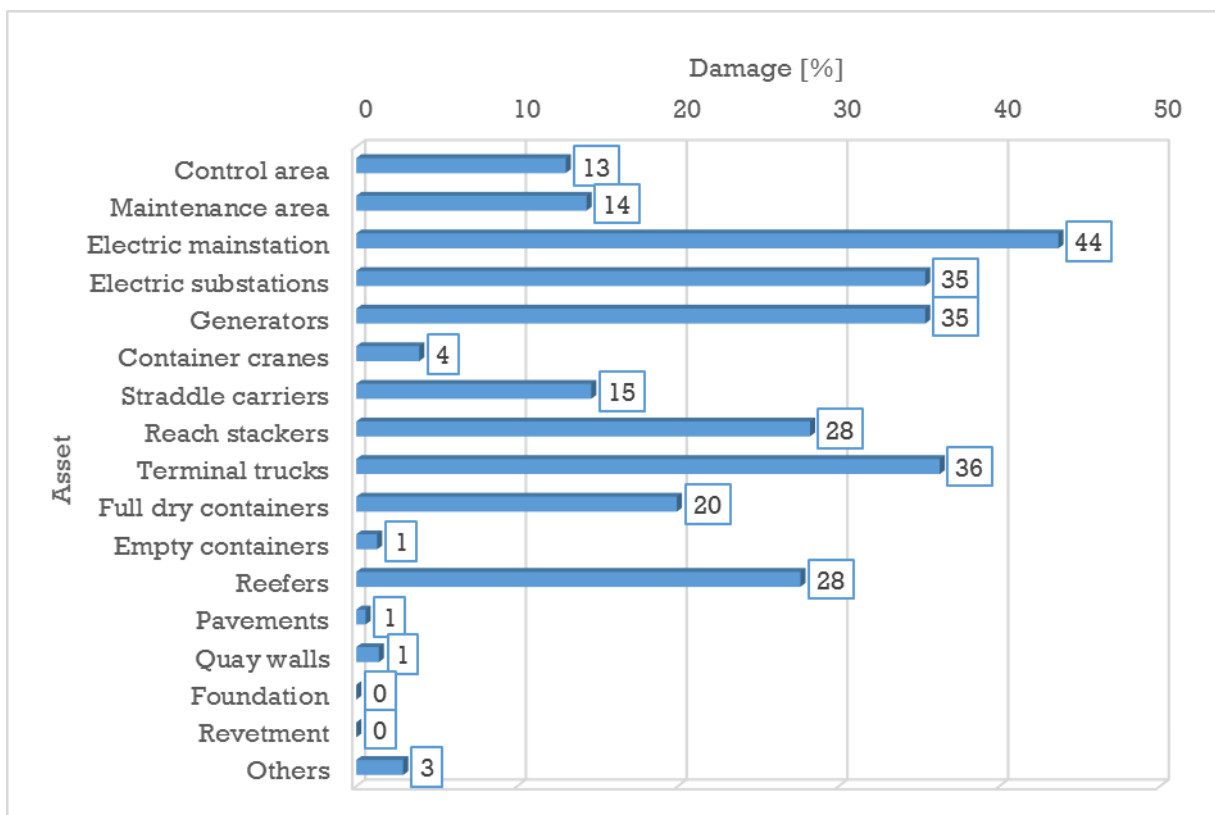


Figure 6-1: Asset damage percentages 0-situation

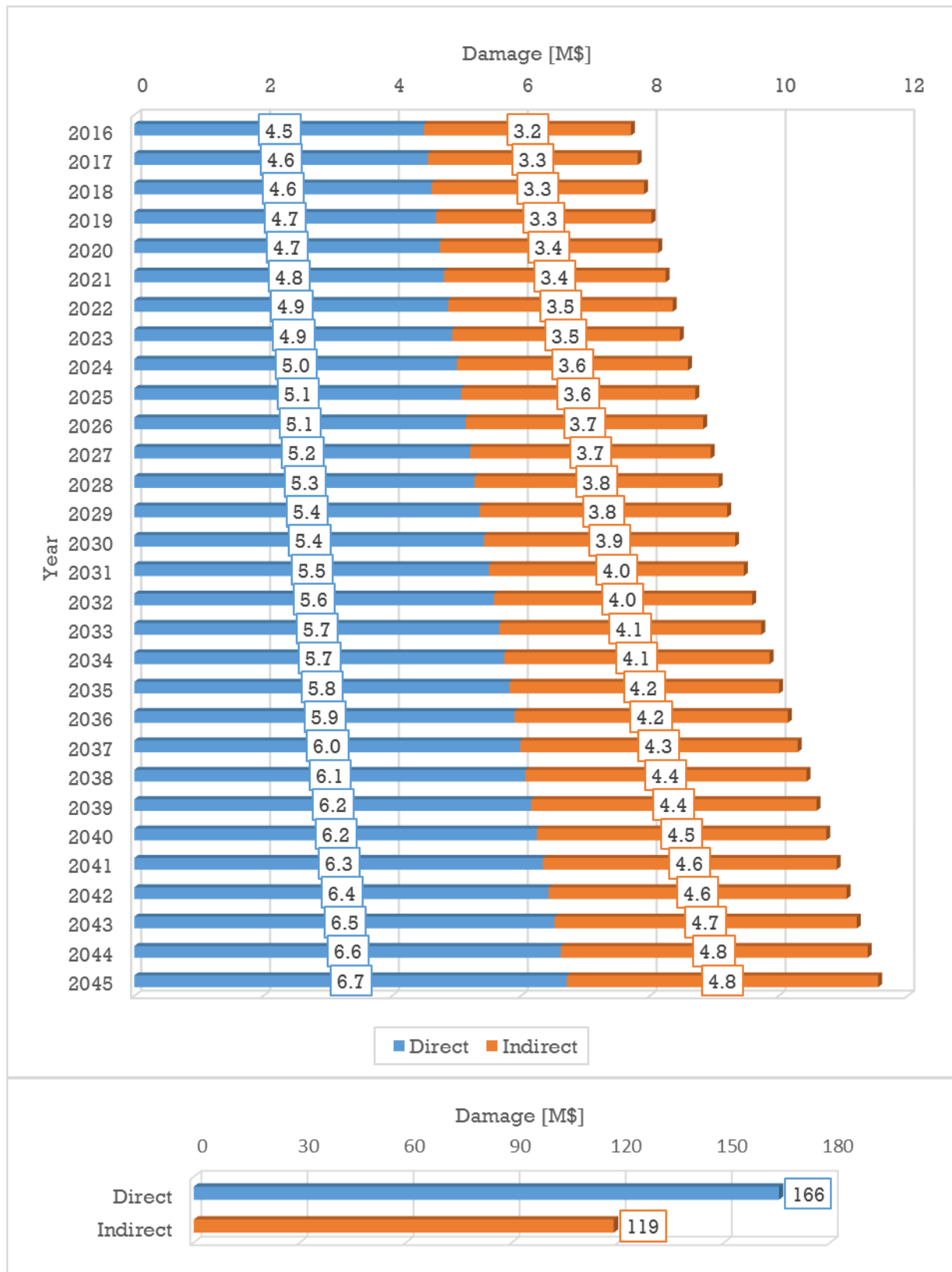


Figure 6-2: Annual and total damage 0-situation

6.2 Individual interventions

Now the 0-situation of the container terminal is simulated, one could start by defining the interventions that could be applied to the container terminal case-study. These intervention options are displayed via a list (Table 6-1) showing the number, affected section and method. Each individual intervention is elaborated in Appendix E, containing a description of the method, until what extent the intervention affects which assets, price structure and results. The results of the simulation are displayed in damage reduction, investment and CBA. During the simulation process the extent of each intervention is optimized (this process is described in Paragraph 3.2.3). The intervention extent, in this case, holds the protection height. Therefore, the CBA is an interaction between the damage reduction and intervention investment, whereby the most cost-beneficial point corresponds to the optimal protection height.

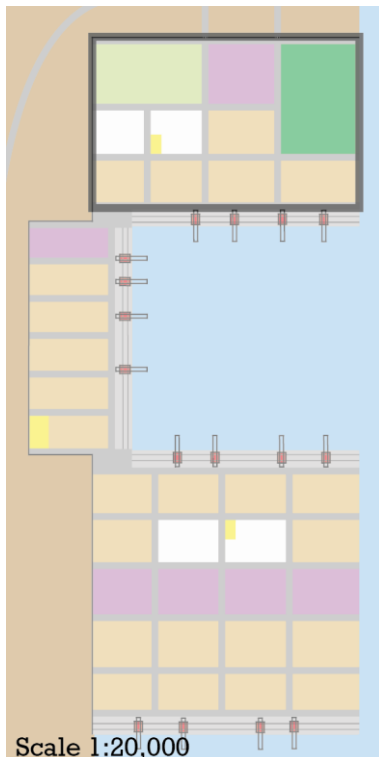


Figure 6-3: Illustration sectional Terminal A enclosure

Table 6-1: Flood interventions overview

#	Intervention	
P	Prevention layer	
1 P1a	Entire Terminal	Heighten
2 P1b		Enclose
3 P2a	Sectional Terminal	Heighten
4 P2b		Enclose
5 P3	Coastline	Flood defenses
S	Spatial planning layer	
6 S1a	Entire Terminal A	Heighten
7 S1b		Enclose
8 S2a	Sectional Terminal A	Heighten
9 S2b		Enclose
10 S3a	Control area	Heighten
11 S3b		Enclose
12 S4a	Maintenance area	Heighten
13 S4b		Enclose
14 S5a	Electric mainstation	Heighten
15 S5b		Enclose
16 S5c		Immediate relocate
17 S5d		Relocate during replacement
18 S6a	Container cranes	Depot
19 S6b		Moveable to Terminal A
D	Disaster management layer	
20 D1a	Dredging	Vessel purchase
21 D1b		Pre-arrangement
22 D2a	Fuel facility	Pre-order contracts
23 D2b		Rental contracts
24 D3a	Electric stations	Pre-order contracts
25 D3b		Rental contracts
26 D4a	Transport equipment	Pre-order contracts
27 D4b		Rental contracts

Sectional Terminal A enclosure

In Figure 6-3 the sectional enclosure of Terminal A is illustrated. Enclosure means that a wall is realized to protect the area against floods. To move from the protected section to an unprotected section, several passages are constructed within the wall. One of the passages is situated at the entrance gate, another one can be found at the exit gate. The remaining gates are located precisely at the roads between the northern quay wall and terminal A. Protecting terminal A sectional means that the quay wall will be unattached, something that appeared an extensive execution (as can be seen at other intervention options in Appendix E). The enclosure is a less expensive solution than raising the height of the ground surface level because a smaller parts (e.g. the asphalted surface or underground wiring) of the terminal need to be adjusted. However, in case the walls are too low for the occurring storm surge, the protected area becomes a filling bathtub. This means that the maximum damage factor will directly be reached, instead of moving the entire damage function to the right, which happens when the surface is heightened.

To assess the impact of a certain intervention, the impact on each individual asset needs to be determined. This is done by establishing the impact on each asset via the following variables:

- Partial protection [%]: in case an intervention only influences a part of the asset;
- Heighten surface [m]: increasing the ground level underneath the asset;
- Heighten enclosure [m]: realizing a wall around the asset;
- Improved protection [%]: improve the asset in such a way that it's better protected against storm surges;
- Downtime reduction [%]: reduce the length of any downtime;
- Downtime reduction [months]: reduce the maximum downtime.

A process that is clearly visible in the excel sheets and therefore elaborated in Appendix A.4. In Table 6-2 is shown what this means for the enclosure of terminal A. The control area is, e.g., entirely protected, where one of the two electric substations (50%) is situated in the borders of the protection. This intervention (S2b) affects the assets by heightening the enclosure. The exact height of the enclosure needs to be simulated in combination with the investment. To realize terminal A enclosure a fixed investment of \$ 0.63 M is needed. The variable investment is equal to \$ 29.91 M as can be shown in Table 6-3. Apart from to the investments, the optimal protection height of 2.32 m can be seen, which is marked yellow.

A yellow mark implies the outcome of a simulation. The damage reduction integrated with the needed investment, both matching the optimal intervention height, leads to a cost-benefit of \$71.9 M. This score corresponds to a rate of return of 3.4. Making the intervention S2b the most cost-beneficial option when the interventions are individual applied. An overview of the simulation outcomes can be seen in Figure 6-4, which also illustrate with intervention (S2b) is simulated by marking it blue. The same process is executed for the other intervention options as can be read in Appendix E.

	P1a	P1b	P2a	P2b	P3		
 S1a	 S1b	 S2a	 S2b	 S3a	 S3b	 S4a	 S4b
	 S5a	 S5b	 S5c	 S5d	 S6a	 S6b	
 D1a	 D1b	 D2a	 D2b	 D3a	 D3b	 D4a	 D4b
Damage reduction: \$ 102.5M			Investment: \$ 30.5M		Cost-benefit: \$ 71.9M		

Figure 6-4: Simulation outcomes sectional terminal A enclosure

Table 6-2: Intervention impact sectional terminal A enclosure

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b			
Maintenance area	100					
Electric substations	50					
Generators	73					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	32					

Table 6-3: Investment structure sectional terminal A enclosure

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	4.1	15.30	0.63
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Total varibale investment:			29.91
Total investment:			30.54

Overview

Simulation outcomes of the flood interventions, described in Appendix E, are overviewed in Table 6-4. Here could be seen that flood intervention S1a leads to a total loss of \$ 63.2 M, due to the high investment, and is discouraged to construct. S2b appeared to realize to highest expected cost-benefit throughout the concession period (\$ 71.9 M) and is advised to cope with the flooding threat.

Table 6-4: Outcomes single intervention simulations

Inter-vention	Protection height [m]	Damage reduction [M\$]			Investment [M\$]	Cost-benefit [M\$]	
		Direct	Indirect	Total			
S1a	1.90	46.3	58.0	104.3	167.5	-63.2	
S1b	2.40	47.3	57.5	104.8	64.1	40.7	
S2a	1.90	45.7	57.2	102.9	63.8	39.1	
S2b	2.32	45.8	56.7	102.5	30.5	71.9	
S3a	2.00	2.4	16.5	18.9	11.1	7.8	
S3b	2.31	2.3	16.2	18.5	4.7	13.9	
S4a	2.00	5.2	50.7	55.9	15.7	40.2	
S4b	2.40	5.2	50.0	55.2	8.3	46.9	
S5a	2.03	1.4	12.4	13.8	6.5	7.2	
S5b	2.40	1.4	12.4	13.8	0.9	12.9	
S6a	0.00	0.0	0.0	0.0	1.5	-1.5	
D1a	-	0.0	1.9	1.9	0.2	1.7	
D1b	-	0.0	1.0	1.0	0.0	1.0	

6.3 Combined interventions

Due to the fault event relationships, elaborated in Paragraph 5.3, a simple summation of the benefits of single interventions is not possible. Promising interventions could reinforce each other and be able to achieve more cost-beneficial solutions. On the other hand, there is the possibility that interventions cover the same assets or unrelated fault events, causing a negative interaction. The goal is to find the most cost-beneficial intervention combination, therefore several promising options are simulated and compared. The entire process is elaborated in 0. In this Paragraph only the most cost-beneficial combination will be elaborated.

Interventions S2b & S5b & D1a

A combination of sectional terminal A enclosure (S2b), electric mainstation enclosure (S5b) and purchasing a dredging vessel (D1a) appeared to be most cost-beneficial. This combination is drawn in Figure 6-6 as can be shown by the two enclosures and darker blue water. The interventions are separately described in Appendix E and affect numerous assets by heightening enclosure or downtime reduction (Table 6-5). The optimal protection height of this intervention option is +2.32m MSL (S2b) and +2.40m MSL (S5b). The resulting simulation outcomes are overviewed in Paragraph 6.5.

		P1a	P1b	P2a	P2b	P3		
								
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b	
								
		S5a	S5b	S5c	S5d	S6a	S6b	
								
D1a		D1b	D2a	D2b	D3a	D3b	D4a	D4b
Damage reduction: \$ 140.6M				Investment: \$ 31.5M		Cost-benefit: \$ 109.1M		

Figure 6-5: Simulation outcomes interventions S2b & S5b & D1a

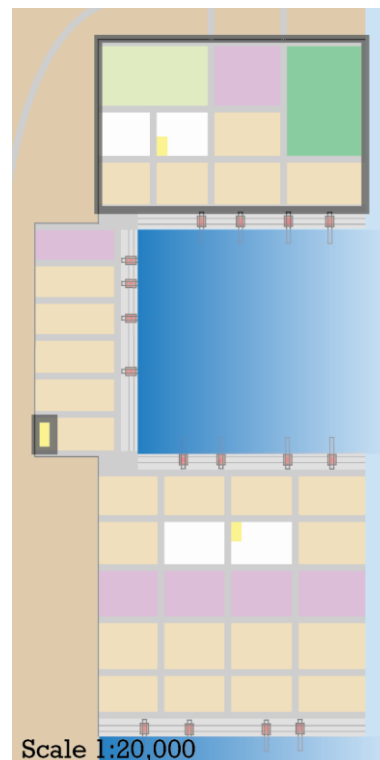


Figure 6-6: Illustration S2b & S5b & D1a

Table 6-5: Intervention impact interventions S2b & S5b & D1a

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b			
Maintenance area	100					
Electric mainstation	100					
Electric substations	50					
Generators	82					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					
Waterway	100					D1a

Table 6-6: Investment structure interventions S2b & S5b & D1a

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	6.4	15.30	0.99
Purchase dredging vessel [%]	10	1.50	0.15
Total fixed investment:			1.14
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Wall electric mainstation [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Total variable investment:			30.39
Total investment:			31.53

Overview

Simulation outcomes of the flood intervention combinations, described in Appendix F, are overviewed in Table 6-7, whereby can be concluded that intervention combination 6 is most cost-beneficial.

Table 6-7: Outcomes combined intervention simulations

Inter- ventions	Protection height [m]	Damage reduction [M\$]			Investment [M\$]	Cost-benefit [M\$]	
		Direct	Indirect	Total			
1	S3b	7.5	56.7	64.2	7.6	56.6	
	S4b						
2	S3b	27.9	56.7	84.6	29.6	54.9	
	S4b +						
3	S2b	47.2	78.3	125.5	31.4	94.1	
	S5b						
4	S2b	46.6	75.6	122.2	35.1	87.1	
	S5c						
5	S2b	46.2	78.3	124.5	31.3	93.2	
	S5d						
6	S2b	47.2	93.4	140.6	31.5	109.1	
	S5b						
	D1a						
7	S2b	47.2	86.5	133.6	31.4	102.2	
	S5b						
	D1b						
8	S2b	49.2	80.8	130.0	31.5	98.5	
	S5b						
	S6a						
							
9	S2b	47.8	79.2	126.9	31.8	95.1	
	S5b						
	S6b						
10	S2b	49.2	93.3	142.5	35.0	107.4	
	S5b						
	S6a						
							
	D1a						

6.4 Sensitivity analysis

A sensitivity analysis of a model implies that the effect of each input variable on the outcome is examined. This is done by changing the input values according to stepwise percentages relative to the base value (Bots and Bouwans, 2016). In this report, the sensitivity analysis is divided into two parts. The first part examines the sensitivity of the model itself by determining the effect of the input variables on the 0-situation, after which the sensitivity of the interventions within the improved situation is calculated.

The effect of changing the input variables with $\pm 10\%$ and $\pm 25\%$ on the expected damage at the 0-situation is shown in Table 6-8 and Figure 6-7. In case the inundation heights of the upcoming storm surges are lower than expected the expected damage will decrease heavily (20.3%), something that also occurs in the other direction when higher inundation heights will occur (16.5%). Therefore, can be said that this variable is very sensitive. The variables which are responsible for the direct damage (asset values and damage functions) appeared more sensitive than the indirect damage ones (revenues, downtimes, capacity loss functions). A result that can be declared by the fact that the direct damage base value (\$ 166M) covers 58%, where 42% relates to the indirect damage (\$ 119M). The sensitivity percentages are precisely corresponding to this range. Last, the

Table 6-8: Sensitivity of the MLS-Model

Variable	Difference			
	-25%	-10%	+10%	+25%
Inundation heights	-20.3%	-7.7%	7.1%	16.5%
Asset values	-14.6%	-5.8%	5.8%	14.6%
Damage functions	-14.6%	-5.8%	5.8%	14.6%
Revenues	-10.6%	-4.3%	4.0%	10.3%
Downtimes	-10.4%	-4.2%	4.2%	10.4%
Capacity loss functions	-10.4%	-4.2%	4.2%	10.4%
Growth rate	-0.5%	-0.2%	0.2%	0.5%
Discount rate	0.5%	0.2%	-0.2%	-0.5%

economic growth and discount rates appeared rather insensitive compared to the other variables. However, these variables are hard to predict for a period of 30 years and can heavily fluctuate, especially in the Caribbean (IMF, 2016).



Figure 6-7: Sensitivity of the MLS-Model

In the second section of the sensitivity analysis, the effect of a fluctuating intervention height is examined. The effect on three outcome variables is calculated by changing the intervention height with

$\pm 2.5\%$ and $\pm 10\%$. Beforehand it can be said that increasing the height by 10% will lead to minor extra damage reduction, due to the maximum inundation height is already protected for terminal A by increasing the height with 2.5%. This was the reason to choose the used percentages steps. The assumption appeared to match with the sensitivity outcomes, as can be seen in Table 6-9 and Figure 6-8. A slightly higher deviation when the height is increased, compared to decreasing, the investment variable, can be explained with the variable investment. The investment is divided in a fixed and variable part (Paragraph 3.2.3), where the influence of the variable part becomes larger on the overall investment as the height increases. With sensitivity percentages of the last outcome variable (CBA), the optimization is verified. Hereby is clearly visible that the optimum height corresponds to 0%, meaning that the maximum cost-benefit is achieved by using the applied intervention height.

Table 6-9: Sensitivity of the interventions

Variable	Difference			
	-10.0%	-2.5%	+2.5%	+10%
Damage reduction	-10.0%	-2.6%	0.5%	1.3%
Investment	-14.6%	-3.8%	3.8%	15.7%
Cost-benefit analysis	-8.7%	-2.3%	-0.4%	-2.9%

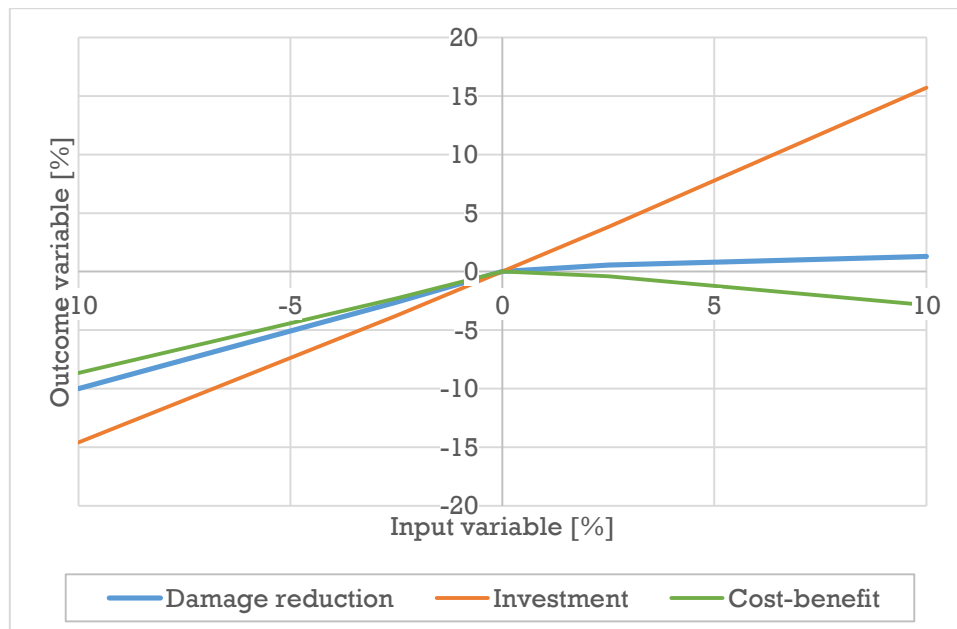


Figure 6-8: Sensitivity of the interventions

6.5 Conclusion

The simulation outcomes of the 0-situation are clear and show that the expected damage through storm surges during the upcoming 30 years is very high (\$ 284.4 M, as can be seen in Paragraph 6.1). This outcome, together with the cost-beneficial outcomes of the intervention simulations, leads to the advice to directly realize the most cost-beneficial intervention option. The combination consists of the interventions sectional terminal A enclosure (S2b), electric mainstation enclosure (S5b) and purchasing a dredging vessel (D1a) (as described in Paragraph 6.3). Shown in several graphs, the simulation outcomes of this intervention combination applied are overviewed. By looking at the graphs, a clear overview of the improvements achieved by applying these interventions relative to the 0-situation is made. In Figure 6-9 the direct flood damage reduction and remaining expected occurring damage are visualized. Both graphs are expressed in a percentage, which is equal to the expected damage relative to the asset value. The realized damage reduction at, e.g., the electric mainstation is 44% since the expected damage was 44% during the 0-situation (Figure 6-1), the expected occurring damage becomes 0%.

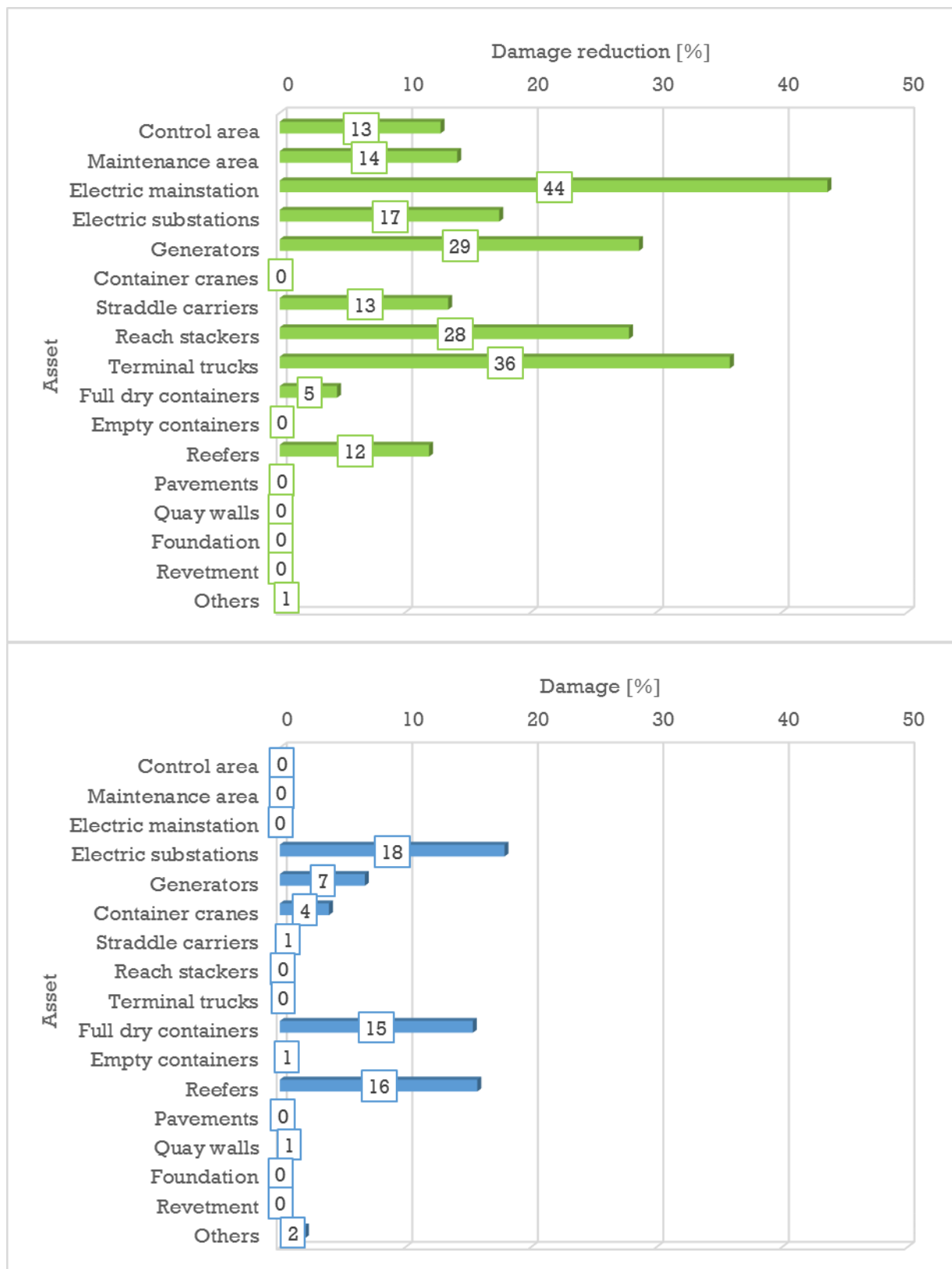


Figure 6-9: Asset damage reduction and damage percentages most cost-beneficial situation

Annual direct, indirect and total flood damage reductions, expressed in million dollars are graphed in Figure 6-10. In the beginning of the concession period (2016), the damage reduction amounts \$ 1.3 M (direct) and \$ 2.6 M (indirect), a reduction that gradually increases to \$ 1.9 M and \$ 3.7 M in 2045. Resulting in a total expected damage reduction throughout the concession period of \$ 140.6 M, achieved with an investment of \$ 31.5 M, which is equal to an investment ratio of 4.46.

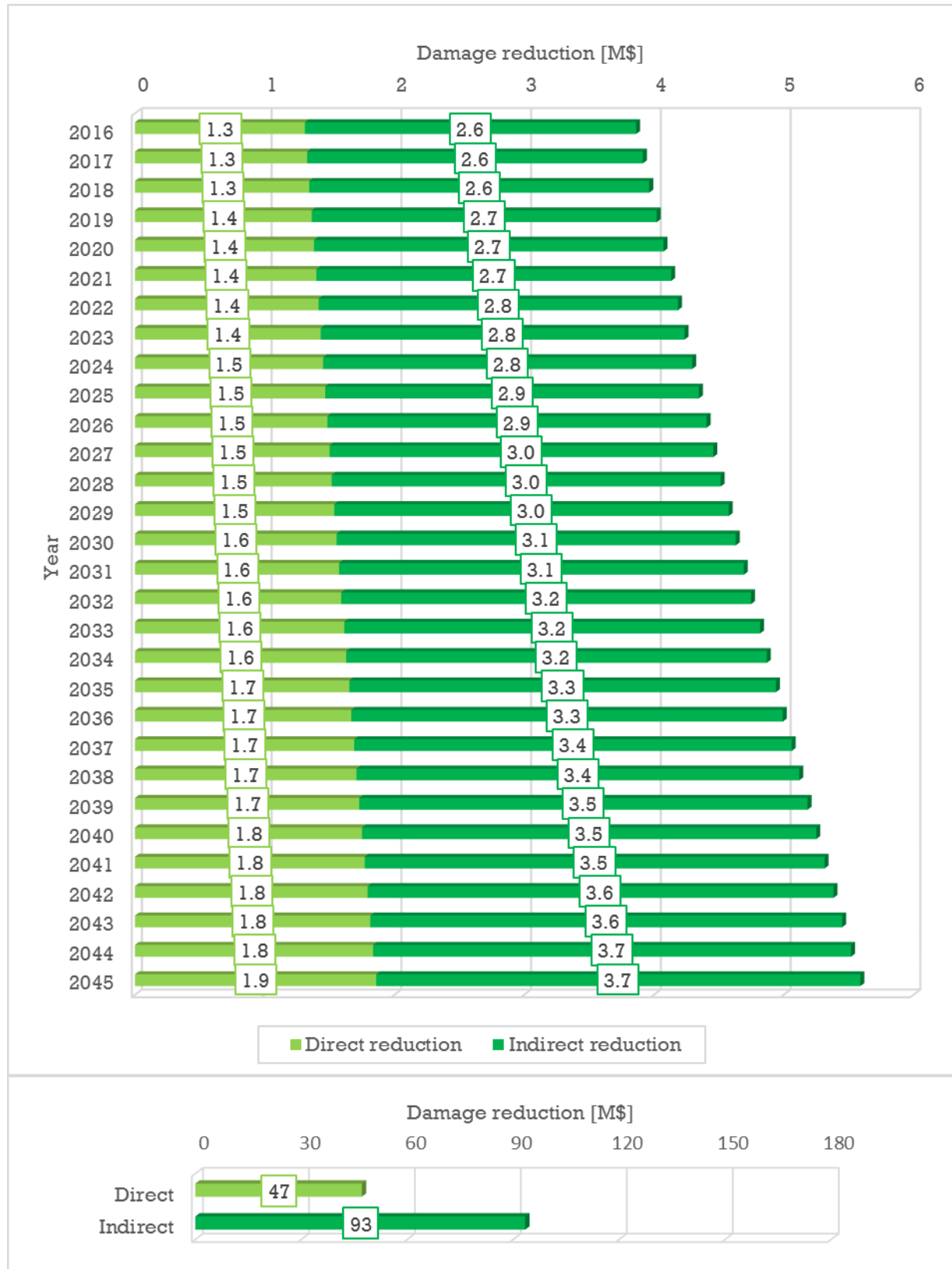


Figure 6-10: Annual and total damage reduction most cost-beneficial situation

Occurring damage after the interventions are constructed are shown in Figure 6-11, implying a yearly expected damage reduction between the \$ 3.2 M and \$ 4.9 M (direct) and \$ 0.7 M and \$ 1.1 M (indirect). The total expected flood damage throughout the concession period is \$ 143.8 M, meaning that the expected flood damage over the whole concession period is reduced by 54%.

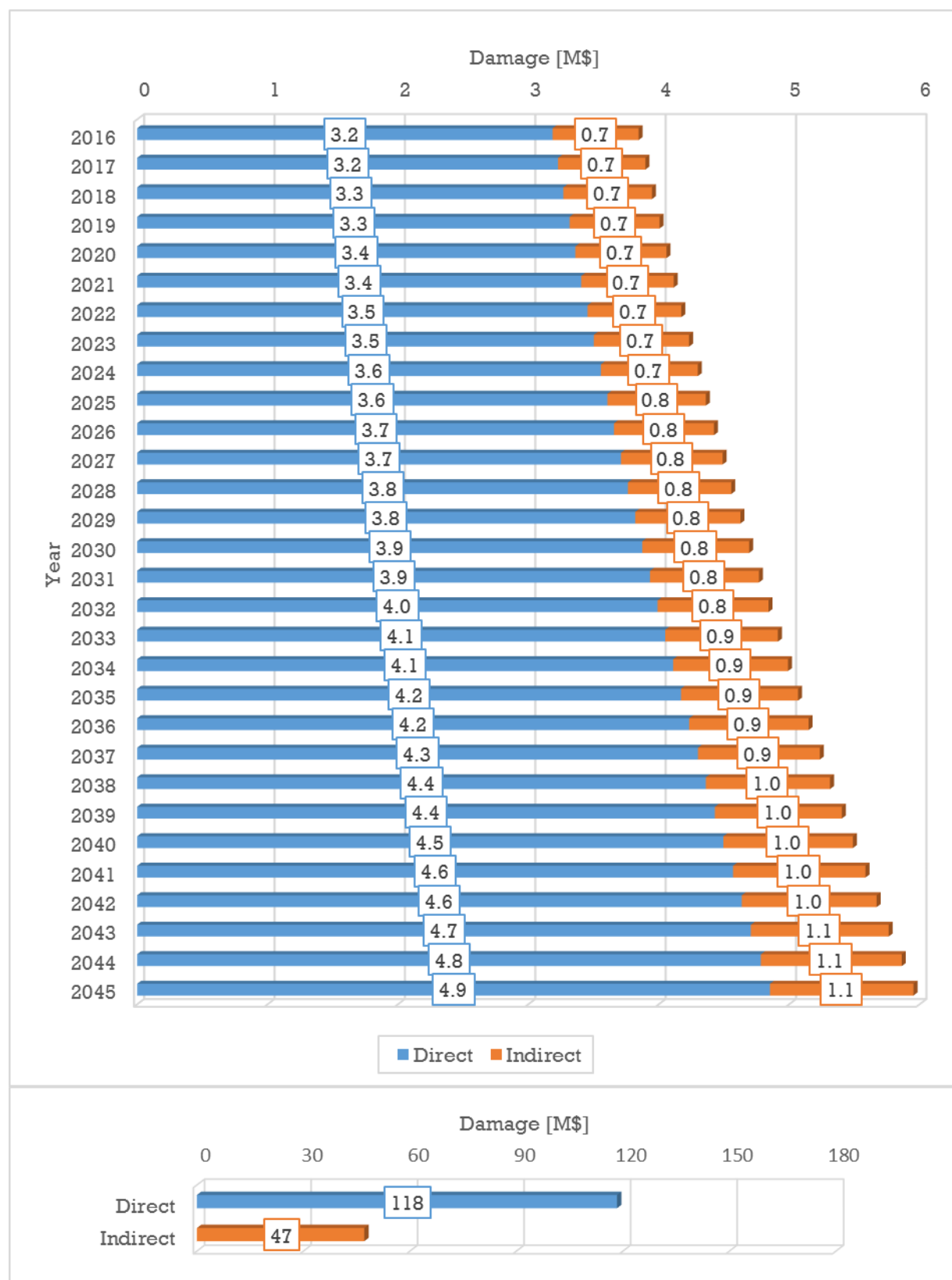


Figure 6-11: Annual and total damage most cost-beneficial situation

7

Conclusions

This report contains the development of a method to assess the impact of interacting MLS interventions on the economic damage caused by storm surges at container terminals. Subsequently, the developed method is applied within a container terminal case-study, to show its proof of concept. Given this development and application, the following conclusions are formed. The conclusion should be read in conjunction with the discussion.

7.1 Answering questions

In order to answer the main research question, the sub research questions are answered in this Paragraph. The specific question is indicated by “SQ” for a sub question and “MQ” stands for the main question. This research builds on the proposition that multi-layer safety is a promising approach assessing the impact of storm surges on the economic damage. The objective was to develop a model to study this proposition. This led to the first research question, which corresponds to Chapter 3 and consists of the *model structure*. Chapter 4 describes the case, whereby the *assets* and *fault events* have been identified, answering the second research question, followed by research question three, answered during Chapter 5, containing the *damage* and *capacity loss functions*. Subsequently, Chapter 6 elaborates on the fourth research question by showing the impact of *interventions* when applied within the case-study. Lastly, the main question is answered by considering the application of *MLS*.

Model structure (SQ 1)

In this present report, a model was developed according to a generic outline that holds an input, simulation and outcome phase. The input phase contains the selection of variables and establishment of their values. In order to assess multi-layer safety, the variables need to consist of flooding data (cause), its impact on the case (consequences), and possible interventions (solutions). It is important that the relationships between the cause and consequence of flooding have been identified for each single component in the case. Only by identifying the relationships for each element of the case (e.g. for a single building) it becomes possible to simulate the impact of interventions that just affect a section of the case. This is especially important when applying interventions from layer 2 and/or layer 3. The simulations led to an outcome that showed the consequence of flooding (0-situation); from there the impact of different interventions have been determined (improved situations). Based on the theory, an identical index is defined, which enables the model to compare the impact of interventions originating from different layers.

A container terminal case-study is elaborated in this research. The container terminal is situated in a harbor bay; due to the situation, storm surges have been the main cause of flooding. The influence of waves has been dismissed as their impact is limited, because of the sheltered locations. Dividing the impact of storm surges into direct and indirect damage, the relative repair costs and revenue losses have been determined. The partitioning of elements is performed by the assets, due to its application on container terminals, which enables the MLS-model to determine the direct damage of storm surges for each specific asset. Another important opportunity, realized by the partitioning, is that it has become possible to determine the impact of spatial planning and disaster management interventions (layer 2 and 3) on the indirect damage. This opportunity is possible when the assets are linked to relative fault events and structured in a fault tree. In this stage, the MLS-Model is able to calculate the impact of storm surges on the direct and indirect damage at container terminals (0-situation). The identical index has been expressed in dollars since container terminals typically hold a lot of value and revenue, no inhabitants and no historic buildings.

Identify assets and fault events (SQ 2)

Several steps were undertaken in mapping the case through the usage of the theory FMEA (failure mode and effects analysis). The most extensive step during this process has been the partitioning of the case, covering the description of functions of the system, their relationships, and potential failure modes. The functions are realized by assets, and their relationships and failure modes are defined by using the theory FTA (fault tree analysis). The result of this process considers the identification of the assets and fault events present in the case.

Assets of the container terminal case-study were divided into the following groups:

- Operations areas (control and maintenance);
- Electrical (mainstation, substations and generators);
- Ground transport (container cranes, straddle carriers, reach stackers and terminal trucks);
- Containers (full dry, empty and reefers);
- Fundamental (pavements, quay walls, foundation, revetment and others);
- External (backup data server, power supply, waterway, access road).

The upper parts of the possible fault events caused by storm surges at the container terminal case-study are visualized in Figure 7-1 (identical to Figure 4-29), which is a simplification of the entire fault tree (Figure 4-26).

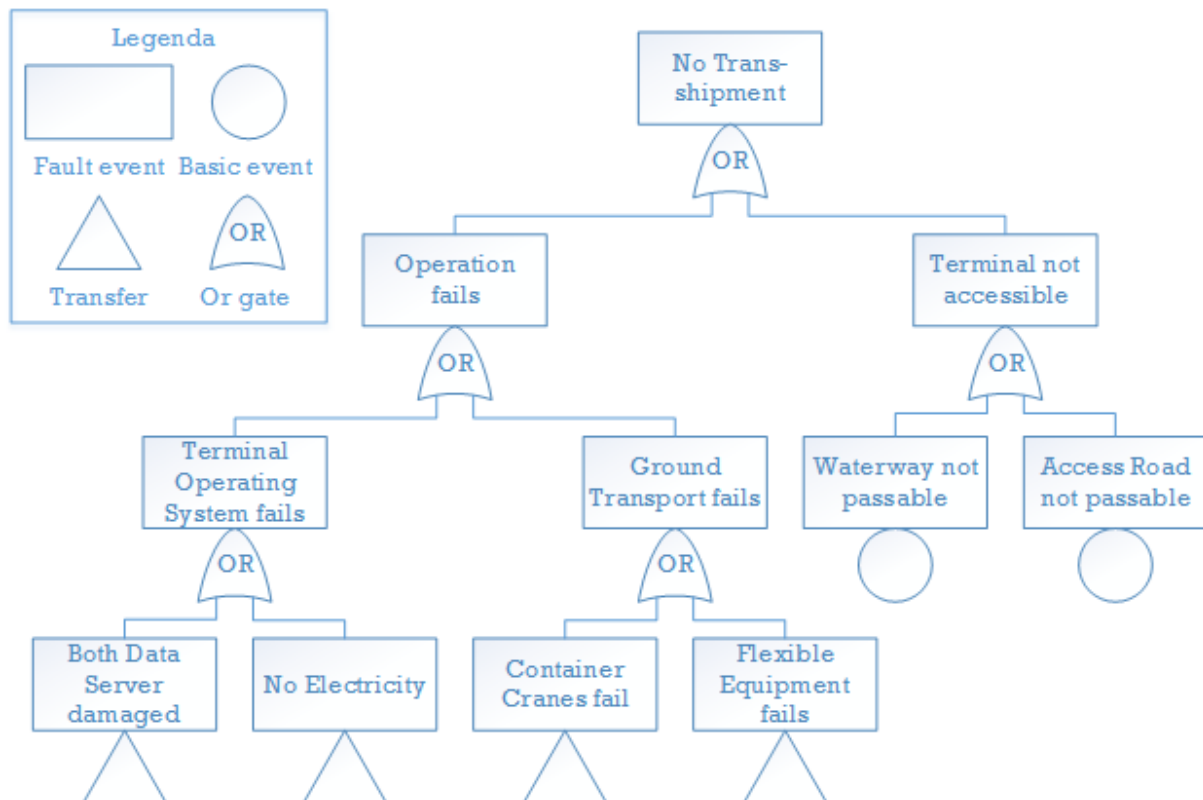


Figure 7-1: Simplified container terminal fault tree (based on Schüller et al., 2005)

Decisive assets and fault events (SQ 3)

Several functions, of the damage and capacity loss, have been designed during this research. These functions and other values needed within this case-study (i.e. asset values, downtimes, terminal revenues, economic growth and discount rate) are established by making use of several sources and the input of specialists in this field. The functions have been displayed via graphs and indicate to what extent the asset is damaged or has lost its capacity, relative to the inundation height.

A result of this process is that the occurring direct damage of each asset has been predicted according to the relative inundation height. The damage functions of the electrical assets appeared very steep, compared to the other functions. This means that these assets are extremely vulnerable to floods of low inundation heights. Other assets containing electrical components, such as straddle carriers, reach stackers, terminal trucks and reefers, scored slightly better but remain vulnerable. Contrary to this, the assets container cranes, empty containers, pavements and quay walls can withstand floods of higher inundation heights, whereas the foundation and revetment will not be affected at all. The damage functions of the remaining assets have an average score. Full dry containers appeared to be the asset with the most influence on the direct damage, due to their immense value in combination with an average damage function.

The capacity loss functions have been established via the same principle as the damage functions, supplemented by the FTA (fault tree analysis), whereby the assets have been linked to relative fault events (e.g. the asset container cranes relates to the fault event when container cranes fail). Given the inundation height, the estimated indirect damage of each asset can be predicted, due to the position in the fault tree and relationships to other fault events. The capacity loss functions of the control area, electric mainstation and waterway appeared the steepest, showing the big impact of floods. Due to the interaction between the fault events and influence on the terminal process, certain capacity loss functions will not reach their maximum, which applies for the electric substations, reach stackers, terminal trucks and access road. The assets foundation, revetment, generators and backup data server will not be affected by floods. Lastly, the remaining assets consider the average capacity loss functions, showing their moderate impact of floods. Due to the way the fault tree is structured and interrelationships between the fault events, several assets have a significant impact on the indirect damage. In particular the decisive assets electric mainstation, straddle carriers and waterway, because of their steeper capacity loss functions compared to other impactful assets.

Most cost-beneficial combination (SQ 4)

By using the established data of both functions (impact) and the expected storm surges (cause), the 0-situation of the case-study container terminal has been simulated via the MLS-Model. This simulation shows the impact of storm surges on each asset by determining the expected direct damage throughout the 30 year concession period. The total expected indirect damage for the case-study is calculated as well, by integrating the capacity loss functions, terminal revenue and fault tree. This simulation led to an expected storm surge damage of \$ 284.4 M during the concession period.

After the 0-situation was mapped, the simulation process continued by adding several interventions individually to the container terminal. Via an economic optimization, the extent to which the intervention should be constructed has been found, resulting in scores that imply to what extent the intervention should be applied to maximize the CBA. The CBA is the difference between the expected storm surge damage reduction and the investment needed to construct the intervention. The most cost-beneficial intervention appeared to be the enclosure of terminal A and realized an expected damage reduction of \$ 102.5 M through an investment of \$ 30.5 M, which corresponds to a rate of return of 3.4 and a cost-benefit of \$ 71.9 M.

Due to the outcomes of the individual applied interventions, a prediction of the most promising interactions between combined applied MLS interventions was formed. In simulating and optimizing the impact of these interventions, the most cost-beneficial combination has been found. The combination of the following interventions led to the most cost-beneficial effect: sectional enclosing terminal A, enclosing the electric mainstation and purchasing a dredging vessel. With a simulated required investment of \$ 31.5 M, the expected economic damage caused by storm surges is reduced by \$ 140.6 M during the concession period. Leading to a total cost-benefit of \$ 109.1 M, and a 4.6 rate of return.

Multi-layer safety interventions (MQ)

Now that the answer has been given to each of the four sub research questions, the main research question will be answered, which is been defined as follows:

Main research question

What is the impact of interacting multi-layer safety interventions on the expected economic damage caused by storm surges at container terminals?

Realizing prevention interventions (layer 1) to reduce the expected economic damage within the case-study appeared too costly. The investment needed to construct these interventions is higher than the maximum damage reduction. However, when the scope of the case is enlarged the prevention interventions will likely surpass interventions from other layers. This is because the maximum damage reduction is much higher. Spatial planning (layer 2) is able to reduce a significant amount of the expected damage for a relatively low investment, and therefore, appeared to be the most cost-beneficial intervention layer. This conclusion is based on the simulation outcomes within the case-study, where a moderate investment led to high damage reductions. Though a small investment is needed to realize the disaster management interventions (layer 3), they will have a relatively low impact on the damage reduction. The short building time in combination with the appearance that most of these interventions can only be applied in addition to other interventions, it can be concluded that disaster management is the most flexible intervention layer to apply.

Several combined applied MLS interventions occurred that had promising interactions, resulting in higher cost-beneficial outcomes compared to individually applied interventions. When the right intervention combinations are made, a very favorable cost-benefit score can be achieved. The most favorable interactions have been found in case interventions affecting relative fault events. This outcome can be explained by the extreme increase in the reduction of indirect damage. In case one relative input fault event occurs the output fault event takes place, but when both input fault events are prevented the output fault event will not appear, resulting in an extremely favorable MLS solution.

7.2 Discussion

A reflection of the undertaken research is described in this Paragraph. First, it looks at to the broader perspective, by elaborating limitations and critical notes, after which the opportunities of the study are covered.

Case complexity

The complexity of the MLS-Model will increase extremely when the scale of the case increases. Larger cases have an impact on the *complexity of variables* (e.g. the quantity of assets will grow or it becomes more difficult to establish the exact revenue). This is especially possible if the fault events and corresponding fault tree become unmanageable. This will occur when the MLS-Model is applied on, e.g., a large city. Therefore, making use of *asset management* seems incorrect in these situations. Of course, there are other methods to partition a case or determining the indirect damage (as suggested in Paragraph 7.3). However, it seems that changing the method will not reduce the complexity, without losing accuracy on the outcome. The present application is considered as a relatively small case, wherein asset management did prove to be a viable method.

Repeating interventions

Within the developed MLS-Model, it is not possible to determine the effect of interventions that appear several times during the concession period. The MLS-Model is structured in such a way that the impact of interventions is determined by first applying these interventions on the case, where after the expected economic damage through floods is calculated. Therefore, the effect of repeating interventions cannot be determined via the current method. This limitation occurs when disaster management interventions (layer 3) are used to temporarily replace standard elements. However, because of storm surges in which realize damage can only occur if a hurricane hits the terminal, the limitation is minimal. Hurricanes are a relatively rare event and, therefore, unlikely to hit the same location twice a year at the same location. Examples of this in the present case-study are the interventions containing rental contracts. Assets with a long downtime that have been damaged by a flood could temporarily be replaced by rentals. This effect could be calculated via the MLS-Model, but when another flood hits the terminal a few years later and the same temporary replacements need to be executed again, it becomes incalculable. To be able to calculate the effect of repeating interventions the model structure and the way of simulating needs to be adjusted. A small note on the researched case-study: it appeared that the disaster management (layer 3) interventions involving rental contracts (D2b, D3b and D4b) were less efficient than the spatial planning interventions (layer 2) affecting the same assets. The reasoning behind this is that the direct damage reduction of spatial planning interventions was higher than the needed investment, bearing in mind that the effect on the indirect damage of spatial planning interventions is at least equal to the disaster management interventions.

Identical index

Calculating other impacts than the economic ones are not possible within the current set-up. Of course, in order to compare the impact of MLS interventions, one identical index is essential. This is because of the fact that the impact of interventions originating from different layers needs to be compared, as well as the impact when these interventions interact in a combined applied solution. However, it cannot assess the effect on things like human lives or historic buildings. This limitation especially occurs when cases beyond container terminals need to be assessed and more effects than the economic ones are calculated.

Excel tool

During the process of building the MLS-Model in the program Excel, the scale of the model grew steadily. In the early stages, the program Excel seemed to be the right tool. This is a program that was able to transform the functions of storm surges and damage functions into direct damage throughout the entire concession period, by using the right commands and intermediate steps, something that was not always an easy thing to do. However, as the dataset became bigger and bigger, Excel was having a hard time executing the simulation. The MLS-Model became particularly intensive, due to the extensive Excel sheets containing the storm surge impact on the assets. There were seventeen sheets, matching the sum of assets, each considering a 30 year concession period multiplied by the storm surges of 100,000 different return periods. This means that there are seventeen sheets with 30 million different storm surges. To reduce the intensity, the data set was rationalized in such a way that it became functional again (as extensively elaborated in Appendix A). Other difficulties that occurred during the development of the MLS-Model in Excel have been the interrelationships calculating the indirect damage and simulating the impact of the multiple intervention options. In the end, the program was able to show its proof of concept and by that to create the data needed to answer the research questions; however, for more intense case studies the usage of another tool needs to be taken into account (Paragraph 7.3).

Flooding threat

Due to the increasing threat of flooding on a global scale, as a result of climate change and the associated sea level rise strengthened by land subsidence, the assumption could be made that the demand for flooding solutions is increasing. This could be done via a method that will indicate the flood risk and assess the potential interventions to cope with this risk. Not only by governmental agencies that tend to aim for larger scale cases like cities or countries, also in the private sector, where companies want to know their risk and opportunities to protect their assets.

7.3 Recommendations for further research

Further research on this topic could be executed in several ways, here are a few suggestions:

- **Other applications**

Considering the promising outcomes, it could be favorable to apply the same method in other cases. In this research, the newly developed method is applied on a relatively small scale. By quantifying the MLS-Model, one will be able to compare the outcomes and gain more insight into MLS applications. Even cases with a larger scale can be chosen for this purpose; this will increase insight into the possibilities of MLS and the method even more.

- **Other tool**

To translate the input data into the outcomes, the simulation process is fulfilled by using Excel, a program that has its difficulties (as described in Paragraph 7.2). Using another tool to fulfill the simulations can be favorable or even necessary when one wish to apply the method in case studies of a larger scale.

- **Other method**

It could be interesting to develop a method that results in similar outcomes as the MLS-Model, but is based on other theories. Within this research, a combination of the theories, flood risk and asset management, is made one the partitioning process that enables the MLS-Model to assess the impact of storm surges on each asset. Replacing asset management with other theories is especially interesting when other solutions may be more applicable (e.g., in case tons of assets are situated in the area the partitioning can be realized by, e.g., dividing the area into different of a surface).

- **Add failure modes**

The MLS-Model is based on one failure mode: storm surges. This was chosen as the failure mode because the assumption is made that this failure mode is decisive. However, in other circumstances, it can be that different or multiple failure modes (e.g. wave run-up or heavy rainfall) are decisive. Taking more failure modes into account in these situations increases the accuracy and possibilities of the model. Even failure modes outside hydraulic engineering could be interesting (e.g. a potential fire, earthquake or strike)

- **Add solutions**

As the title of the model implies, the MLS-Model looks to flood interventions originating from three layers. By looking to a wider scope of solutions outside hydraulic engineering, more beneficial results could be achieved. This especially applies when other failure modes are added to the method, which makes adding solutions affecting these failure modes necessary. Examples are additional insurance, fire stations, or regular contact with labor unions.

IV

Literature

Ackoff, R. (1967), *Management of misinformation systems*, pages B147-156. Management Science, vol. 14, no. 4, Pennsylvania, USA.

AIAG (1995), *Potential Failure Mode and Effect Analysis (FMEA) Reference Manual*, 4th Edition. Automotive Industry Action Group, Michigan, USA.

Alconet (2016), *Image of a reefer*. Retrieved on May 26, from <http://www.alconet-containers.com/containers/reefer-containers/40-ft-reefer-container-new/>.

Alibaba (2016), *Numerous prices on 20ft and 40ft reefers and regular container compared*. Retrieved on April 13 until 27, 2016, from alibaba.com.

Arnell, N. W. (1989), *Expected Annual Damages and Uncertainties in Flood Frequency Estimation*. Journal of Water Resources Planning and Management, Vol. 115, No. 1, Oxon, United Kingdom.

Bardet, L., Duluc, C.M., Rebour, V. and L'Her, J. (2011), *Regional frequency analysis of extreme storm surges along the French coast*. European Geosciences Union, Fontenay aux Roses Cedex, France.

Beroggi, G.E.G. and Wallace, W.A. (1998), *Operational risk management : the integration of decision, communications, and multimedia technologies*. Kluwer Academic Publishers.

Bloomberg, 2012, *Image of fully dry container stack*. Gettyimages. Retrieved on May 26, from <http://www.gettyimages.nl/detail/nieuwsfoto's/straddle-carrier-moves-a-freight-container-on-the-quay-nieuwsfotos/138992408>.

Boersma, C. (2015), *Land subsidence in peat areas*. Deltares, Delft.

Boudali, H. Crouzen, P. and Stoelinga, M. (2010), *A Rigorous, Compositional, and Extensible Framework for Dynamic Fault Tree Analysis*, vol. 7, no. 2. IEEE, Noordwijk.

Briggeman (2016), *Image of maintenance hangar inside*. Retrieved on April 20, from <http://www.briggeman.co.za/training-for-durban-container-terminal/>.

Boekhout, P. (2013), *Reefer ships versus containers*. Seatrade Reefer Chartering N.V., Retrieved on April 27, 2016, from <http://www.freshplaza.com/article/109657/Reefer-shipsversus-containers>.

Bots, P. and Bouwmans, I (2016), *Systeemmodellering*. TU Delft. Retrieved on August 30, 2016, from <https://mod-est.tbm.tudelft.nl/wiki/index.php/Hoofdpagina>.

Brouwer, C. (2015), *Sneller engineeren dankzij functionele decompositie*. EPLAN Software & Services B.V. Retrieved on January 14, 2016, from <http://www.eplanblog.nl/eplanblog-nl-blogitemprintheadler.asp?b=17>.

CameliaTWU (2008), *Image of an electric station*. Flickr, Ardmore, Oklahoma, USA.

Campbell, J.D., Jardine, A.K.S. and McGlynn, J. (2011), *Asset Management Excellence: Optimizing Equipment Life-Cycle Decisions*. CRC Press, Taylor & Francis Group, Boca Raton, USA.

Central Dutch Government (2009), *Nationaal Waterplan 2009-2015*.

Central Dutch Government (2013), *Dordrecht, Marken en IJssel-Vecht proefgebied voor 'meerlaagse' bescherming tegen hoogwater*. Central Dutch Government. Retrieved on January 6, 2016, from <https://www.rijksoverheid.nl/actueel/nieuws/2013/11/15/dordrecht-marken-en-ijssel-vecht-proefgebied-voor-meerlaagse-bescherming-tegen-hoogwater>.

Central Dutch Government (2015a), *Memorie van toelichting wijziging van de Waterwet nieuwe normering primaire waterkeringen: consultatieversie*.

Central Dutch Government (2015b), *Nationaal Waterplan 2016-2021: Ons Water in Nederland*.

Central Dutch Government (2016a), *Waterbeheer*. Retrieved on January 8, 2016, from <http://www.helpdeskwater.nl/onderwerpen/gebruiksfuncties/waterbeheer>.

Central Dutch Government (2016b), *Waterwet*. Retrieved on April 2, 2016, from <http://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/waterwet/>

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D. and Unnikrishnan, A.S. (2013), *Sea Level Change*. In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J.A., White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X. (2004), *Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period*. CSIRO Marine Research, Hobart, Australia.

Church, J.A., White, N.J., Aarup, T., Wilson, W.S., Woodworth, P.L., Domingues, C.M., Hunter, J.R., Lambeck, K. (2008). *Understanding global sea levels: past, present and future*. Integrated Research System for Sustainability Science and Springer.

CIA (2016), *Field Listing: Natural Hazards*. Central Intelligence Agency. Retrieved April 19, 2016, from <https://www.cia.gov/library/publications/the-world-factbook/fields/2021.html>.

Coburn, C., Cornwell, A., Gloster J., Hylton, P., Risher, J., Skinner, J., Wilson, R. (2013), *Working Waterfronts: The Economic Impact of Sea Level Rise on Port of Savannah's Garden City Terminal & City of Darien*. Georgia Institute of Technology, School of City & Regional Planning, USA.

Congo Terminal (2016), *Image of maintenance hangar outside*. Retrieved on April 20, from http://www.congo-terminal.net/uploads/images/Gallery/terminal/Atelier-de-Maintenance/dt_1.jpg.

Cummins and Cederberg (2016), *Image of revetment*. Cummins and Cederberg Coastal and Marine Engineering. Retrieved on May 26, from <http://www.cumminscederberg.com/projects/caribbean/goldeneyeddevelopment.aspx>.

CUR (2005), *Handbook Quay walls*. Civieltechnisch Centrum Uitvoering Research en Regelgeving, Gouda.

DACE (2012), *Prijzenboekje: editie 29*. Dutch Association of Cost Engineers, Nijkerk.

Dalton, S. (2013), *Hurricane Sandy Impact on Marine Insurance Market and Lessons Learned*. Zurich Global Corporate in North America.

Dekker, N. (2014), *Global reefer trades: 2014*. Drewry Maritime Research, Long Beach, USA.

Delaunay, N. (October 31, 2015), *Dutch technology leads the world in helping conquer the rising seas*. Shanghai Daily.

Delic, M., Ilić, S., Glišović, J. and Ćatić, D. (2015), *Dynamic Fault Tree Analysis of Lawnmower*. 9th International Quality Conference, Faculty of Engineering, University of Kragujevac.

Deltares (2015), *Sinking cities: An integrated approach towards solutions*, first update January 2015. Deltares, Delft/Utrecht.

Delta Committee (1960), *Rapport Deltacommissie: Eindverslag en interimadviezen*. Staatsdrukkerij, Den Haag.

Delta Committee (2008), *Samen werken met water: Bevindingen van de Deltacommissie 2008*.

Deviant Art (2016), *Image of straddle carrier*. Retrieved on April 20, from <http://trebornehoc.deviantart.com/art/straddle-carriers-296083445>.

Dircke, P., Aerts, J. and Molenaar, A. (2010), *Connecting Delta Cities: Sharing Knowledge and Working on Adaptation to Climate Change*. City of Rotterdam, Rotterdam.

Dorfman, M. and Mehta, M. (2011), *Thirsty for Answers: Preparing for the Water-related Impacts of Climate Change in American Cities*. NDRC, USA.

Dutch power generators (2016), *Image of a generator*. Dutch power generators, retrieved on May 26, from <http://dutchgenpower.com/>.

Expert group (2014), *Draft guidelines on vessel's safe under keel clearance*. Group of Experts on Safety of Navigation, Helsinki Commission, Finland.

El-Asmar, H.M. and Hereher, M.E. (2010), *Change detection of the coastal zone east of the Nile Delta using remote sensing*. Springer-Verlag, Egypt.

ESB, 2016, *Standard Prices for Generator Connections*. ESB Networks, Ireland.

FEMA, 2013, *Hazus®-MH MR5: Technical Manual*. Department of Homeland Security, Federal Emergency Management Agency and Mitigation Division, Washington, D.C., USA.

Front page: Wikimedia (2011), *Japanese container terminal after a tsunami*. Wikimedia, retrieved on September 16, from <https://upload.wikimedia.org/wikipedia/commons/c/cc/USMC-110401-M-QE984-444.jpg>.

Gerritsen H (2005), *What happened in 1953? The Big Flood in the Netherlands in retrospect*. Philosophical Transactions of the Royal Society, vol. 363, pp. 1271-1291, Delft.

Hamilton, T. M. (2013), *River disruptions and strikes lower U.S. petroleum product exports to Northwest Europe*. U.S. Energy Information Administration. Retrieved on December 14, 2015, from <http://www.eia.gov/todayinenergy/detail.cfm?id=13691>.

Hall, J.W., Sayers, P.B. and Dawson, R.J. (2004), *National-scale Assessment of Current and Future Flood Risk in England and Wales*. Springer, Newcastle, United Kingdom.

Hallegatte, S., 2006. *A cost-benefit analysis of the New Orleans Flood Protection System*. AEI-Brookings Joint Center. Regulatory Analysis, pp. 1-18.

Heijnen, P.W. and Bots, P.W.G. (2015), *Dictaat TBI35A Besliskunde*, chapter 1. TU Delft, Delft.

Hemer, M. A., Y. Fan, N. Mori, A. Semedo, and X. L. Wang (2013), *Projected future changes in wind-wave climate in a multi-model ensemble*. Nature Clim. Change, 3, 471–476. Hungry

Helsloot, I. (2007), *De Symboliek Voorbij*. Boom Juridische uitgevers, Den Haag.

Higgins, A. (November 14, 2012), *Lessons for U.S. From a Flood-Prone Land*. The New York Times.

Hinkelman, E.G. (2005), *Dictionary of international trade: 6th edition*. World Trade Press, California, USA.

Iba-ez, C., Day, J.W., Canicio, A., Prat, N. and Curc A. (1996) *The Ebro Delta, Spain: water and sediment management in the context of relative sea level rise*. Mediterranean coastal environment, MEDCOAST, Ankara, Turkey, pp 809–826.

IMF (2016), *World Economic Outlook: Too Slow for Too Long*. International Monetary Fund, Washington, DC, USA.

Jonkman, S.N., Bočkarjova, M., Kok, M. and Bernardini, P. (2007), *Integrated hydrodynamic and economic modelling of flood*. Elsevier.

Jonkman, S.N., Brinkhuis-Jak, M. and Kok, M. (2004), *Cost benefit analysis and flood damage mitigation in the Netherlands*. HERON, vol. 49, no. 1.

Jonkman, S.N., Kato F. and Vrijling, J.K. (2005), *A comparison on flood risk assessment practices in the Netherlands and Japan*. Proceedings of the 29th International Conference on Coastal Engineering, ICCE 2004, Lisbon, Portugal, pp. 3049-3060.

Jonkman, S.N., Kok, M., Van Ledden, M. and Vrijling, J.K. (2008a), *Risk-based design of flood defence systems: a preliminary analysis of the optimal protection level for the New Orleans metropolitan area*. Journal of Flood Risk Management, Toronto, Canada.

Jonkman, S.N., Kok, M. and Vrijling, J.K. (2008b), *Flood Risk Assessment in the Netherlands: A Case Study for Dike Ring South Holland*. Risk Analysis, vol. 28, issue 5, pp. 1357-1374.

Kalmar (2016), *Several press releases about orders of equipment*. Retrieved on June 7, from e.g. https://www.kalmarglobal.com/newsroom/press_releases/2014/kalmar-gains-important-orders-from-dp-world-for-terminal-tractors-and-empty-container-handlers-for-jebel-ali-port/.

Keen, P.G.W. (1980), *Adaptive Design For Decision Support Systems*. ACM, vol. 1 and 12, pp. 15-25, New York, USA.

Keeney, R. L. (1982), *Decision Analysis: An Overview*. Operations Research, pages; 803-838, San Francisco, USA.

Klijn, F., Baan, P., De Bruijn, K and Kwadijk, J. (2007), *Overstromingsrisico's in Nederland in een veranderend klimaat*. Delft Hydraulics, Delft.

Kok, M., Huizinga, H.J., Vrouwenfelder, A.C.W.M. and Barendregt, A., *Standaardmethode 2004 Schade en Slachtoffers als gevolg van overstromingen*. HKV lijn in water, Lelystad.

Kok, M. (2013), *Meerlaagsveiligheid: nuttig?*. Column in Het Waterschap, vol. 7.

Kolen, B. and Kok, M. (2011), *Basisvisie Afwegingsmethodiek voor meerlaagsveiligheid*. STOWA, Amersfoort.

Kolen, B. and Kok, M. (2013), *An economical optimal investment strategy in a multi-layer flood risk approach*. Comprehensive Flood Risk Management, London, United Kingdom.

Kolen, B, Maaskant, B and Hoss, F (2010), *Meerlaagsveiligheid: Zonder normen geen kans*. HKV lijn in water, Lelystad.

Kosan Crisplant (2016), *Image of terminal fuel facility*. Retrieved on April 20, from <http://www.kosancrisplant.com/en/home/cases/case-vulcano-gas-italy/>.

Kumagai, K. (2013), *Tsunami-induced Debris of Freight Containers due to the 2011 off the Pacific Coast of Tohoku Earthquake*. National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism, Japan.

Lechter, C. (2012), *Why does salt water make hurricane damage so much worse?* Popular Science, retrieved on June 22, from <http://www.popsoci.com/science/article/2012-10/fyi-does-salt-water-make-hurricane-damage-worse>.

Liebherr (2016), *Image of container cranes*. Retrieved on April 3, 2016, from <http://www.liebherr.com/en/deu/products/maritime-cranes/port-equipment/container-bridges/ship-to-shore-container-cranes.html>.

Lopeman, M. (2015), *Extreme Storm Surge Hazard Estimation and Windstorm Vulnerability Assessment for Quantitative Risk Analysis*. Colombia University, USA.

Mabrouki, C., Bellabdaoui, A. and Mousrij, A. (2013), *Risk Analysis and Assessment by Multicriteria Approach Based in RO-RO Port Terminals*. International Journal of Computer Science Issues, vol. 10, issue 3, no. 1, pp. 37-45.

Mai, C.V., Vrijling, J.K., van Gelder, P.H.A.J.M and Mai, T.C. (2008), *Risk analysis of coastal flood defences, a Vietnam case*. Proceedings of the 4th International Conference on Flood Defence, Toronto, Canada, pp. 93/1-93/8.

Marine Exchange of Southern California (2016), *Harbor Safety Program: Appendix XIV. Underkeel clearance*. Los Angeles/Long Beach Harbor Safety Committee, USA.

Martín Soberón, A.M. (2012), *The Capacity in Container Port Terminals*. Valenciaport Foundation, Geneva, Switzerland.

Merle, G., Roussel, J.M. and Lesage J.J. (2010), *Improving the Efficiency of Dynamic Fault Tree Analysis by Considering Gate FDEP as Static*, pp. 845-851 Taylor & Francis, Rhodes, Greece.

My news desk (2016), *Image of container distribution process*. Retrieved on April 20, from http://www.mynewsdesk.com/uk/goteborgs_hamn/pressreleases/new-deep-sea-service-between-the-port-of-gothenburg-and-japan-1114348.

Netherlands Water Partnership (2014), *Groundbreaking event starts work on Jakarta's ambitious 40 billion coastal development NCICD project*. Netherlands Water Partnership. Retrieved on December 14, 2015, from <http://www.dutchwatersector.com/news-events/news/11974-groundbreaking-event-starts-work-on-jakarta-s-ambitious-40-billion-coastal.html>.

NOAA (2005), *Image of the Gulfport after Katrina*. National Oceanic and Atmospheric Administration. Retrieved on April 28, from <http://www.noaa.gov/stories2005/images/katrina-gulfport-miss2-08-30-2005.jpg>.

- O'Donoghue (2016), *Conversation about delivery times of equipment*. Liebherr Container Cranes Ltd., Ireland.
- PBL Netherlands Environmental (2015), *Map of flood-prone areas*. PBL Netherlands Environmental. Retrieved on December 10, 2015, from <http://www.pbl.nl/en/dossiers/Climatechange/content/correction-wording-flood-risks>.
- Pillay, A and Wang, J. (2003), *Modified failure mode and effects analysis using approximate reasoning*. Reliability Engineering and System Safety, vol. 79, pp. 69-85.
- PLS (2016), *Image of a reach stacker*. PLS Logistics. Retrieved on May 25, from <http://info.plslogistics.com/blog/the-history-of-containers>.
- Pötz, H., Anholts, T. and De Koning, M. (2014), *Meerlaagsveiligheid: waterrobuust bouwen in stedelijk gebied*. STOWA, Amersfoort.
- ProRail, Rijkswaterstaat, Bouwend Nederland, NLingenieurs, de Vereniging van Waterbouwers and Uneto-VNI (2013), *Leidraad voor Systems Engineering binnen de GWW-sector: versie 3*. Grafisch Bedrijf Bokhorst, Nunspeet.
- QES, 2016, *Image of Pavements*. Quality Engineering Solutions. Retrieved on May 26, from http://01f1a8d.netsolhost.com/05-031_pic1.html.
- Rodrigue, J-P., Comtois, C. and Slack, B. (2013), *The Geography of Transport Systems, Third Edition*. New York: Routledge.
- Roman C.T. (2011): Natural Resource Management Issues Confronting Estuaries in the Northeast: Focus on Salt Marshes and Habitat Restoration. *North Atlantic Coast Cooperative Ecosystem Studies Unit and University of Rhode Island, Narragansett, USA*.
- Safety4sea (2016), *Image of empty container stack*. Retrieved on May 26, from <http://www.safety4sea.com/the-do-s-and-dont-s-for-containers/>.
- Sayarah, J. and Ahouei, R. (2013), *Failure Mode and Effects Analysis (FMEA) for Reducing the Delays of Cargo Handling Operations in Marine Bulk Terminals*. Journal of maritime research, vol. X., no. 2, pp. 43-50.
- Schüller, J.C.H., Brinkman, J.L., Van Gestel, P.J. and Van Otterloo, R.W. (2005), *Methods for determining and processing probabilities: Red Book*. Publication Series on Dangerous Substances, Den Haag.
- Searates (2016), *The world's largest online shipping platform*. Retrieved on May 14, from <https://www.searates.com/>.
- Seyed-Hosseini, S.M., Safaei, N. and Asgharpour, M.J. (2006), *Reprioritization of failures in a system failure mode and effects analysis by decision making trail and evaluation laboratory technique*. Reliability Engineering and System Safety, vol. 91, pp. 872-881.
- Smest (2016), *Image of a electric substation*. Retrieved on May 30, from <http://www.smest.com/Info/?id=4>
- Slangen, A.B.A., Katsman, C.A., Van der Wal, R.S.W., Vermeersen, L.L.A. and Riva, R.E.M. (2011), *Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios*. Springerlink.com.
- Smith, O. (July 21, 2015), *What are the seven wonders of the world?*. Telegraph.
- Southafrica (2016), *Image of operation building impression*. Retrieved on April 23, from <http://www.southafrica.to/transport/cruises/Starlight/Sinfonia/boarding-Sinfonia-Durban.php5>.

Stamatis, D.H. (2003), *Failure Mode Effect Analysis: FMEA from Theory to Execution, 2nd Edition*. Quality Press, Milwaukee, Wisconsin.

Steketee, H. (March 9, 2013), *Nederlandse waterbouw poldert in de hele wereld*. NRC.

Stoeten, K. (2013), *Hurricane Surge Risk Reduction For Galveston Bay*. TU Delft, Delft.

Tebodin (2000). *Schadecurves industrie ten gevolge van overstroming*. Tebodin consultants & engineers, document nr 334666, Nederland.

Terpstra, T. (2009), *Flood preparedness: Thoughts, feelings and intentions of the Dutch public*. University of Twente, Enschede.

The President Post (2016), *Image of terminal truck*. Retrieved on April 3, from <http://www.thepresidentpost.com/2011/12/29/organda-recommends-5600-trucks-to-access-priok-port/>.

The Tioga Group, University of Texas, and University of Carolina (2011), *NCFRP Report 11: Truck Drayage Productivity Guide*. Transportation Research Board, Washington D.C., USA.

Total (2016), *Building a service station*. Retrieved on June 9, from <http://www.totaloil.com.ph/service-stations/become-partner.html>.

Tsimopoulou, V. (2015), *Economic optimisation of flood risk management projects*. TU Delft, Delft.

Tsimopoulou, V., Vrijling, J.K., Kok, M., Jonkman, S.N. and Stijnen, J.W. (2013), *Economic implications of multi-layer safety projects for flood protection*. TU Delft, Delft.

USACE (2016), *Hydrologic Engineering Center*. US Army Corps of Engineers, retrieved on May 15, from <http://www.hec.usace.army.mil/software/hec-fda/>.

Van Dantzig, D. (1956), *Economic decision problems for flood prevention*. *Econometrica*, vol. 24, pp. 276-287.

Van den Brink, H.W. and Können, G.P. (2009), *Estimating 10000-year return values from short time series*. Royal Netherlands Meteorological Institute, De Bilt.

Verschuren, P., Doorewaard, H., & Mellion, M. (2010), *Designing a research project: second edition*. Eleven International Publishing, Den Haag.

Volker Stevin (2016), *Image of Quay walls*. Volker Stevin. Retrieved on May 26, from <http://www.volker-stevin.com/en/marine-structures/quay-walls>.

Voorendt, M (2015), *The development of the Dutch Flood safety strategy*. TU Delft, Delft.

Vrijling, J.K. (2014), *Multi layer safety: A generally efficient solution or work for all. Safety, Reliability and Risk Analysis: Beyond the Horizon*. Taylor & Francis Group, London, United Kingdom.

Walton T.L. Jr. (1999), *Distributions for storm surge extremes*. US Army Engineer Research and Development Center, Vicksburg, USA.

World Shipping Council (2016), *About the industry: containers*. World Shipping Council. Retrieved on March 16, 2016, from <http://www.worldshipping.org/about-the-industry/containers>.

Zethof, M., Maaskant, B., Stone, K. Kolen, B and Hoogendoorn, R. (2012), *Handreiking Meerlaagsveiligheid: Methode Nader Verklaard*. HKV lijn in water and Deltares.

V Confidential literature

For confidentiality reasons this section of literature is hidden.

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VI Appendices

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Appendix A Excel sheets

In this Appendix the structure of the MLS-Model in Excel is described. As can be read in Paragraph 3.3, the 65 excel sheets are structured via the Figure App A-1 visualized way, consisting of the following groups:

- 7 data sheets (A.1)
- 17 direct damage sheets (0)
- 17 indirect damage sheets (A.3)
- 23 intervention sheets (A.4)
- 1 optimization sheet (A.5)

A.1 Datasheets

The input data consist the following seven Excel sheets:

1. Storm surges
2. Probabilities
3. Revenue
4. Asset values
5. Damage functions
6. Downtimes
7. Capacity loss functions

Storm surges and probabilities

A forecast of the expected storm surges for the upcoming 30 years are displayed by year and return period (Paragraph 5.1). There is chosen to divide the storm surges per year, because of the differences throughout the year in inundation heights, realized by inter alia the hurricane season. The associated probability of each storm surge is determined according to the return period. Table App A-1 shows an illustration how both data sets are processed in Excel. The inundation heights and probabilities of the return periods 3 until 100,000 years are omitted, because of illustration reasons. However, these values are included in the Excel sheet. The increase of inundation heights associated to return periods higher than 100,000 years are very close to 0, just as the delta probability that such an inundation will occur. These reasons lead to the decision to excluded higher return periods than 100,000 years.

Table App A-1: Storm surges and probabilities Excel illustration

Year Return period [years]	Inundation heights [m]				Delta probability [-]
	2016	2017	...	2045	
1	0.00	0.00	...	0.00	0.50
2	0.00	0.00	...	0.00	0.17
...	...	...	...	...	...
100,000	2.31	2.31	...	2.45	0.00

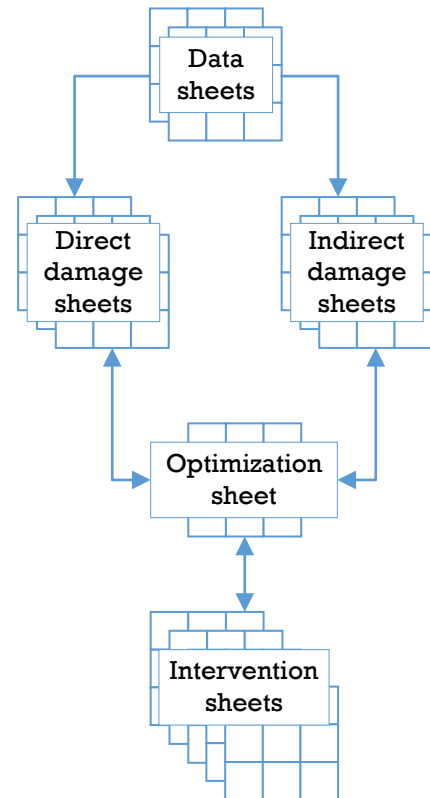


Figure App A-1: Implemented MLS-Model

Working via this way creates extreme data intensive Excel sheets. Imagine that storm surges of 100,000 return periods throughout a 30 year concession period are equal to 30 million data points. However, not only the storm surge sheet becomes this data intensive, the asset and fault event sheets are not different. These 34 sheets are used in the simulation process and consist of direct and indirect damage of each possible storm surge (described in Appendix 0 and A.3), meaning that each sheet has 30 million data points as well. Leading to an extreme intensive database, whereby simulation became unmanageable for regular computers. Therefore, the sheets are designed fewer data intensive by dividing the storm surges into groups. Storm surge groups become larger, as the return period gets higher. This decision is made to maintain a high accuracy because the increase in inundation height becomes smaller, just as the delta probability of storm surges. The division of

Table App A-2: Storm surge groups

Return period [years]	Steps [years]
1 – 100	1
101 – 1000	10
1001 – 5000	100
5001 – 50,000	1000
50,001 – 100,000	10,000

the group is illustrated in Table App A-2, showing that the storm surges of the first 100 return period are separated per return period. Followed by steps of 10 years, meaning that the average storm surge of a 10 year return period is used, according to Equation 3-3 and Equation 3-4. The next steps were fulfilled according to the same principle. By using this way of organizing the data, simulation becomes feasible for regular computers.

Revenue

Increase in revenue at the container terminal throughout the concession period is determined per year, this enables the model to calculate the indirect damage annually. The revenue increase is visualized via a line graph in Figure App A-2, which consists of the same data as the Excel sheet illustration (Table App A-3).

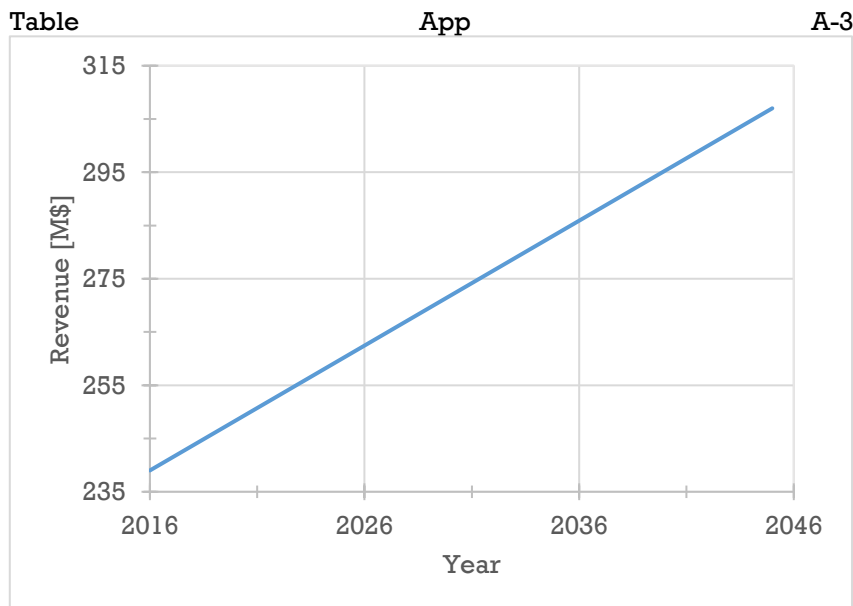


Table App A-3: Annual revenue of the container terminal Excel illustration

Year	Revenue [M\$]
2016	239
2017	241
...	...
2045	307

Figure App A-2: Revenue of the container terminal throughout the concession period

Assets and fault events

The assets and their corresponding fault events, values, damage functions, downtimes and capacity loss functions are extensively elaborated in Appendix C and 0. An overview of the results can be seen in Table 5-5. In Excel, these data sets are divided into the four eponymous sheets.

A.2 Direct damage sheets

There are seventeen direct damage sheets, which are divided according to the assets:

1. Control area
2. Maintenance area
3. Electric mainstation
4. Electric substations
5. Generators
6. Container cranes
7. Straddle carriers
8. Reach stackers
9. Terminal trucks
10. Full dry containers
11. Empty containers
12. Reefers
13. Pavements
14. Quay walls
15. Foundation
16. Revetment
17. Others

The damage functions are divided into several parts, where each part corresponds to a particular sub-function. By separating the damage functions, data from the graph can be translated into actual numbers, which allows the model to automate the simulation process. An example of a separation is shown in Figure App A-3, where the damage function of the control area is divided into several sub-functions. This process leads to (1) data sets containing the expected asset damage per inundation height (Table App A-4). The word “sim” means that these values will be found by running the simulation and making use of the previously described data sheets. There is chosen for inundation heights in steps of a centimeter and damage of a million dollars. The reasoning behind these decisions is that these indexes are best suited, compared to the input data, and the MLS-Model is still able to fulfill the simulation process on regular computers because the data intensiveness remains manageable.

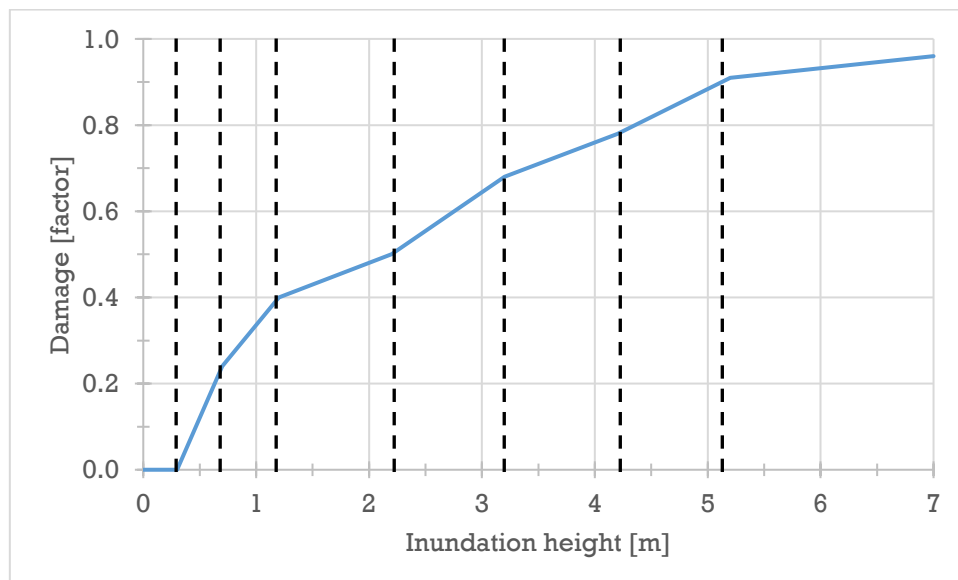


Figure App A-3: Damage function control area with sub-functions

Table App A-4: Damage factor and asset damage per inundation height Excel illustration

Inundation height [m]	Damage factor [-]	Asset damage [M\$]
0	sim	sim
0.01	sim	sim
...	sim	sim
2.46	sim	sim

Considering the integration of the data sets expected storm surges, probabilities and damage on assets, the next step results in (2) the delta damage (Table App A-5). The delta damage is the increase in asset damage compared to the previous return period, as described in Equation 3-3. The described steps need to be fulfilled for each of the seventeen assets, meaning that each asset will have its own simulation sheet. Summing the outcomes enables the model to determine (3) the expected total direct damage at the container terminal.

Table App A-5: Asset damage throughout the concession period Excel illustration

Return period [years] \ Year	Asset damage [M\$]			
	2016	2017	...	2045
1	sim	sim	sim	sim
2	sim	sim	sim	sim
...	sim	sim	sim	sim
100,000	sim	sim	sim	sim

A.3 Indirect damage sheets

The Excel model has seventeen indirect damage sheets, divided by the following assets, in relationship to the influential fault events:

1. Control area
2. Maintenance area
3. Electric mainstation
4. Electric substations
5. Container cranes
6. Straddle carriers
7. Reach stackers
8. Terminal trucks
9. Full dry containers
10. Empty containers
11. Reefers
12. Pavements
13. Quay walls
14. Others
15. Power supply
16. Waterway
17. Access road

Calculating the indirect damage, caused by the expected storm surges at container terminals throughout the concession period, is slightly different compared to the direct damage steps. A different calculation method, is the reasoning behind this difference, as explained in Paragraph 3.2.2. The first step is similar, whereby the (1) downtimes of each of the seventeen fault events and associated inundation heights are established (Table App A-6).

Table App A-6: Capacity loss factor and downtime per inundation height Excel illustration

Inundation height [m]	Capacity loss factor [-]	Downtime [months]
0	sim	sim
0.01	sim	sim
...	sim	sim
2.46	sim	sim

The next step differs from the direct damage approach because the (2) fault tree (Figure App A-4) must be integrated, in order to determine the decisive fault events. Knowing the (3) decisive fault event (Table App A-7) for each inundation height enables the model to calculate the impact of each specific storm surge on the indirect damage. This is realized by matching the capacity loss factors and downtimes with the associated inundation heights. (4) Summing these outcomes results in one table of the expected total indirect damage throughout the concession period at the container terminal (Table App A-8).

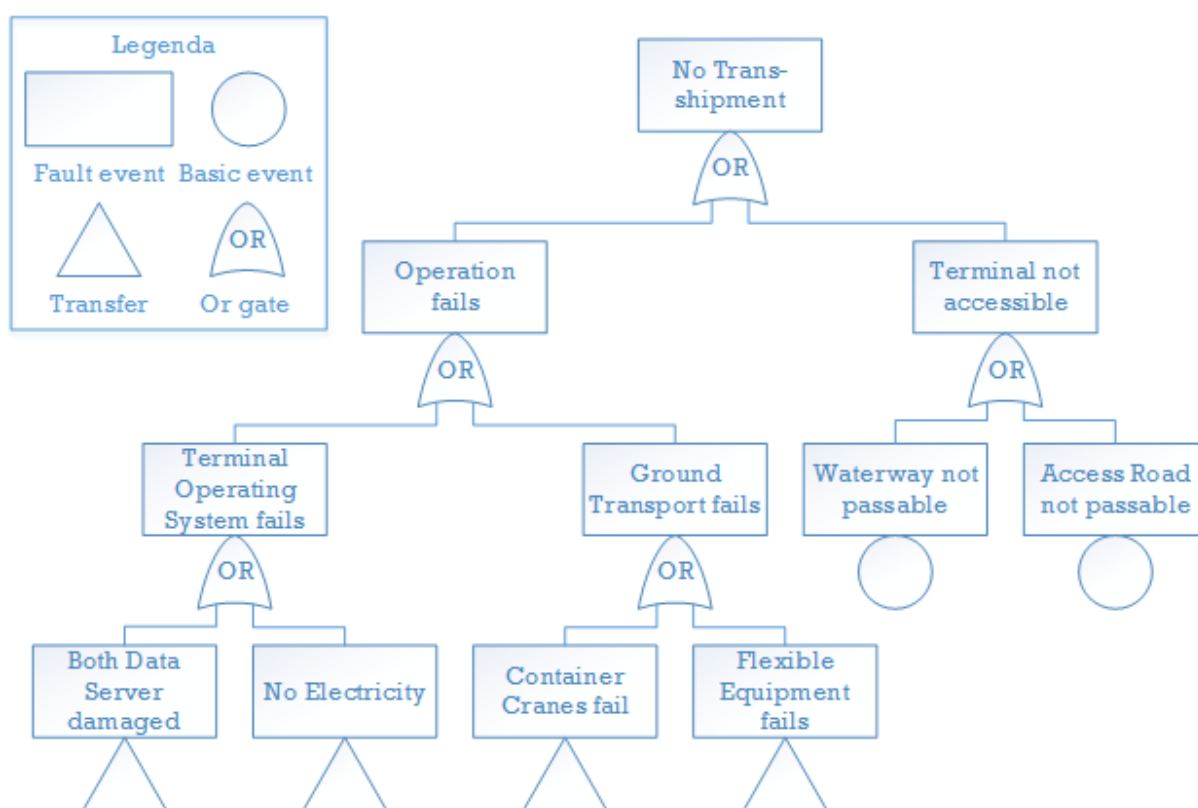


Figure App A-4: Simplified container terminal fault tree (based on Schüller et al., 2005):

Table App A-7: Integrated fault tree revenue loss Excel illustration

Inundation height [m]	Revenue loss [M\$]
0	sim
0.01	sim
...	sim
2.46	sim

Table App A-8: Indirect damage throughout the concession period Excel illustration

Year Return period [years]	Revenue loss [M\$]			
	2016	2017	...	2045
1	sim	sim	sim	sim
2	sim	sim	sim	sim
...	sim	sim	sim	sim
100,000	sim	sim	sim	sim

A.4 Intervention sheets

As described in Chapter 6, 37 different intervention options are created to cope with the flooding problem at the container terminal. The options are divided into 27 individually applied interventions and 10 combined applications, however, 14 individual interventions appeared failed to meet the criteria of “damage reduction > needed investment” (elaborated in Paragraph 3.1). Therefore, 27 Excel sheets containing individually applied interventions and 10 combined applied interventions are used, resulting in the following intervention sheets:

1. Entire terminal A heighten
2. Entire terminal A enclose
3. Sectional terminal A heighten
4. Sectional terminal A enclose
5. Control area heighten
6. Control area enclose
7. Maintenance area heighten
8. Maintenance area enclose
9. Electric mainstation heighten
10. Electric mainstation enclose
11. Container cranes depot
12. Dredging waterway by vessel purchase
13. Dredging waterway by pre-arrangement
14. Control area enclose & maintenance area enclose
15. Control area enclose & maintenance area enclose +
16. Sectional terminal A enclose & electric mainstation enclose
17. Sectional terminal A enclose & electric mainstation immediate relocate
18. Sectional terminal A enclose & electric mainstation relocate during replacement
19. Sectional terminal A enclose & electric mainstation immediate relocate & dredging waterway by vessel purchase
20. Sectional terminal A enclose & electric mainstation immediate relocate & dredging waterway by pre-arrangement
21. Sectional terminal A enclose & electric mainstation immediate relocate & container cranes depot 8
22. Sectional terminal A enclose & electric mainstation immediate relocate & container cranes moveable to terminal A
23. Sectional terminal A enclose & electric mainstation immediate relocate & container cranes depot & dredging waterway by vessel purchase

Each of the 23 intervention options consists of two tables corresponding to the investment costs needed to realize interventions and impact of interventions on the storm surge damage. A distinction between the fixed and variable investments (Table App A-9) must be made to enable the model to optimize the intervention extent. In this research, the intervention extent is expressed in the height of the intervention, as declared in Paragraph 6.2. In the table, the word “in” stands for input and contains data that needs to be established or estimated during the earlier stages. By finding the optimal intervention extent, the most beneficial application (damage reduction minus investment) is found.

Table App A-9: Intervention investment Excel illustration

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
...	in	in	...
...	in	in	...
Total fixed investment:			...
Component	Height [m]	Price per m [M\$]	Total [M\$]
...	sim	in	...
...	sim	in	...
Total variable investment:			...
Total investment:			...

To determine the impact of the interventions on the expected damage caused by storm surges, a relationship between the intervention and container terminal needs to be made. Executions of these application state in the Paragraphs 6.2 and 6.3, plus Appendix E and O. In this research relationships is made via an overview of the assets and impact factors (Table App A-10), whereby the impact of interventions is expressed in impact factors. Besides the impact factors, the construction of interventions can be associated with a downtime on certain sections of the terminal. This aspect is included in the calculation process. Each intervention must be able to fit within this structure, containing the following impact factors:

- Partial protection [%]: in case an intervention only influences a part of the asset;
- Heighten surface [m]: increasing the ground level underneath the asset;
- Heighten enclosure [m]: realizing a wall around the asset;
- Improved protection [%]: improve the asset in such a way that it's better protected against storm surges;
- Downtime reduction [%]: reduce the length of any downtime;
- Downtime reduction [months]: reduce the maximum downtime.

Table App A-10: Intervention impact Excel illustration

Asset \ Impact factors	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	in	in	in	in	in	in
Maintenance area	in	in	in	in	in	in
...	in	in	in	in	in	in
Access road	in	in	in	in	in	in

A.5 Optimization sheet

The final stage of the model consists of a single sheet. This sheet integrates all cause, consequence and solution sheets. By integrating the damage and intervention sheets the intervention extent can be optimized, after which the impact of the intervention option is overviewed in a table (Table App A-11). In repeating the simulation for any intervention option, the impact of all options is calculated. These outcomes can be compared to determine the most beneficial application.

Table App A-11: Outcome Excel illustration

Year Return period [years]		2016	2017	...	2045	Total
Damage [M\$]	Control	sim	sim	sim	sim	sim
	Maintenance area	sim	sim	sim	sim	sim
	...	sim	sim	sim	sim	sim
	Others	sim	sim	sim	sim	sim
	Total direct	sim	sim	sim	sim	sim
	Annual downtime [months]	sim	sim	sim	sim	sim
	Intervention downtime [months]	sim	sim	sim	sim	sim
	Total downtime [months]	sim	sim	sim	sim	sim
	Total indirect damage [M\$]	sim	sim	sim	sim	sim
	Total damage [M\$]	sim	sim	sim	sim	sim

Appendix B Storm surges

B.1 Datasets

It is common to include storm surges with higher return periods of 1000 and 10,000 years, to be able to calculate the impact of bigger storms, as applied in numerous studies (all studies cited in Paragraph 2.1). However, these data is missing for the case, whereas studies established storm surges with a return period up to 100 years, as shown in Figure App B-1. The graph considers storm surge heights of five different studies with return periods from 10 to 100 year. The study that leads to data 1a (Confidential, 1999a) is aimed at the most extreme location in the bay. The expectation is made that these storm surge levels will not occur, because of the narrow bay entrance, coral reefs and offshore cays. Therefore, the storm surges could be reduced by approximately 50%, as expressed in data 1b (Confidential, 1999b). A few years later an extensive study was elaborated, considering numerous coastal locations throughout the Caribbean. One of these studies contained the location of the case and is drawn in data 2 (Confidential, 2002). Data 3 (Confidential, 2008a) are established storm surges from a recent study on the exact location, but doubts are made on the extremely slow increasing storm surge level as the return period increases. Storm surges from outside the bay are graphed in data 4 (Confidential, 2007), where is assumed that the storm surge levels are higher compared to the case location, because of earlier mentioned reasons. While comparing the different data sets and their origin, the conclusion is made that data 2 is the most reliable likely data set, which shall be used during the rest of the report.

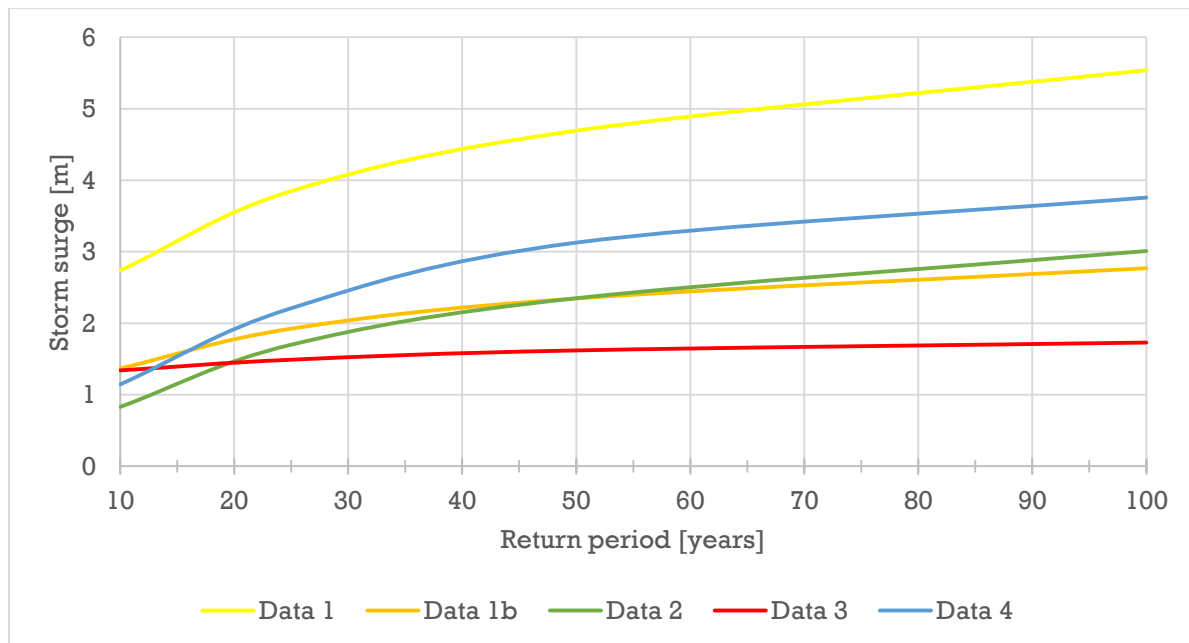


Figure App B-1: Storm surges of different data

B.2 Fits

In order to determine the higher return periods, several fits are applied on the storm surge data (Figure App B-2), whereby the storm surge heights (expressed in meters) plod to the probability of 1.00E-04 (equal to a return period of 10,000 years). The ratio probability and return period is one divided by the other (Equation 2-4). The applied fits are common in these type of studies (e.g. Van den Brink and Können, 2009; Bardet, et al., 2011; Walton, 1999; Lopeman, 2015), for which relative variables (i.e. α , β , γ and δ), are determined for the different fits, expressed in the different equations on the next page.

P(hs)	[factor]	Probability
h _s	[m]	Storm surge height

$$P(h_s) = \alpha e^{\beta h_s}$$

Equation App B-1: Exponential fit

$$\begin{aligned}\alpha &= 0.240 \\ \beta &= -1.056\end{aligned}$$

$$P(h_s) = \alpha + \beta \ln(h_s)$$

Equation App B-2: Logarithm fit

$$\begin{aligned}\alpha &= 0.083 \\ \beta &= -0.072\end{aligned}$$

$$P(h_s) = 1 - \left(1 + \alpha \frac{h_s - \gamma}{\beta}\right)^{\frac{1}{\alpha}}$$

Equation App B-3: Pareto fit

$$\begin{aligned}\alpha &= 25.951 \\ \beta &= 78.287 \\ \gamma &= 3.651\end{aligned}$$

$$P(h_s) = \frac{1}{\beta} e^{\frac{h_s - \alpha}{\beta}} e^{-\frac{h_s - \alpha}{\beta}}$$

Equation App B-4: Gumbel fit

$$\begin{aligned}\alpha &= -1.108 \\ \beta &= 2.192\end{aligned}$$

$$P(h_s) = \frac{1}{\alpha \beta h_s^{\beta-1}} e^{-\alpha h_s^{\beta}}$$

Equation App B-5: Weibull 2 parameter fit

$$\begin{aligned}\alpha &= 2.687 \\ \beta &= 0.585\end{aligned}$$

$$P(h_s) = \alpha - \beta e^{-\gamma h_s^{\delta}}$$

Equation App B-6: Weibull 4 parameter fit

$$\begin{aligned}\alpha &= 0.114 \\ \beta &= 0.122 \\ \gamma &= 1.456 \\ \delta &= -2.048\end{aligned}$$

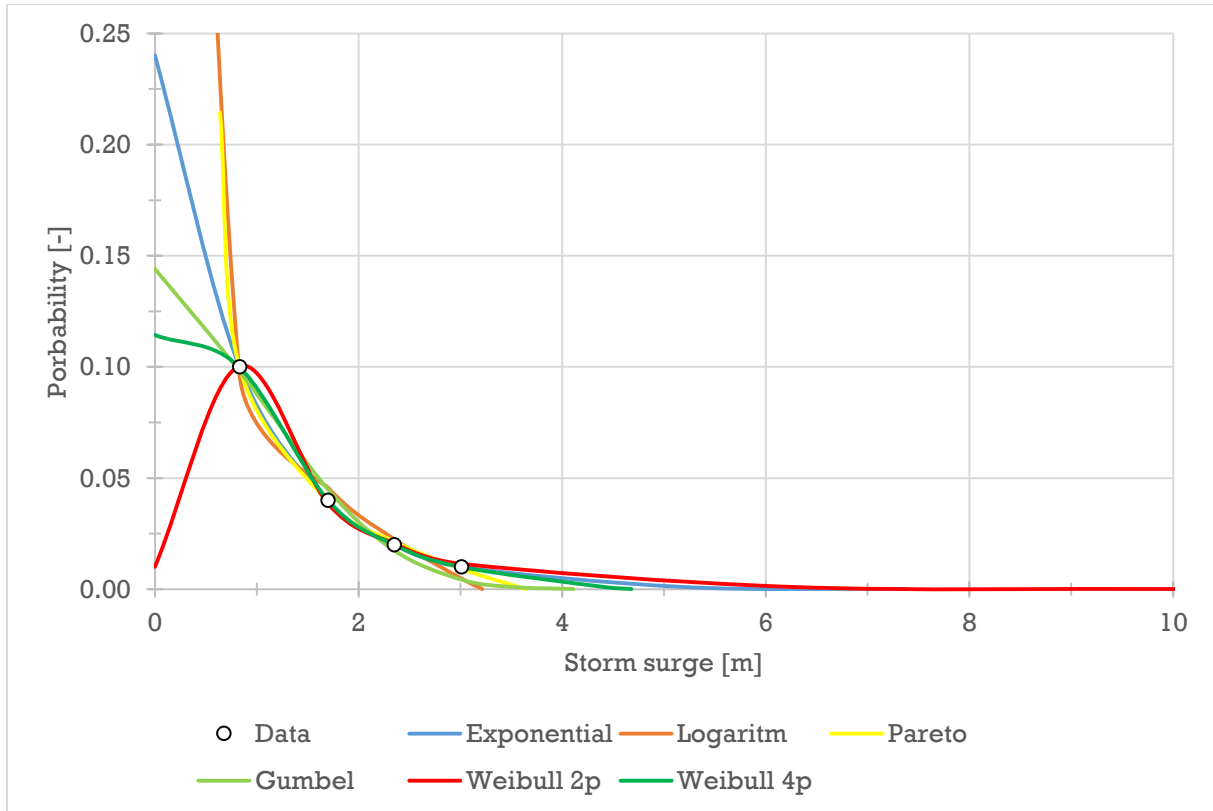


Figure App B-2: Fits applied on storm surge data

In determining the best fit, the logarithm, Pareto and Weibull 2 parameter can be excluded. The logarithm and Pareto fit, because the storm surges with low probabilities are getting unrealistic low, whereas the Weibull 2 parameter fit is getting unrealistic high.

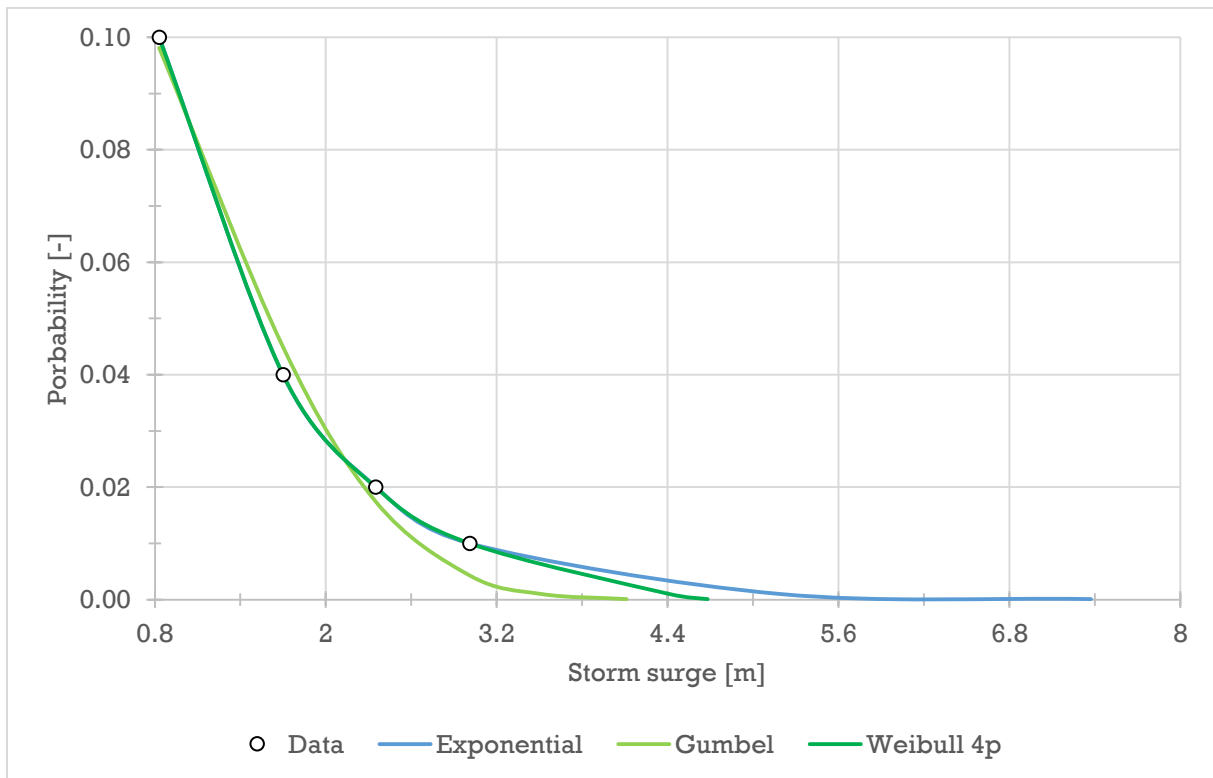


Figure App B-3: Zoomed fits applied on the storm surge data

During the next step is zoomed in further into the remaining fits (Figure App B-3), where can be seen that the Gumbel fit is rather low. The major difference between the exponential and Weibull 4 parameter fit are the peaks, 7.37 and 4.68 meters, at $1,00E-04$ probability. In order to compare these fits and determine if the outcomes are realistic, the two fits are compared with storm surge data of other hurricane areas. As earlier mentioned, these data cannot be found in the Caribbean, but is available in the USA (e.g. Jonkman et al., 2008; Stoeten, 2013). In comparing these studies with the described fits, the Weibull 4 parameter fit corresponds best and seems more realistic than the exponential fit. This means that the Weibull 4 fit will be used, in combination with data set 2 (Appendix B.1), to indicate future storm surges within the case-study.

B.3 Projected changes

Figure App B-4 and Figure App B-5 show the projected changes of the wind wave conditions heights and frequencies in 2075-2100 relative to 1980-2009 (Church et al., 2013). The projected changes are derived from the Coordinated Ocean Wave Climate Project (COWCLIP) (Hermer et al., 2013). Out of these studies is concluded that the wind-wave, and by that the storm surges, will remain similar in both height and frequency during the concession period.

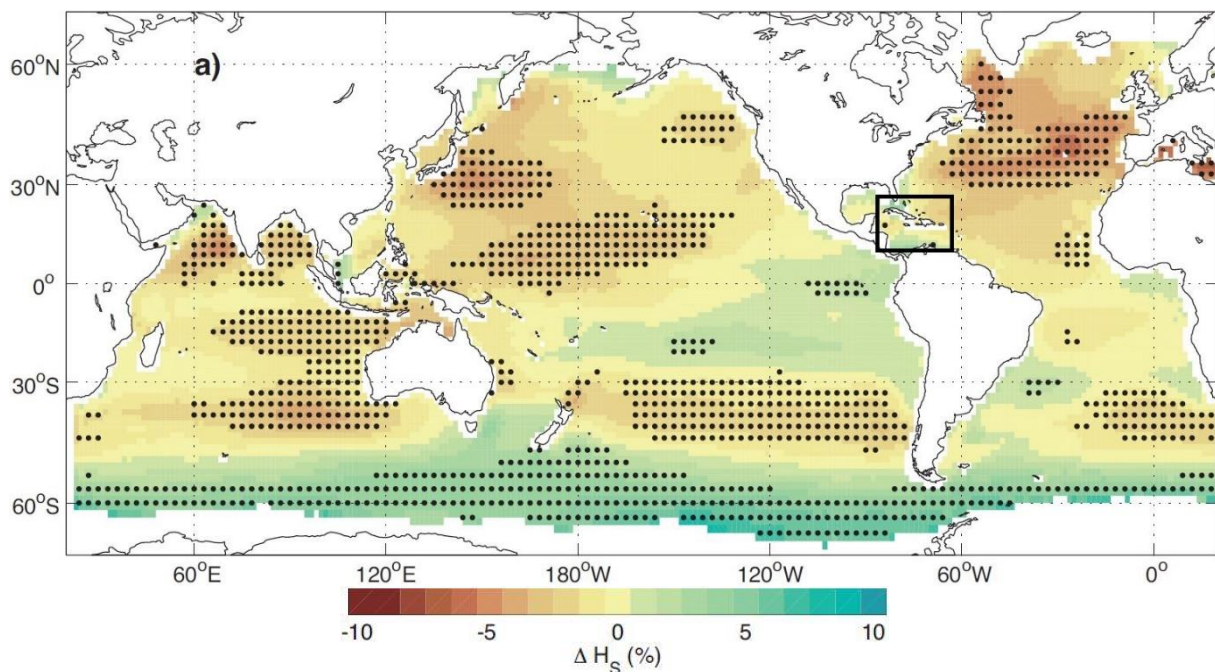


Figure App B-4: Projected wave heights changes (Church et al., 2013)

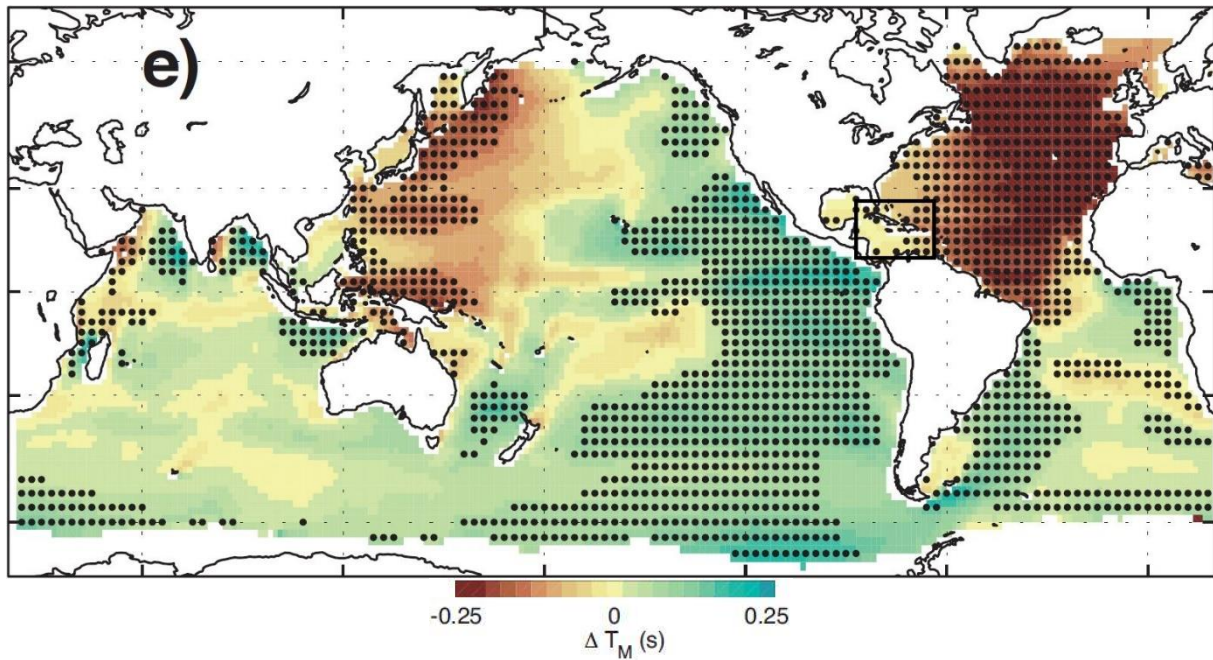


Figure App B-5: Projected wave frequencies changes (Church et al., 2013)

B.4 Function

Considering all input (i.e. data sets, fits, projected changes), the conclusion is made that the storm surge height could be found through the inverse of Equation App B-6. When the height of the storm surges wishes to be calculated, the equations becomes as follows (Equation App B-7).

$$\begin{aligned}
 P(h_s) &= \alpha - be^{-\gamma h_s^\delta} \\
 \frac{\alpha - P(h_s)}{b} &= e^{-\gamma h_s^\delta} \\
 \ln\left(\frac{\alpha - P(h_s)}{b}\right) &= -\gamma h_s^\delta \\
 \ln\left(\frac{\alpha - P(h_s)}{b}\right) &= -\gamma h_s^\delta \\
 h_s &= \sqrt[\delta]{\frac{\ln\left(\frac{\alpha - P(h_s)}{b}\right)}{-\gamma}}
 \end{aligned}$$

Equation App B-7: Storm surge trough probability

By replacing the probability of the storm surge by the return period, the storm surge for the corresponding return period could be found (Equation App B-8).

$$h_s = \sqrt[\delta]{\frac{\ln\left(\frac{\alpha - \frac{1}{RP}}{b}\right)}{-\gamma}}$$

Equation App B-8: Storm surge through return period

RP [year] Return period

Since the values of the Weibull 4 variables (i.e. α , β , γ and δ) are determined (Appendix B.2), the equation to calculate storm surges can be defined (Equation App B-9). Drawing this equation into a line graph shows Figure App B-6.

$$h_s = \sqrt{\frac{-2.048 \ln \left(\frac{0.114 - \frac{1}{RP}}{0.122} \right)}{-1.456}}$$

Equation App B-9: Storm surge within case-study

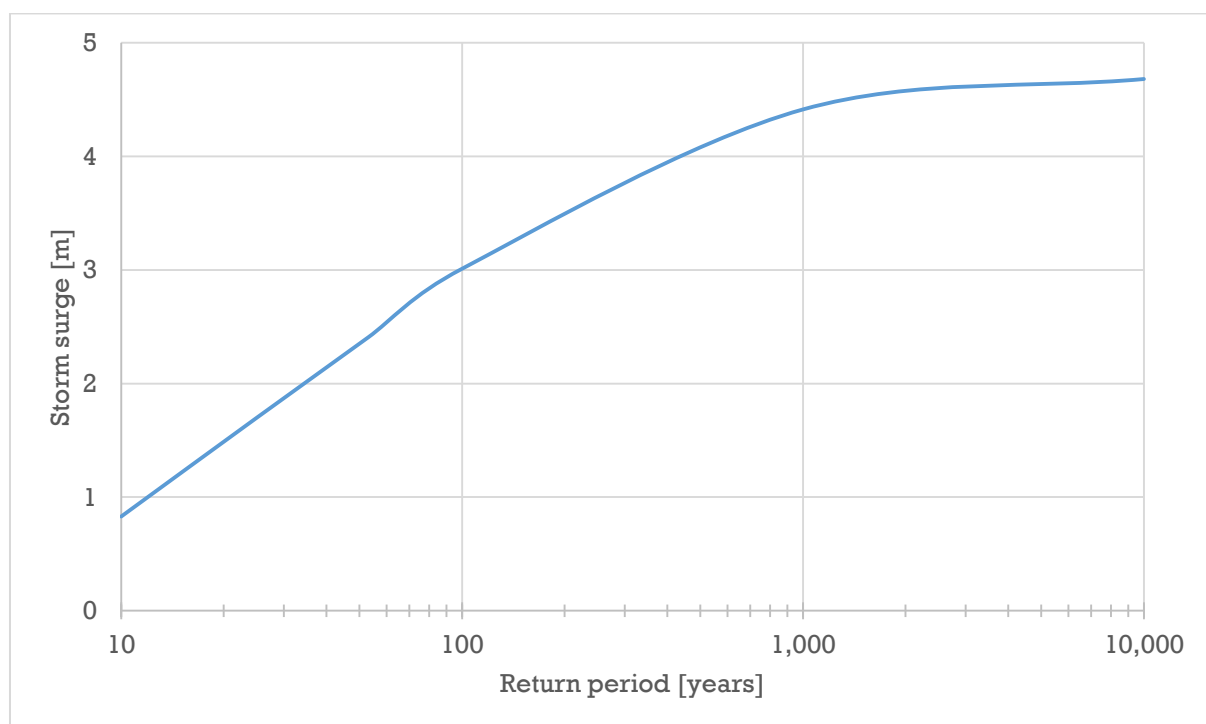


Figure App B-6: Storm surge through return period on the research case

B.5 Climate change

Climate change considers the topics sea level rise (Appendix B.5.1) and land subsidence (Appendix B.5.2).

B.5.1 Sea level rise

Table App B-1 shows the global sea level rise of several prominent studies up until 2100 (Church et al., 2013). The percentage columns (5%, 50% and 95%) correspond to the probability that the sea level rise actually occurs. All studies are drawn in Figure App B-7, where the 5% and 95% probabilities are transparent striped lines. The studies that did not start in the year 1990 are corrected by 3 mm/year sea level rise, which was the average sea level rise over that period (Church et al., 2008). This is done because the sea level rise of the Caribbean appeared to be near to global mean, from estimates observed the mean sea level rise (MSLR) from 1950 to 2000 Church et al. (2004).

Table App B-1: Sea level rise according to prominent studies (Church et al., 2013)

Research	From	To	5%	50%	95%
IPCC AR5 (2013)	1996	2100	0.42	0.60	0.80
Rahmstorf (2007)	1990	2100	-	0.85	-
Horton et al. (2008)	2000	2100	0.62	0.74	0.88
Vermeer and Rahmstorf (2009)	1990	2100	0.98	1.24	1.56
Grinstead et al. (2010)*	1990	2100	0.62	0.98	1.33
Jevrejeva et al. (2010)**	1990	2100	0.70	0.92	1.20

* Average of Grinstead et al. (2010) with two studies temperature for calibration: Brohan et al. (2006) and Moberg et al. (2005).

** Average of Jevrejeva et al. (2010) with three studies forcing for calibration: Crowley et al. (2003), Goosse et al. (2005) and Tett et al. (2007).

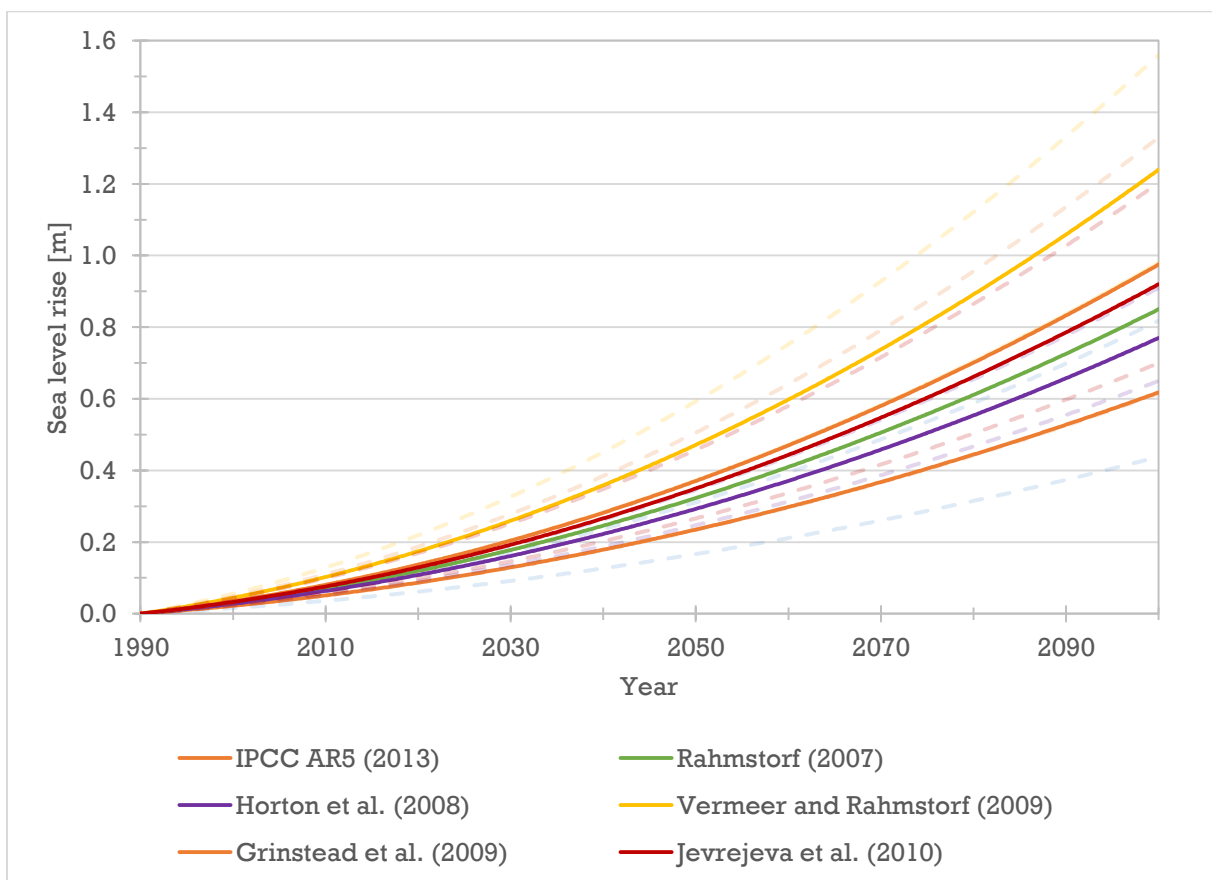


Figure App B-7: Sea level rise in the 21st century

In Figure App B-8 is the projected difference of regional and global MSLR in 2081-2100 relative to 1986-2005 shown (Church et al., 2013). From these data is concluded that the MSLR of the Caribbean is, like the past, near the global mean, leading to a total MSLR of 0.90m from 1990 up until 2100 as drawn in Figure App B-9.

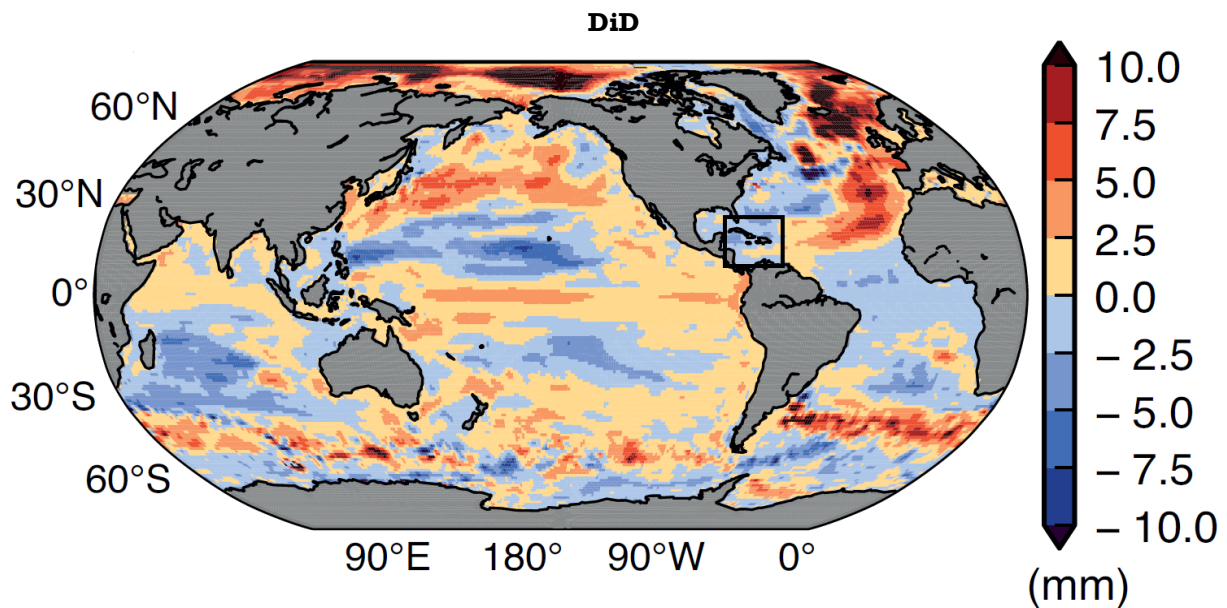


Figure App B-8: Projected difference of regional and global MSLR (Church et al., 2013)

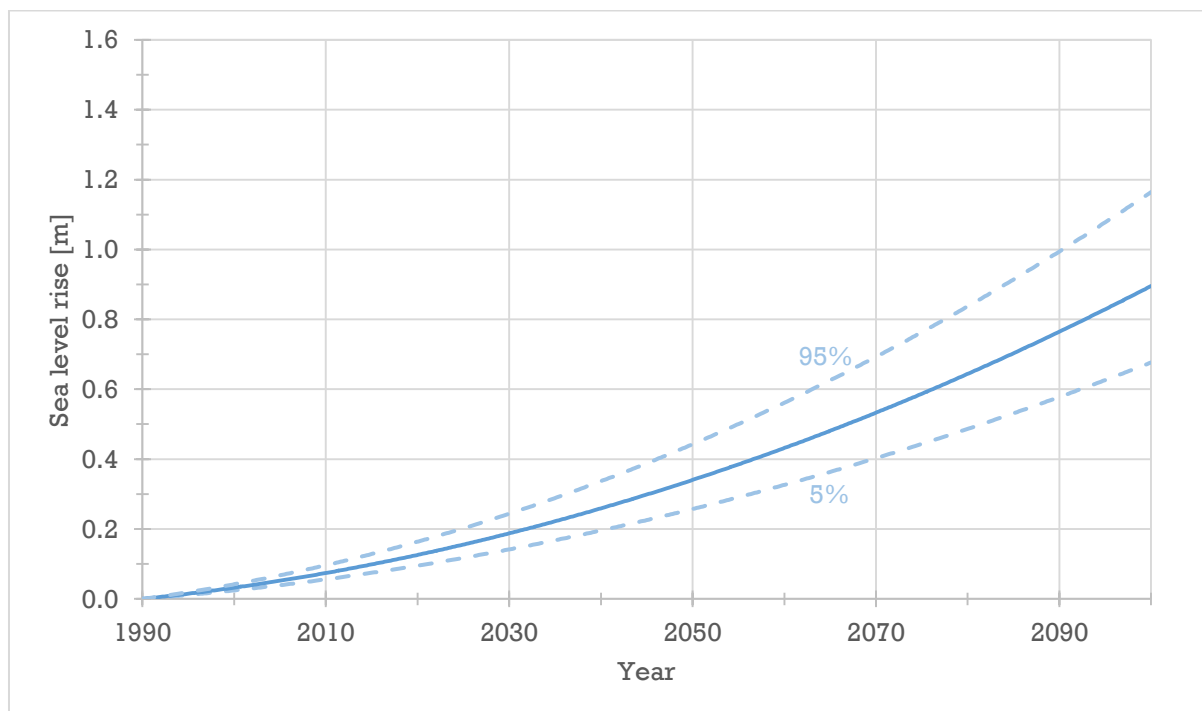


Figure App B-9: Established Caribbean sea level rise in the 21st century

B.5.2 Land subsidence

Land subsidence occurs in the country the case is situated (Confidential, 2004). There is verified if the area is vulnerable to land subsidence, because of the lack of land subsidence data for the area where the case is situated. According to the list of natural hazards, the region is not increased vulnerable (CIA, 2016), which is confirmed by Boersma (2015) that names Italy, America and Indonesia as vulnerable countries because of the soft soils. Based on several land subsidence studies of different coastal locations (Roman 2011; Dircke et al., 2011; Dorfman and Mehta, 2011; El-Asmar and Hereher, 2010; Iba-ez et al., 1996) an average linear decrease of 2 mm/year is estimated as land subsidence within the case-study.

B.6 Overview

As shown in Paragraph 5.1, the storm surges, sea level rise, land subsidence, and starting surface level (2.4 m above MSL) combined lead to the outcomes illustrated in Figure App B-10 (a similar graph as Figure 5-1).

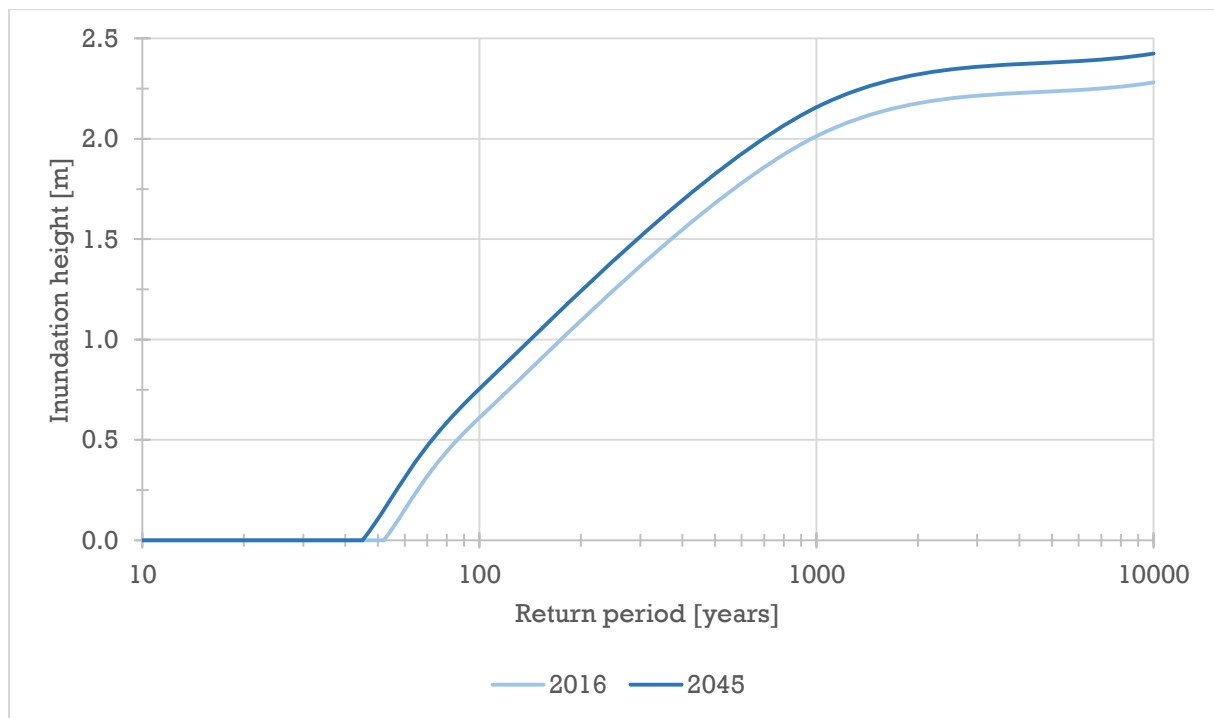


Figure App B-10: Established inundation height on the research case

Appendix C Assets

As elaborated in the main text, the decisive direct damage asset (i.e. containers) is described in Paragraph 5.2, and an overview of all asset values and damage functions can be found in Paragraph 5.4. In this Appendix, a substantiated description of the establishing process to find the variables relative to assets (i.e. asset damage and damage functions) can be found. The process in determining these variables is similar to the explained process in Paragraph 5.2. The assets are divided into the same groups as Paragraph 4.5, and are as follows:

- Appendix C.1: operations areas (control and maintenance);
- Appendix C.2: electrical (mainstation, substations and generators);
- Appendix C.3: ground transport (container cranes, straddle carriers, reach stackers and terminal trucks);
- Appendix C.4: containers (full dry, empty and reefers);
- Appendix C.5: fundamental (pavements, quay walls, foundation, revetment and others);
- Appendix C.6: external (backup data server, power supply, waterway, access road).

All estimations according to the damage functions and value structures of the assets are made under supervision of specialists (Arcadis, 2016) and supplemented by the following data:

- ^[1] = Confidential, 2015
- ^[2] = FEMA, 2013
- ^[3] = DACE, 2012
- ^[4] = ESB, 2016

The following assets will not be damaged by floods: foundation and revetment, their damage function is illustrated in Figure App C-1. The foundation is situated under a thick pavement layer and behind quay walls and revetment. These assets (i.e. pavements, quay walls and revetment) will not or hardly be damaged by floods. There it is very unlikely, if not impossible, to damage the foundation via floods. For the revetment is assumed that it is designed to withstand a sizable storm surge, as long as the revetment stays in a good condition and maintained.

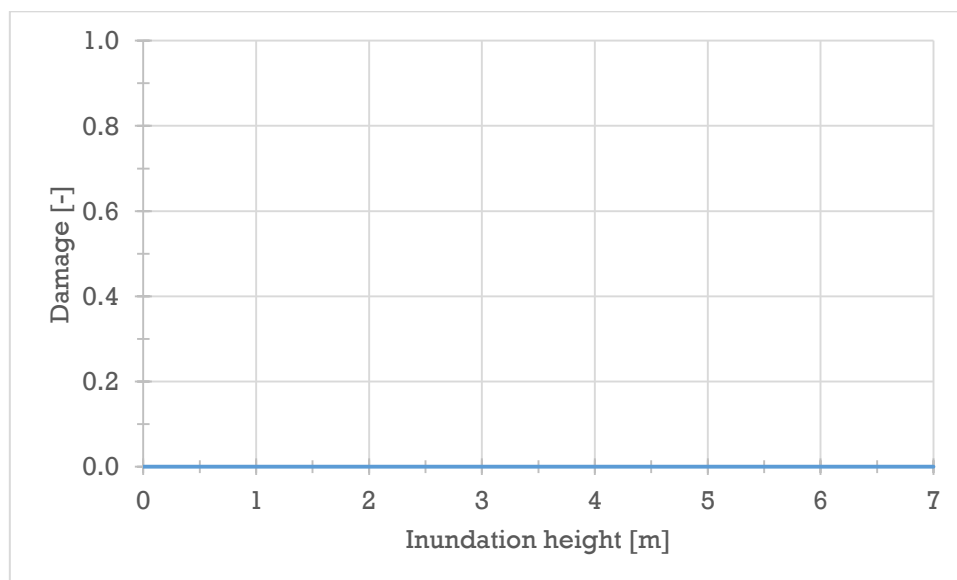


Figure App C-1: Damage function foundation and revetment

C.1 Operation areas

Because of the high valued TOS and data servers, the damage function of the *control area* (Figure App C-2) is based on the damage function of the office and computer industry, as developed by Tebodin (2000). The same applies to the *maintenance area* (Figure App C-3). This function is based on the damage function of the machine and devices industry (Tebodin, 2000), through its purpose and the maintenance equipment of the area. An overview of the value structures can be seen in Table App C-1 and Table App C-2.

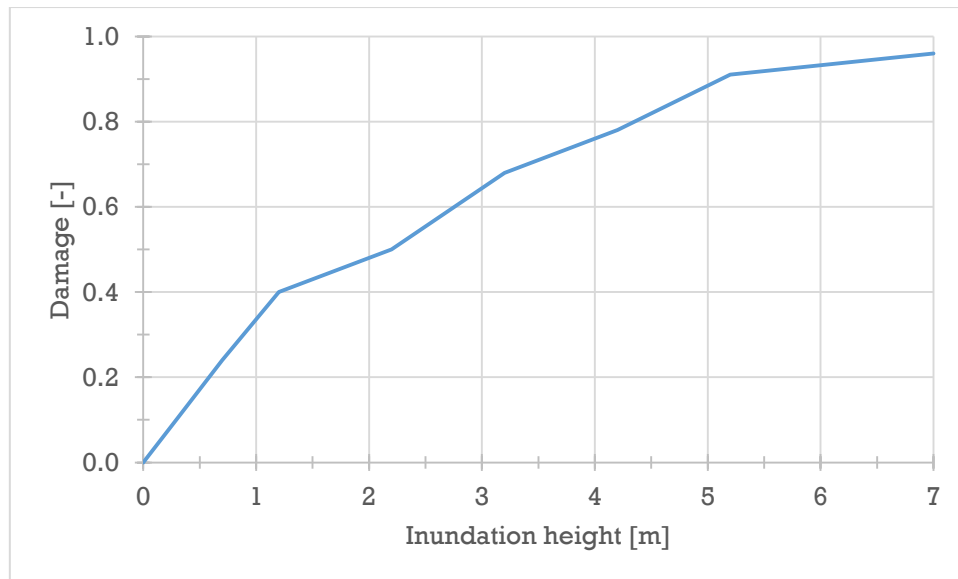


Figure App C-2: Damage function control area (based on Tebodin, 2000)

Table App C-1: Value structure control area

Component	m2	m2 price [\$]	total [M\$]
Operation building ^{[2][3]}	600	1,200	0.72
Conference building ^{[2][3]}	600	1,200	0.72
Entrance building ^{[2][3]}	500	1,200	0.60
Roofed space ^{[2][3]}	4,700	400	1.88
Remaining buildings ^{[2][3]}	400	700	0.28
Terminal Operating System ^[1]	fixed price		8.00
		Total:	12.20

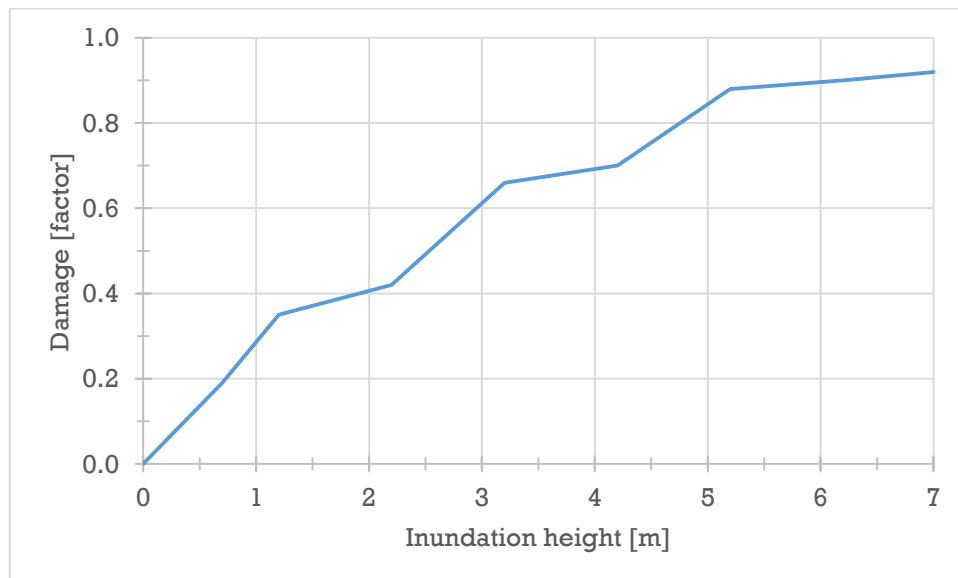


Figure App C-3: Damage function maintenance area (based on Tebodin, 2000)

Table App C-2: Value structure maintenance area

Component	m2	m2 price [\$]	total [M\$]
Warehouses ^{[2][3]}	1,300	700	0.91
Workshop hangar ^[2]	fixed price		3.20
Terminal fuel facility ^[2]	fixed price		2.00
		Total:	6.11

C.2 Electrical

Electrical components are highly vulnerable to sea water. Sea water not only corrodes wires that could transmit electricity, it also conducts a charge itself, which means that it can both wear away our safety insulations (causing outages) and increase the chance of an accidental shock (Lecher, 2012). Therefore, it is assumed that when the water reaches up until the crucial components, the electrical assets will be fully damaged. This leads, partly via a dialogue with an electric specialist, to the following damage functions (Figure App C-4, Figure App C-5 and Figure App C-6). The damage structures are approved by the same specialist, which are shown in Table App C-3, Table App C-4 and Table App C-5.

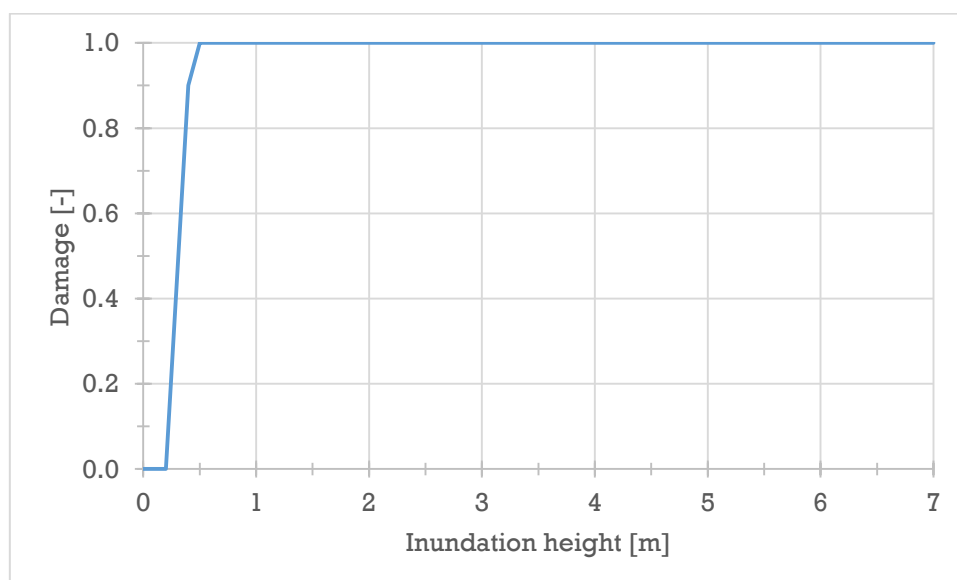


Figure App C-4: Damage function electric mainstation

Table App C-3: Value structure electric mainstation

Component	unit	unit price [\$]	total [M\$]
Electric mainstation ^{[2][3]}	1	6,000,000	6.00

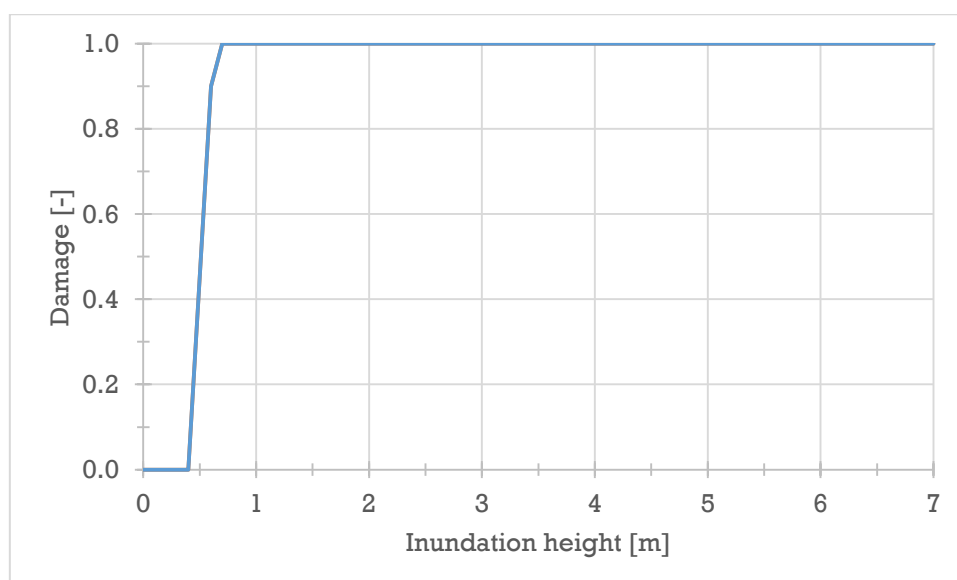


Figure App C-5: Damage function electric substations

Table App C-4: Value structure electric substations

Component	unit	unit price [\$]	total [M\$]
Electric substations ^{[2][3]}	2	2,500,000	5.00

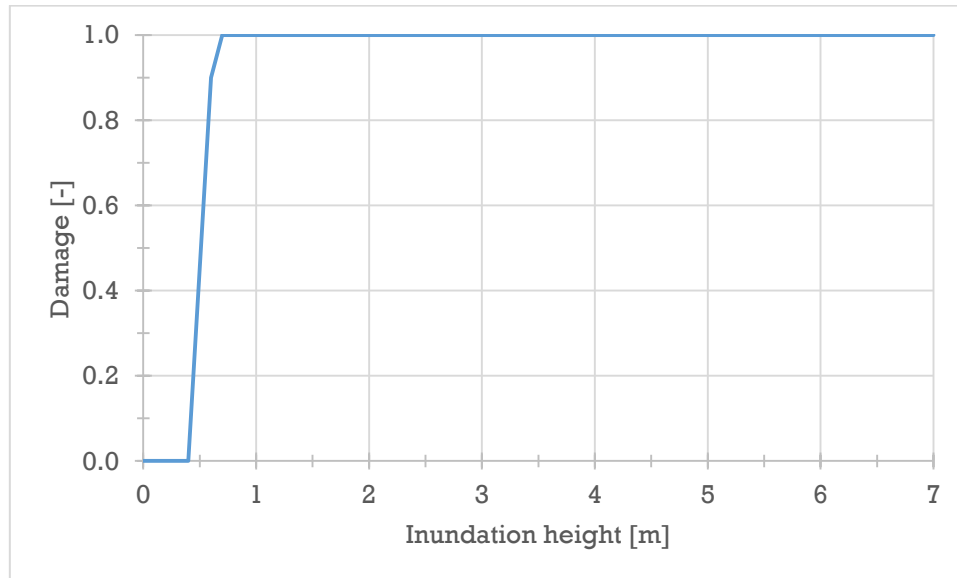


Figure App C-6: Damage function generators

Table App C-5: Value structure generators

Component	unit	unit price [\$]	total [M\$]
Generators ^[3]	11	500,000	5.50

C.3 Ground transport

Salt water damage to container cranes, straddle carriers, reach stackers and terminal trucks are devastating, temporary repairs are useful, but long term replacements are likely needed due to post corrosive damage from salt water (Dalton, 2013). With this in mind, as approved by several specialists related to ports and electricity, the damage functions of the ground transport are determined.

In the bottom section of the *container crane* are the wheels and electrical supply located. The expensive components are in the top of the crane (i.e. the lifting mechanism and power control). Despite the fact that the weight of the crane is enormous and the costly components are located higher than 7 meters, the container crane will be fully damaged when such a storm surge occurs, as happened in the Gulfport of Mississippi (Coburn et al., 2013). Based on these findings the damage factor of container crane is designed and shown in Figure App C-7, whereas the unit and unit price states in Table App C-6.

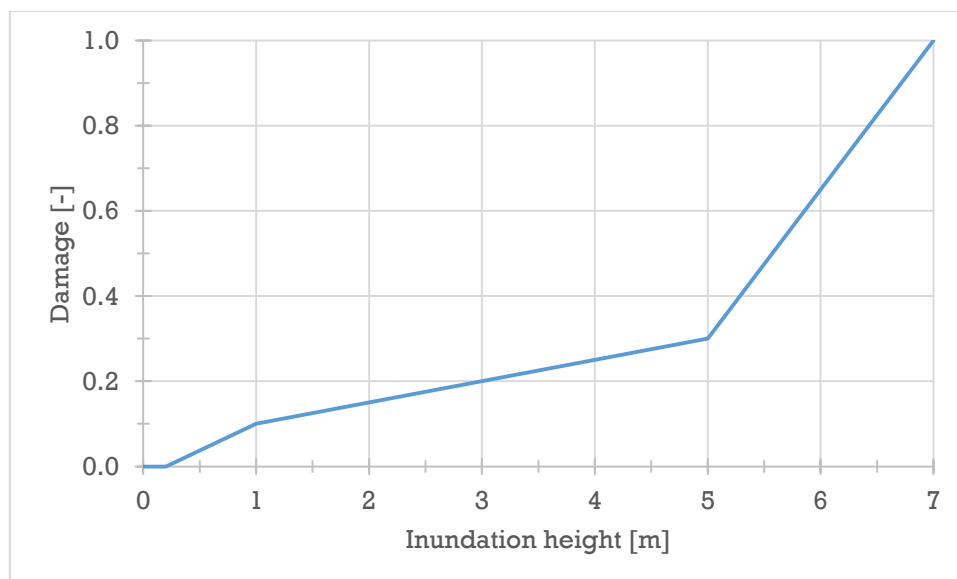


Figure App C-7: Damage function container cranes

Table App C-6: Value structure container cranes

Component	unit	unit price [\$]	total [M\$]
Container cranes ^[1]	16	8,000,000	128.00

The most expensive mechanisms situated in the *straddle carrier* are the engine in the bottom, for horizontal movement, and the lifting mechanism in the upper regions, for vertical movement. The engine is quite high positioned, which makes the straddle carrier capable of coping with medium inundation heights (Figure App C-8). The higher the inundation height on the container terminal, the more containers are floating, which can result in tilting a straddle carrier, leading to damage on the lifting mechanism. The terminal has 62 straddle carriers on average, corresponding to an average price of \$ 900k as can be shown in Table App C-7.

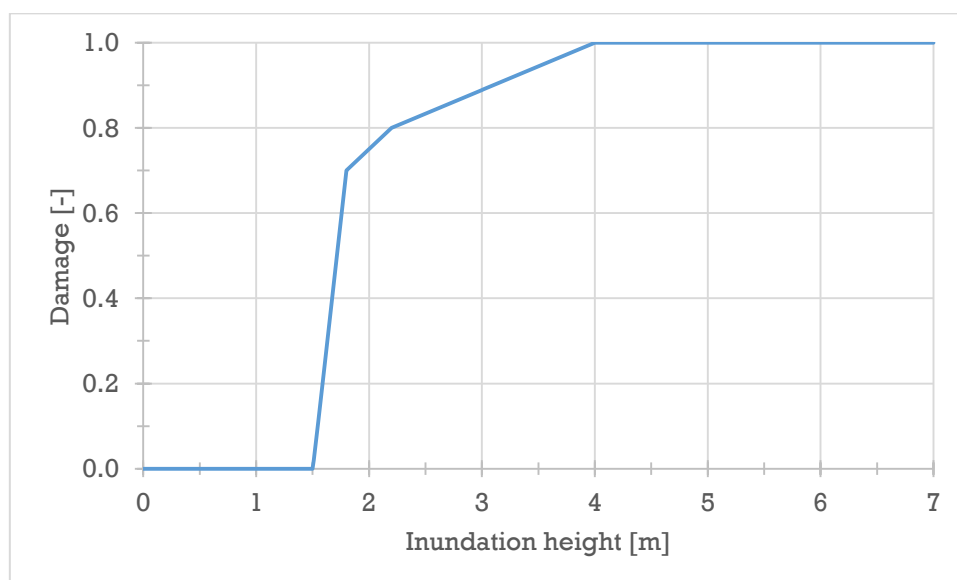


Figure App C-8: Damage function straddle carriers

Table App C-7: Value structure straddle carriers

Component	unit	unit price [\$]	total [M\$]
Straddle carriers ^[1]	62	900,000	55.80

Similar to the straddle carrier, the *reach stacker* consists of an engine and a lifting mechanism. The lifting mechanism is less expensive and vertical situated, whereby damage to this component occurs at lower inundation heights (Figure App C-9). The engine is vulnerable to low inundation heights because it's located closely to the ground. Prices corresponding to the reach stackers can be found in Table App C-8.

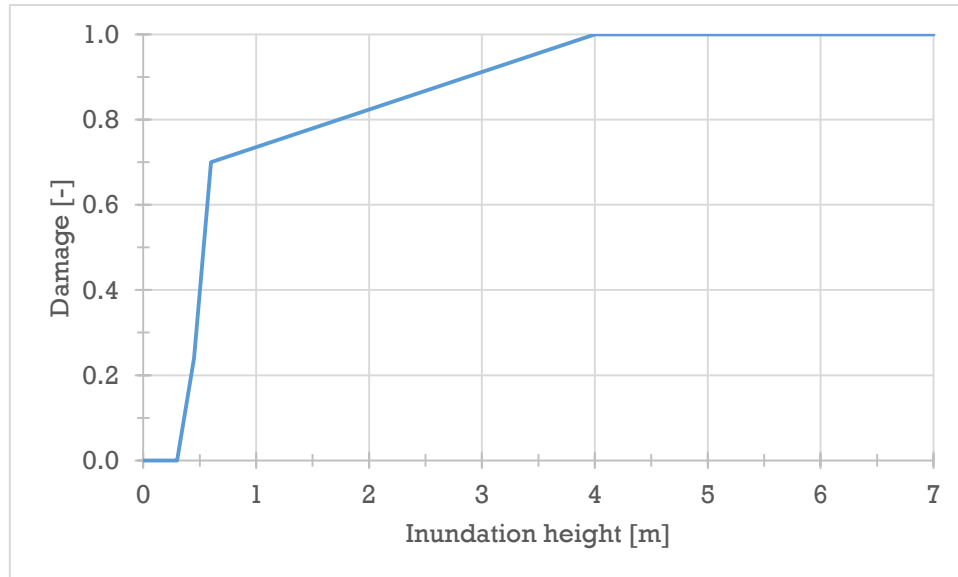


Figure App C-9: Damage function reach stackers

Table App C-8: Value structure reach stackers

Component	unit	unit price [\$]	total [M\$]
Reach stackers ^[1]	18	450,000	8.10

The critical component of a *terminal truck* is the engine, without the engine, the terminal truck becomes rather worthless. Thereby, the engine is located quite close to the ground, which makes it vulnerable to minor storm surges (Figure App C-10). In Table App C-10 is the average situation expressed in dollars, as is the case at every value structure. The reasoning behind this is explained in Paragraph 4.4.

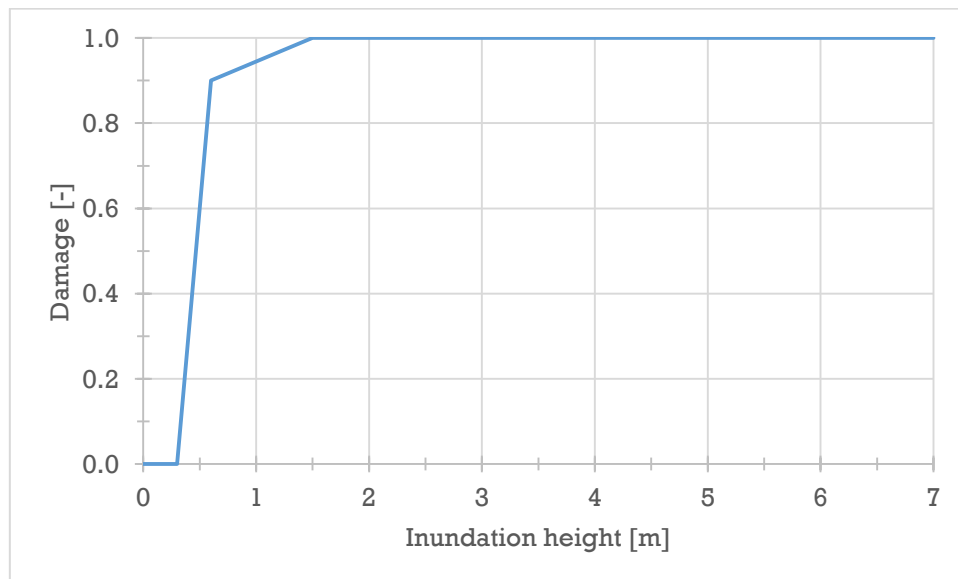


Figure App C-10: Damage function terminal trucks

Table App C-9: Value structure terminal trucks

Component	unit	unit price [\$]	total [M\$]
Terminal trucks ^[1]	25	100,000	2.50
Trailers ^[1]	40	20,000	0.80
Total:			3.30

C.4 Containers

Value structures

Firstly, is determined *how many containers* stand on the container terminal, this is done by multiplying the number of ground slots. How many ground slots are available per stack, divided over terminal A, B and C is shown in Table 4-1. The average stack height throughout the terminal is one and a half container for the full stacks, dry and reefers, and four containers for the empty stack (data originating from Paragraph 4.3). A division in dwell times between the full and empty containers is shown in Figure 4-20. Leading to the amount of containers stacked in the average situation halfway the concession (Table App C-10).

Table App C-10: Containers stacked on the terminal

Terminal \ Stack	Full Dry	Empty	Reefer	Total
Average stack height [TEU]	1.5	4.0	1.5	-
Terminal A [kTEU]	4.3	4.2	0.6	9.1
Terminal B [kTEU]	4.1	3.0	-	7.1
Terminal C [kTEU]	10.0	14.4	0.8	25.2
Total [kTEU]:	18.3	21.6	1.4	41.4

Secondly, the amount of *20ft* and *40ft* containers with cargo is calculated (Equation App C-1), via the container traffic (Figure 4-5) the ratio between 20ft and 40ft containers is established (Table App C-11), whereas the ratio between full containers is the same as the empty ones. Pay attention, the values are in TEU, meaning that the amount of 40ft containers is half the given amount.

$$F_{20ft} = \frac{T_{20ft}}{T_t} = \frac{482}{2,196} = 0.22 \text{ and } F_{40ft} = \frac{T_{40ft}}{T_t} = \frac{1,714}{2,196} = 0.78$$

Equation App C-1: Factor 20ft containers on total

F_{20ft}	[factor]	Factor 20ft containers on total
T_{20ft}	[kTEU]	20ft container transshipment (Figure 4-5)
T_t	[kTEU]	Total container transshipment (Figure 4-5)
F_{40ft}	[factor]	Factor 40ft containers on total
T_{40ft}	[kTEU]	40ft container transshipment (Figure 4-5)

Table App C-11: Distribution of cargo containers on the terminal

Container type	Dry			Reefer			Total
	20ft	40ft	Total	20ft	40ft	Total	
Terminal A [kTEU]	0.9	3.3	4.3	0.1	0.5	0.6	4.9
Terminal B [kTEU]	0.9	3.2	4.1	-	-	-	4.1
Terminal C [kTEU]	2.2	7.8	10.0	0.2	0.6	0.8	10.7
Total [kTEU]:	4.0	14.3	18.3	0.3	1.1	1.4	19.7

Thirdly, the amount of reefers situated on the *empty stack* is determined (Table App C-12). There is assumed that the distribution reefers to dry containers are the same in the full dry/reefer stack (Table App C-10) as in the empty stack. Therefore, the number of reefers is divided by the total amount of full containers, dry and reefer, to find the factor. Multiplying this factor with the 20ft 40ft factor (Equation App C-1) and the amount of empty containers (Table App C-11).

$$F_r = \frac{R_f}{C_f + R_f} = \frac{1.4}{18.3 + 1.4} = 0.07$$

Equation App C-2: Factor reefers on full containers

F_r [factor] Factor reefers on full containers
 R_f [kTEU] Full reefers (Table App C-11)
 C_f [kTEU] Full dry containers (Table App C-11)

Table App C-12: Distribution of empty containers on the terminal

Container type	Dry			Reefer			Total
	20ft	40ft	Total	20ft	40ft	Total	
Terminal A [kTEU]	0.9	3.1	3.9	0.1	0.2	0.3	4.2
Terminal B [kTEU]	0.6	2.2	2.8	0.0	0.2	0.2	3.0
Terminal C [kTEU]	2.9	10.5	13.4	0.2	0.8	1.0	14.4
Total [kTEU]:	4.4	15.7	20.1	0.3	1.2	1.5	21.6

Fourthly, the number of containers is multiplied by the average container new price, which is \$4,000 for dry 20ft containers and \$20,000 for 20ft reefers (Boekhout, 2013; Alibaba, 2016), for 40ft containers, the price is 1,5 times this high (Alibaba, 2016). Via this multiplication the values of the containers (Table App C-13 and Table App C-14) could be found.

Table App C-13: Cargo container values on the terminal

Container type	Dry			Reefer			Total
	20ft	40ft	Total	20ft	40ft	Total	
Terminal A [M\$]	3.7	10.0	13.7	2.6	7.0	9.7	23.4
Terminal B [M\$]	3.6	9.6	13.2	-	-	-	13.2
Terminal C [M\$]	8.7	23.3	32.1	3.4	9.1	12.5	44.6
Total [M\$]	16.1	42.9	59.0	6.1	16.1	22.2	81.2

Table App C-14: Empty container values on the terminal

Container type	Dry			Reefer			Total
	20ft	40ft	Total	20ft	40ft	Total	
Terminal A [M\$]	3.4	9.2	12.6	1.3	3.5	4.8	17.4
Terminal B [M\$]	2.5	6.6	9.0	0.9	2.5	3.4	12.4
Terminal C [M\$]	11.8	31.4	43.2	4.4	11.8	16.2	59.4
Total [M\$]:	17.7	47.1	64.8	6.6	17.7	24.4	89.2

Fifthly, the *depreciation* (Appendix C.6) is included to the container values, the outcomes are shown in Table App C-15.

Table App C-15: Container values on the terminal depreciation included

Container type	Full dry	Empty	Reefer	Total
Terminal A [M\$]	6.9	8.7	4.8	20.4
Terminal B [M\$]	6.6	6.2	-	12.8
Terminal C [M\$]	16.0	29.7	6.3	52.0
Total [M\$]:	29.50	44.60	11.10	85.2

Sixthly, the *cargo value* (Table App C-16) is calculated by multiplying the average cargo value, \$35,000 (Maersk, 2011; Harrison, 2010), with the amount of containers (Table App C-10).

Table App C-16: Cargo values on the terminal

Container type	Full dry	Empty	Reefer	Total
Terminal A [M\$]	149.2	-	21.0	170.2
Terminal B [M\$]	143.5	-	-	143.5
Terminal C [M\$]	348.8	-	27.2	376.0
Total [M\$]:	641.4	-	48.2	689.6

Seventh, by summing the container values with the cargo values, the total values could be found (Table App C-17). This table has the same context as Table 5-1. There is no depreciation included for the cargo itself, meaning that the price is the average cargo value. The reasoning behind this decision that the containers stand for a very short period and depreciation is negligible.

Table App C-17: Value structure containers

Container type	Full dry	Empty	Reefer	Total
Terminal A [M\$]	156.0	8.7	25.8	190.5
Terminal B [M\$]	150.1	6.2	-	156.3
Terminal C [M\$]	364.8	29.7	33.5	428.0
Total [M\$]:	670.8	44.6	59.3	774.8

Damage functions

The damage functions of containers are established via a study that investigated the impact of a tsunami on the containers on Japanese terminals (Kumagai, 2013). The tsunami was created by the Tohoku earthquake and resulted in a broad variation of storm surges throughout a large part of the coast of Japan. Different inundation heights occurred on multiple container terminals, resulting in different impacts. Out of these results, the interaction between the damage on containers and the inundation height is derived. There is begun with the interaction between the *mass* of the container and the *inundation height* (Figure App C-11).

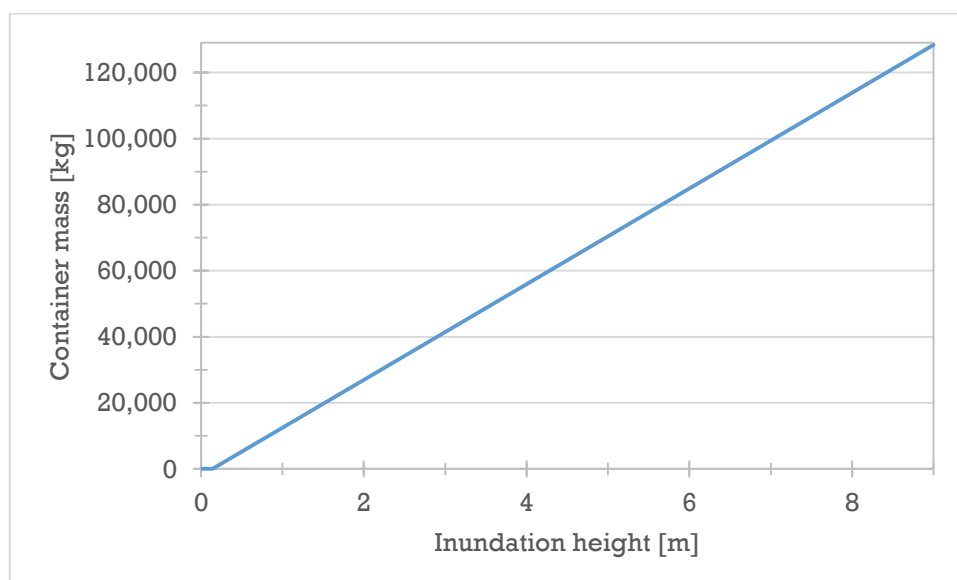


Figure App C-11: Container damage via mass and inundation height (based on Kumagai, 2013)

Secondly, the damage function of *empty containers* is established (Figure App C-12), a graph that corresponds to Figure 5-3. This is a derivation from the measured data on multiple Japanese terminals (Kumagai, 2013), which are displayed as dots. Within the process, the stack conditions are included, since there were several stack heights at the container terminal (based on Paragraph 4.3). The container terminals in the survey were low to medium tech container terminals, so reasonable to compare with the case.

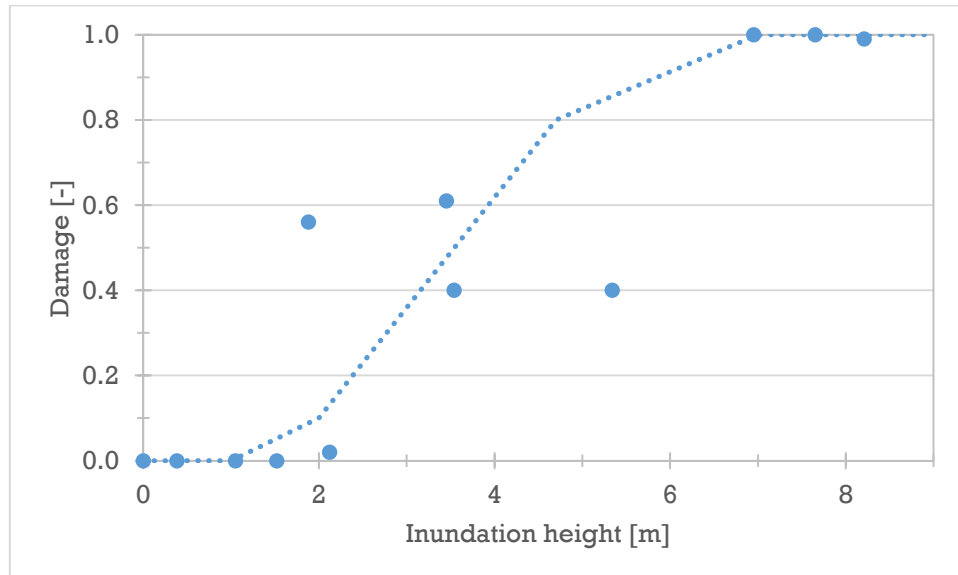


Figure App C-12: Damage function empty containers (based on Kumagai, 2013)

Thirdly, the damage factor of *cargo* is very cargo-specific, containers containing goods that cannot withstand water are sooner worthless than goods that can. Therefore, the difference in cargo value needs to be integrated into the damage function, when the multiplication of value times factor wants to be made, to determine the direct damage. A method that is used to calculate the damage of all assets. In Figure App C-13 is the outcome of this integration shown for single stacked containers, whereby is assumed that the biggest damage occurs when the water is halfway the container height (1.3 m). In case the container is completely inundated, the water protected cargo is still not damaged. This cargo will be lost if the container gets heavily damaged (e.g. when the container floats away, sinks or washed ashore). At an inundation height of 7 meters, the cargo is worthless, based on Figure App C-11 and Figure App C-12. According to the same principle, the damage function of double-stacked cargo containers is established (Figure App C-14).

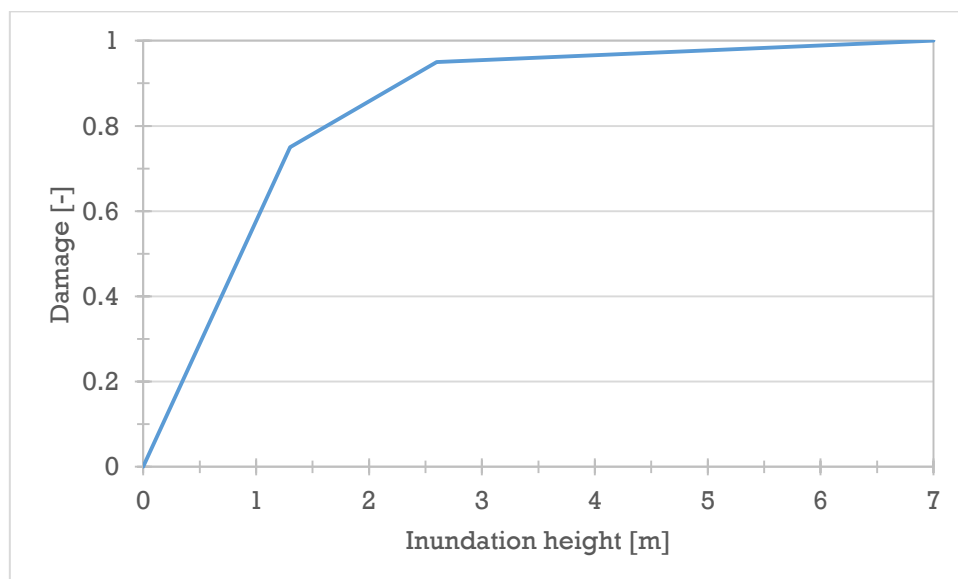


Figure App C-13: Damage function cargo in single stacked containers

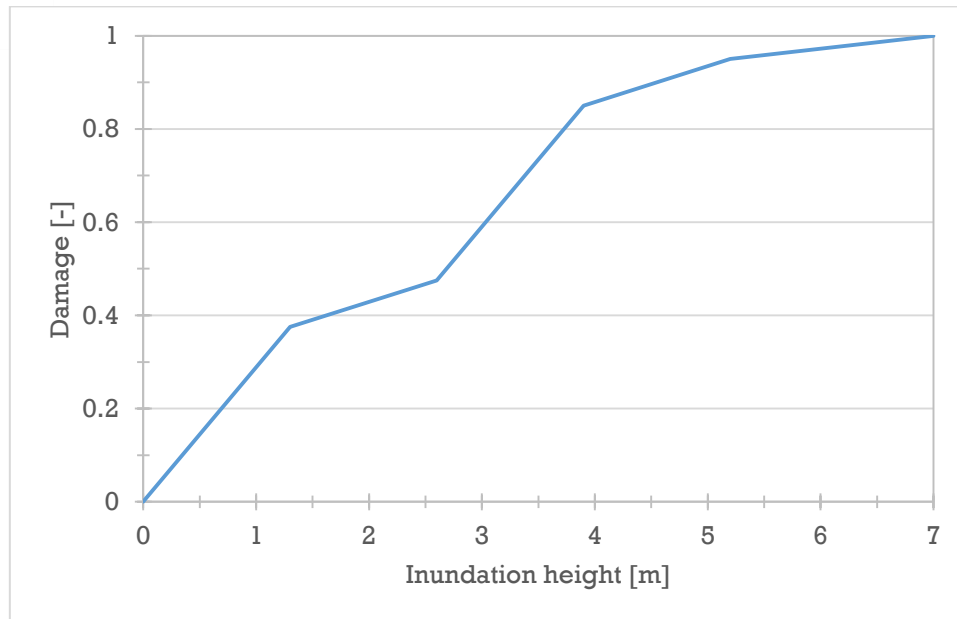


Figure App C-14: Damage function cargo in double stacked containers

Fourthly, from the single and double stacked cargo damage functions, the *1.5 stacked cargo* could be derived (Figure App C-15), hereby the bottom containers contain two-third of the total damage and the containers stacked above one-third.

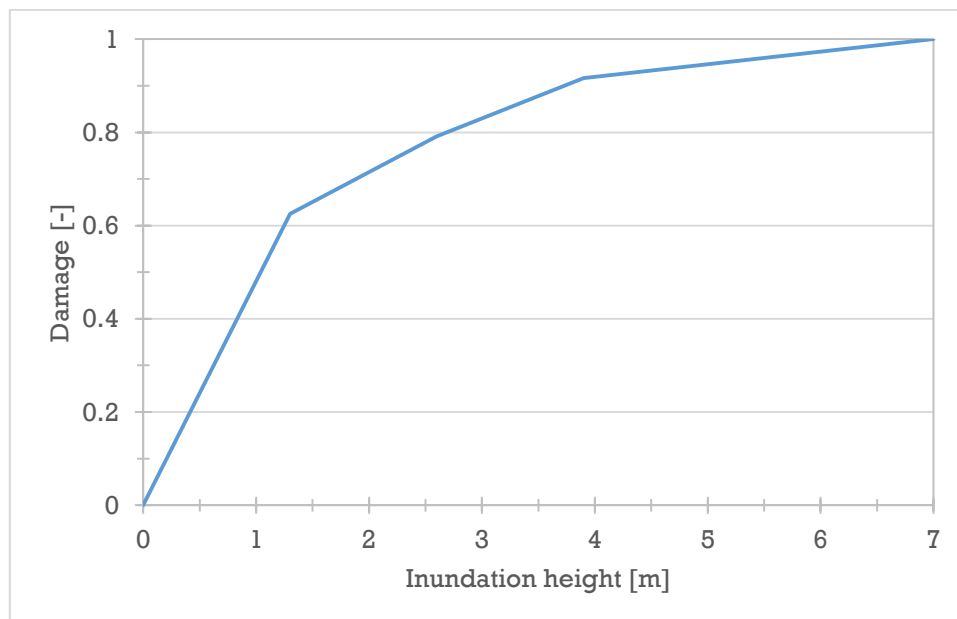


Figure App C-15: Damage function cargo in 1.5 stacked containers

Fifthly, the damage function of *full dry containers* (Figure App C-16, matching Figure 5-2) could then be derived from the damage functions on the cargo (Figure App C-15) and the empty containers (Figure App C-12), in addition to the fact that the containers will be heavier and will get damaged less soon.

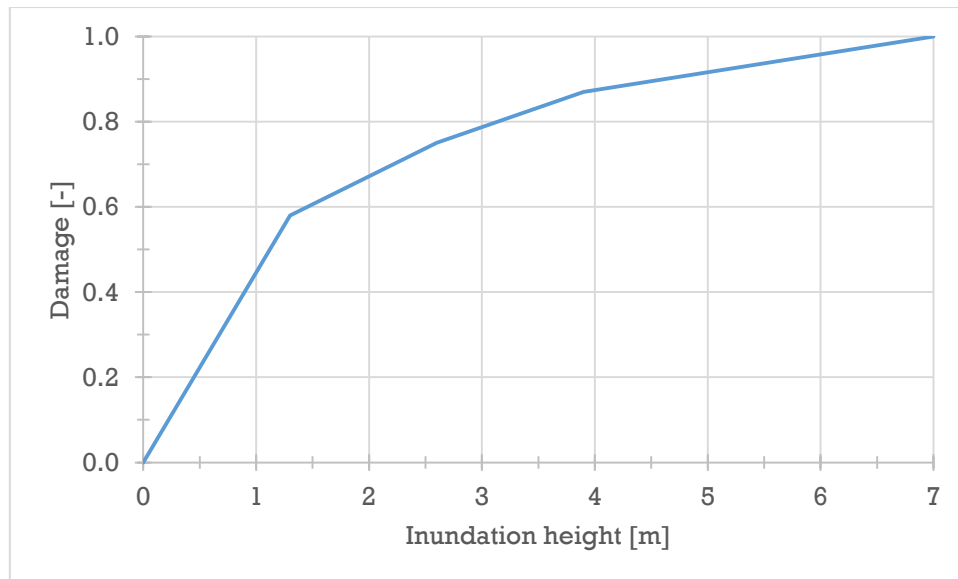


Figure App C-16: Damage function full dry containers

Sixthly, the damage function of the reefers (Figure App C-17, similar to Figure 5-4) is established according to another method, because the assumption is made that the electricity is the crucial factor in the process. When sea water comes into the internal electric supply, this will be devastating for the reefer and will lead to electrical short and a fully depreciated container, whereas, the cargo within a reefer cannot withstand any sea water. The most common cargo of reefers are bananas, citrus, deciduous, exotics, fish and seafood, meat and poultry, and dairy (Dekker, 2014). However, it occurs that a water protected seal covers the cargo within the reefer to reduce or prevent the damage through sea water. Tough shall it be difficult to withstand inundation over a longer period, especially when the electric supply is lost, in that case, the cargo becomes worthless.

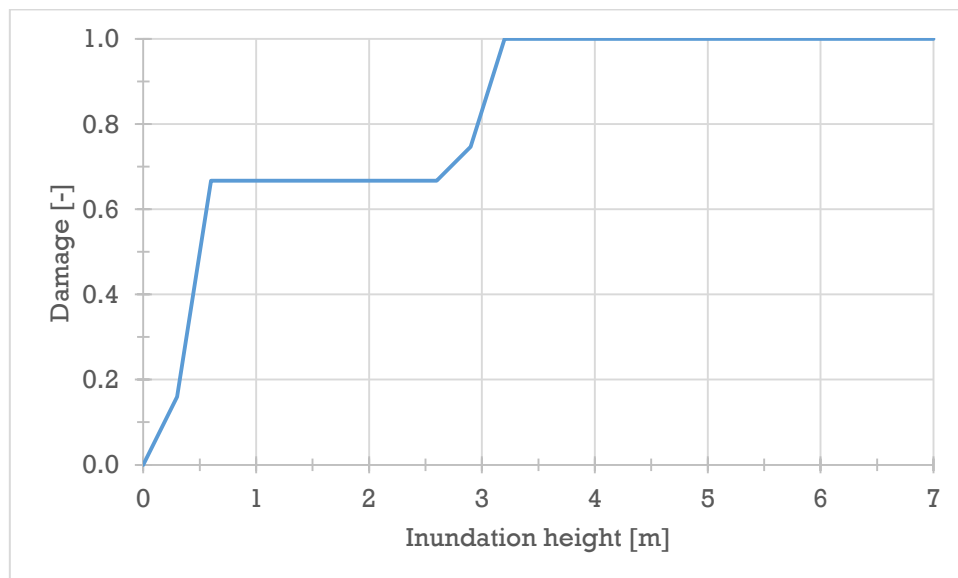


Figure App C-17: Damage function reefers

C.5 Fundamental

The *pavement* will not directly be damaged by sea water, but indirectly, via moving assets as containers (Figure App C-18). However, the pavements will remain largely passable, where preparing needs to be executed locally, as turned out at the Gulfport after hurricane Katrina (NOAA, 2005). In Table App C-18, the value structure of pavements is shown.

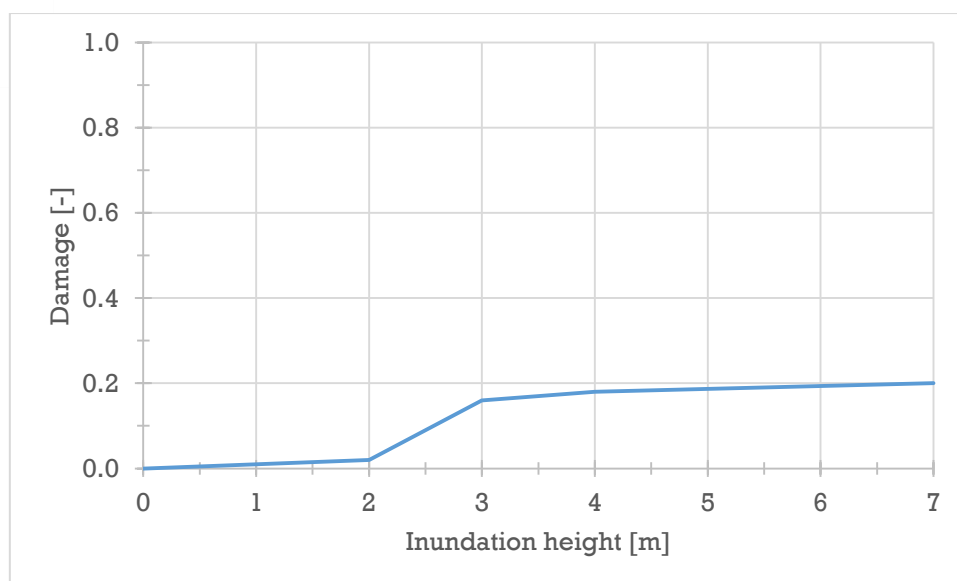


Figure App C-18: Damage function pavements

Table App C-18: Value structure pavements

Component	m3	m3 price [\$]	total [M\$]
Pavements ^[3]	1,020,000	75	76.50

The biggest failure mechanism occurring through flooding is in case the soil gets saturated with water (Confidential, 2016a). This will occur if the container terminal will be inundated for a longer time. Therefore, the assumption is made, the higher the inundation height, the longer the container terminal stays inundated, which can ultimately lead to 20% damage to the *quay walls* (Figure App C-19: Damage function quay walls). The value structure is displayed in Table App C-19, wherein a distinction between an older and newer realized quay wall is made.

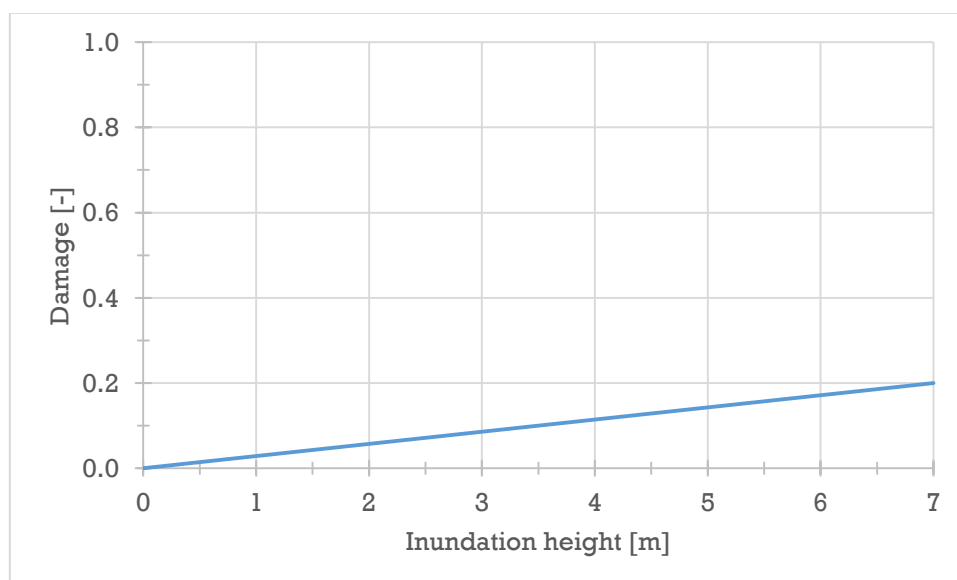


Figure App C-19: Damage function quay walls

Table App C-19: Value structure quay walls

Component	m	m price [\$]	total [M\$]
Quay wall Terminal A&B ^[3]	1,100	70,000	77.00
Quay wall Terminal C ^[3]	1,300	100,000	130.00
Crane rails ^{[2][3]}	2,400	1,500	3.60
		Total:	210.60

No damage will occur because of a flood through the foundation or revetment, as described in the introduction of this Appendix. The value structures of both assets are positioned below, in Table App C-20 and Table App C-21.

Table App C-20: Value structure foundation

Component	m3	m3 price [\$]	total [M\$]
Foundation Terminal A&B ^[3]	3,100,000	20	62.00
Foundation Terminal C ^[3]	7,500,000	20	150.00
Total:			212.00

Table App C-21: Value structure revetment

Component	m	m price [\$]	total [M\$]
Revetment ^[3]	1,600	15,000	24.00

The group others hold the remaining assets of the terminal, containing minimal value or influence on the fault events. The group consists of electric and data cables, which are mostly tucked underground, however, do not underestimate the immense dimension of these high-quality cables. Another component is the drainage, which removes the sea water through an underground pipe system. Fences are surrounding the container terminal when attached to land, where an entrance and exit consist in the form of gates. Lighting poles provide the light throughout the entire terminal. Components that were still not mentioned, fall under the rest value. All remaining assets and their value structure are merged in Table App C-22. The damage function of this group is, just as the other functions, determined according to the value of the components. This means that the cables and drainage form an important contribution. Both could withstand a certain flood since they are not affected by seawater (the high-quality cables are sea waterproof), however, they could receive indirect damage via fractured pavement or crashing heavy materials. Integrating the impact of storm surges and the values of the group assets leads to an integrated damage function, graphed in Figure App C-20.

Table App C-22: Value structure others

Component	unit	unit price [\$]	total [M\$]
Fences ^[3]	1,000	540	0.54
Lightning poles ^[3]	128	3,000	0.38
Gates ^[3]	2	12,000	0.02
Component	ha	ha price [\$]	total [M\$]
Cables ^{[3][4]}	102	100,000	10.20
Drainage ^{[2][3]}	102	50,000	5.10
Rest value	add 20%		3.25
		Total:	19.50

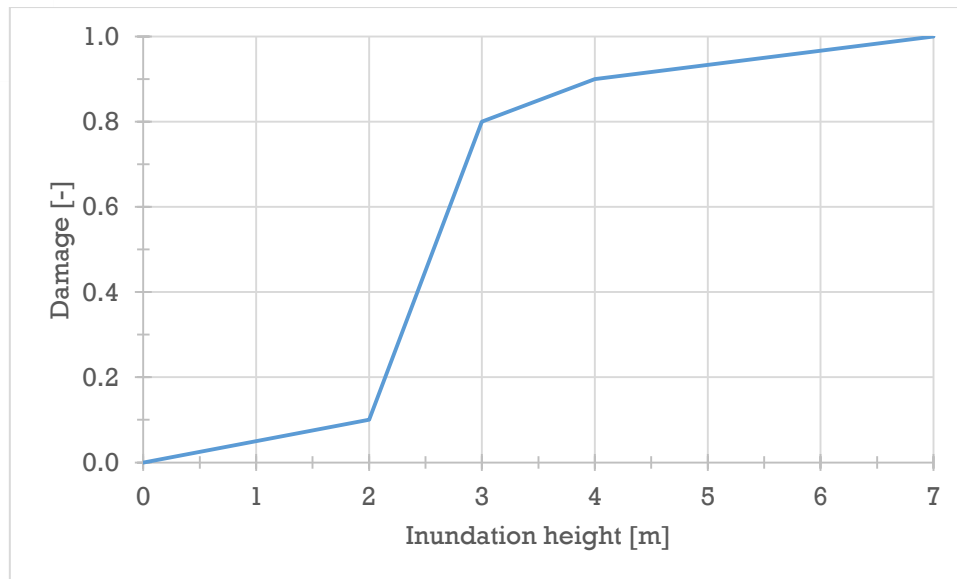


Figure App C-20: Damage function others

C.6 Depreciation

Because of the concession period is 30 year, and the lifespan of an asset is within this period, the value after depreciation corresponds to the worth of the assets halfway its lifespan. An example of this assumption is elaborated via an average straddle carrier. On the container terminal, the average straddle carrier is 3.3 years old, with an average lifespan of 10 years (Arcadis Confidential, 2015; Portstrategy, 2016; Huang and Chu, 2003). This means that every 10 years, the used straddle carrier will be replaced by a new one. If the storm surge hits shortly after the new straddle carrier is bought, the damage will be close to the new price, on the other hand, in case a storm surge hits after 10 years, the straddle carrier is almost fully depreciated. Therefore, can be said that the average value of a straddle carrier is half its lifespan, including the depreciation, as visualized in Figure App C-21.

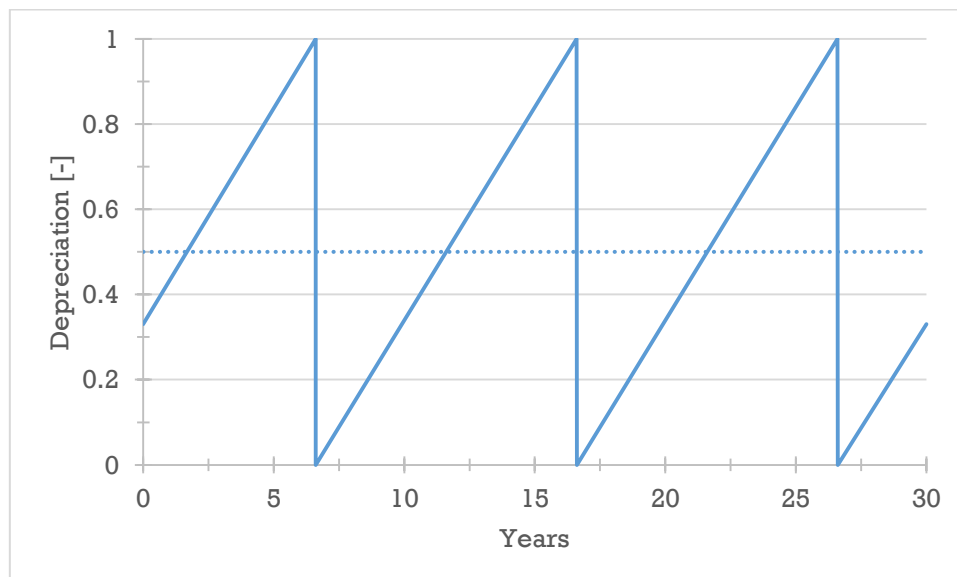


Figure App C-21: Depreciation average straddle carrier

Another example to substantiate the depreciation approach, the average container crane is 10.1 years old and has a lifespan of 25 years (Arcadis Confidential 2015; Vuojolainen and Van der Waal, 2015), an illustration of its depreciation is drawn in Figure App C-22.

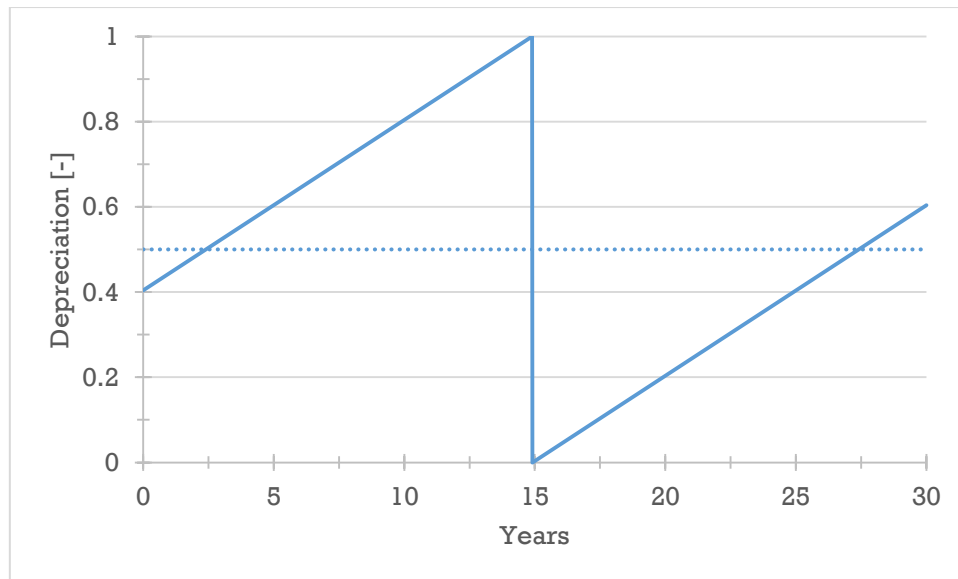


Figure App C-22: Depreciation average container crane

The same application applies for the electric stations, generators, reach stackers, terminal trucks, containers because all lifespans are within the concession period. The buildings on the control and maintenance area have a longer lifespan than the concession period. However, there is established they have a lifetime of at least 50 years (Arcadis Confidential 2015), this in combination with an estimated lifespan of 100 years, the estimation is made that the average value of these assets corresponds also halfway the lifespan (Figure App C-23). For the pavements, quay walls, revetment and group others applies the same.

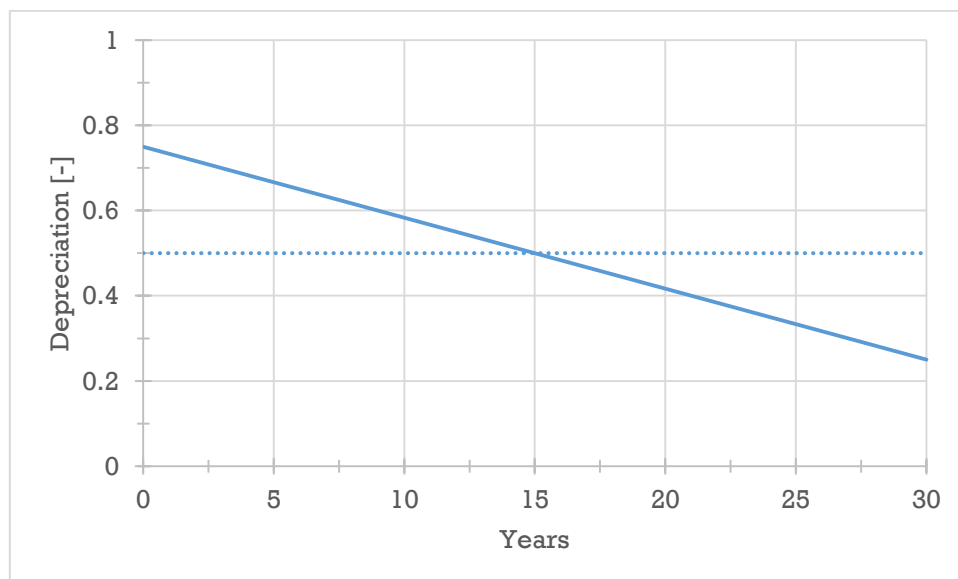


Figure App C-23: Depreciation buildings

The asset foundation retains the majority of its value because it consists mostly of a raw material (i.e. sand). Determining the exact value and influence of depreciation is difficult, because of the value is very dependent on the market and inflation. Therefore, is assumed that the value halfway the lifespan, and by that the average asset value, is half the new price. An overview of the container terminal new prices, corresponding to the data originating from the different asset value structures, and the results out of the depreciation application are shown in Table App C-23.

Table App C-23: Value structure entire terminal with depreciation

Assets	Container terminal new price [M\$]	Price after depreciation [M\$]
Control area	12.20	6.10
Maintenance area	6.11	3.06
Electric mainstation	6.00	3.00
Electric substations	5.00	2.50
Generators	5.50	2.75
Container cranes	128.00	64.00
Straddle carriers	55.80	27.90
Reach stackers	8.10	4.05
Terminal trucks	3.30	1.65
Full dry containers	700.39	670.89
Empty containers	89.20	44.60
Reefers	70.44	59.34
Pavements	76.50	38.25
Quay walls	210.60	105.30
Foundation	212.00	212.00
Revetment	24.00	12.00
Others	19.50	9.75
Total	1633	1267

Appendix D Fault events

The decisive fault events (i.e. electric mainstation, straddle carriers and waterway), having the most influence on the resulting indirect damage, are described in Paragraph 5.3. In Paragraph 5.4 can the overview of fault event variables downtime and capacity loss function be found. Divided into the following groups, an extensive estimation process is written in this Appendix, based on the principle explained in Paragraph 5.3:

- Appendix D.1: operation areas (control and maintenance);
- Appendix D.2: electrical (mainstation and substations);
- Appendix D.3: ground transport (container cranes, straddle carriers, reach stackers and terminal trucks);
- Appendix D.4: containers (empty containers);
- Appendix D.5: fundamental (pavements, quay walls and others)
- Appendix D.6: external (power supply, waterway and access road)

All estimations are made under supervision of specialists (Arcadis, 2016) and supplemented by the following data:

- ^[1] = Searates, 2016
- ^[2] = Total, 2016
- ^[3] = O'Donoghue, 2016
- ^[4] = Kalmar, 2016
- ^[5] = CUR, 2005

There is begun by linking the assets, causing certain fault events, to relative fault events in the fault tree (as visualized in Figure 5-5 and Figure 5-6). In general, can be said, in case a fully damaged asset leads to 100% capacity loss, the capacity loss is equal to the damage factor, which is the case for the assets: electric mainstation, foundation, revetment and the group others. The backup data server will not be damaged by floods, meaning that there will no capacity loss through this asset, where the generators appeared a non-critical asset. The availability of generators increases the flexibility, mainly in the maintenance area and the electric substations, due to their deployability, so the generators have a clear function. However, if the other electrical assets keep online, the loss of the generators can be temporary compensated. In case the other electrical assets will get damaged, the generators are not able to compensate their capacity loss. This means, that the generators will not cause capacity loss. The same applies for the backup data server, due to its flood protected location (Paragraph 4.3). An illustration of the assets not losing capacity when a flood hits the container terminal (i.e. foundation, revetment, generators and backup data server) is shown in Figure App D-1.

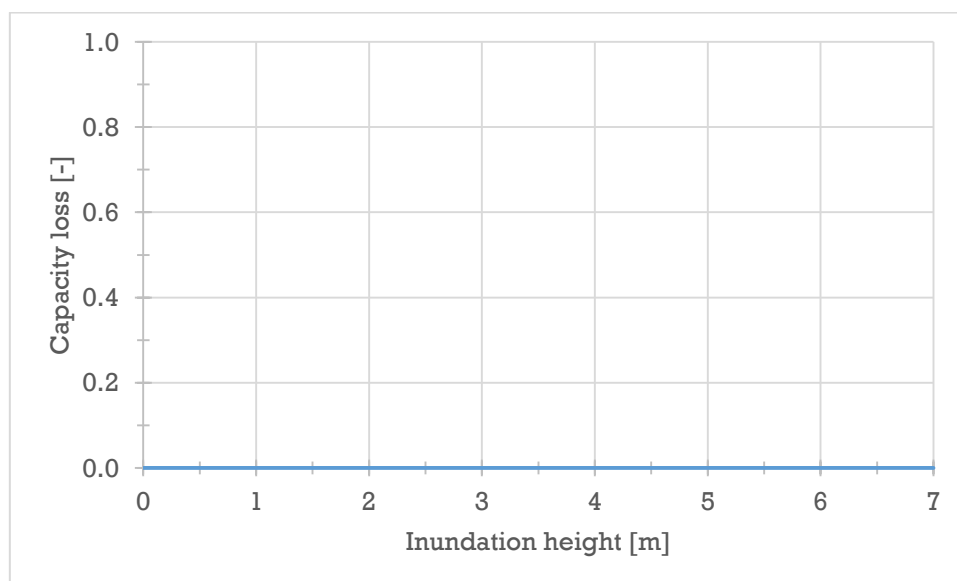


Figure App D-1: Capacity loss function generators, foundation, revetment, backup data server

D.1 Operation areas

It is not the entire control area that leads to capacity loss, it is the crucial TOS and data server that could lead to occurring fault events. These components are situated in the operation building, with limited distance above the ground level, leading to the capacity loss function shown in Figure App D-2. Just as the damage factor of the maintenance area, is the capacity loss function derived from Tebodin, 2000. The same applies to the maintenance area, where the fuel facility will trigger the fault event. Therefore, the capacity loss function increases faster than the damage function, until an inundation height of 4.2 m where the full downtime is needed to recover. The downtimes of both operation areas can be found in Table App D-1 and Table App D-2.

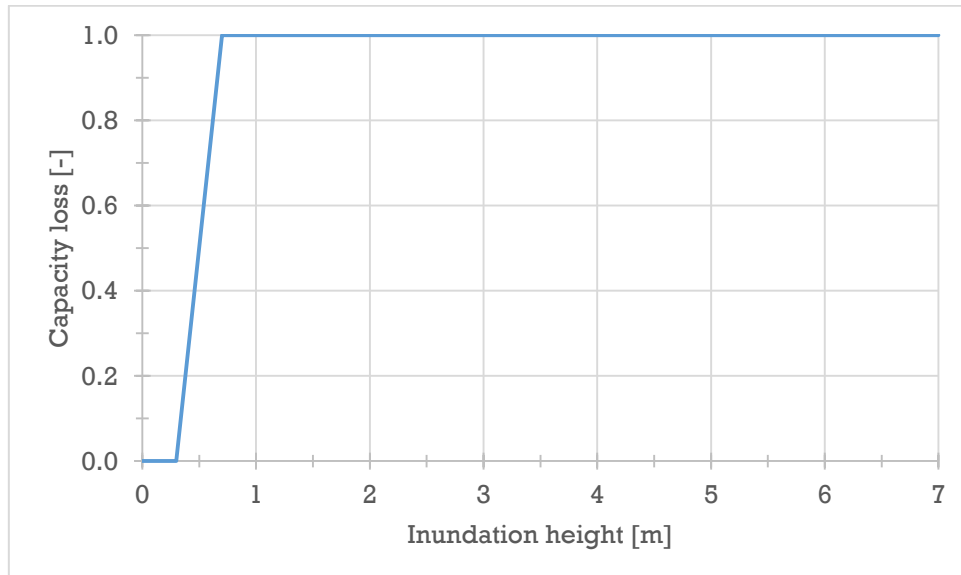


Figure App D-2: Capacity loss function control area

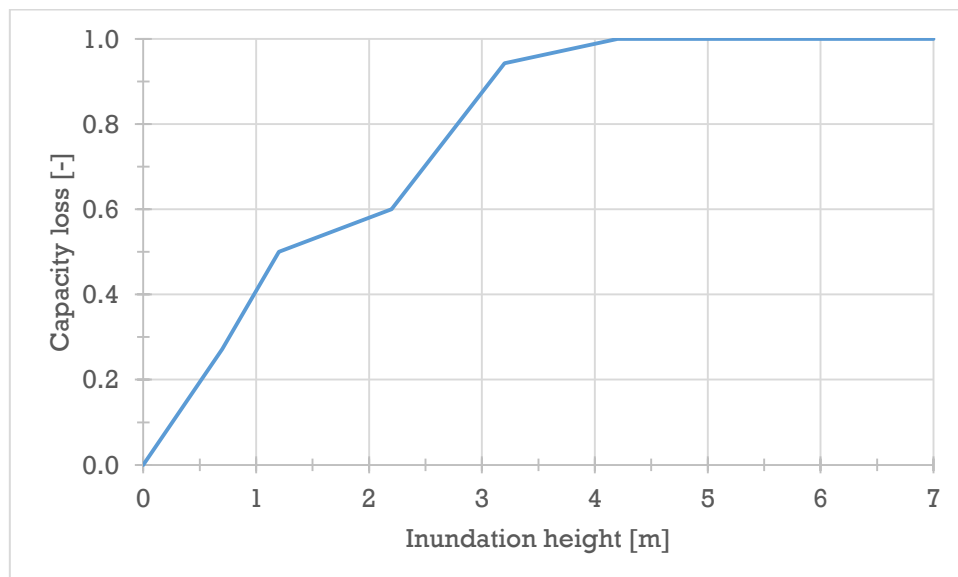


Figure App D-3: Capacity loss function maintenance area

Table App D-1: Downtime structure control area

Section	Downtime [months]
Inspect	1.00
Construct	-
Transport ^[1]	0.50
Install	0.50
Total:	2.00

Table App D-2: Downtime structure maintenance area

Section	Downtime [months]
Inspect	1.00
Construct ^[2]	1.00
Transport ^[1]	1.00
Install ^[2]	4.00
Total:	7.00

D.2 Electrical

Where the generators will not trigger a crucial fault event, the electric mainstation has a capacity loss function similar to their damage function (Table App D-4 equal to Figure 5-7). The electric substations will not result in a fully capacity loss because Terminal B is electric supplied via the electric mainstation, this section of the container terminal will continue working in case both substations become out of order. The capacity of Terminal B is estimated via the number of operational container cranes, equal to four of the sixteen, leading to a maximum capacity loss of 0.75 through the electric substations (Figure App C-5). The downtimes of both electric events are shown in Table App D-3 (similar to Table 5-2) and Table App D-4.

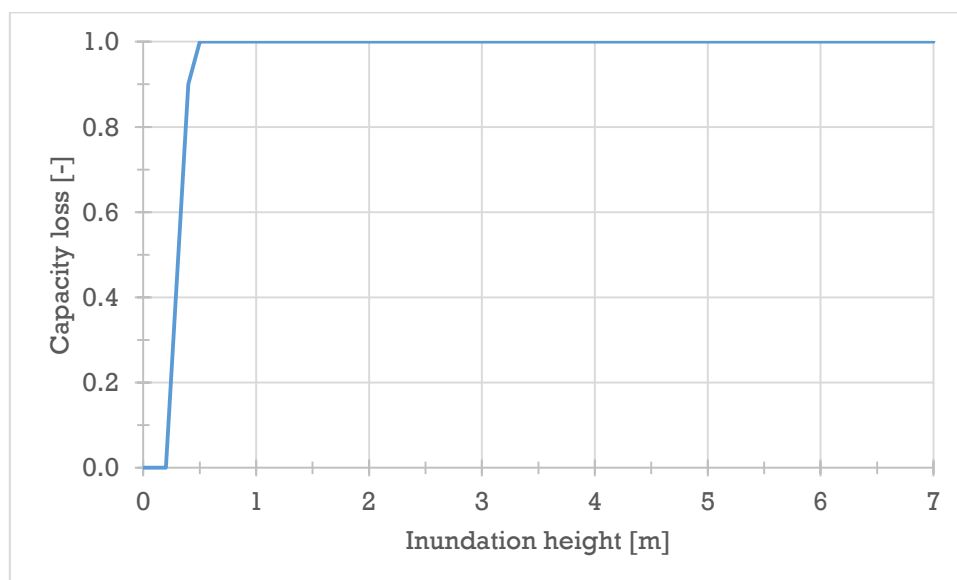


Figure App D-4: Damage function electric mainstation

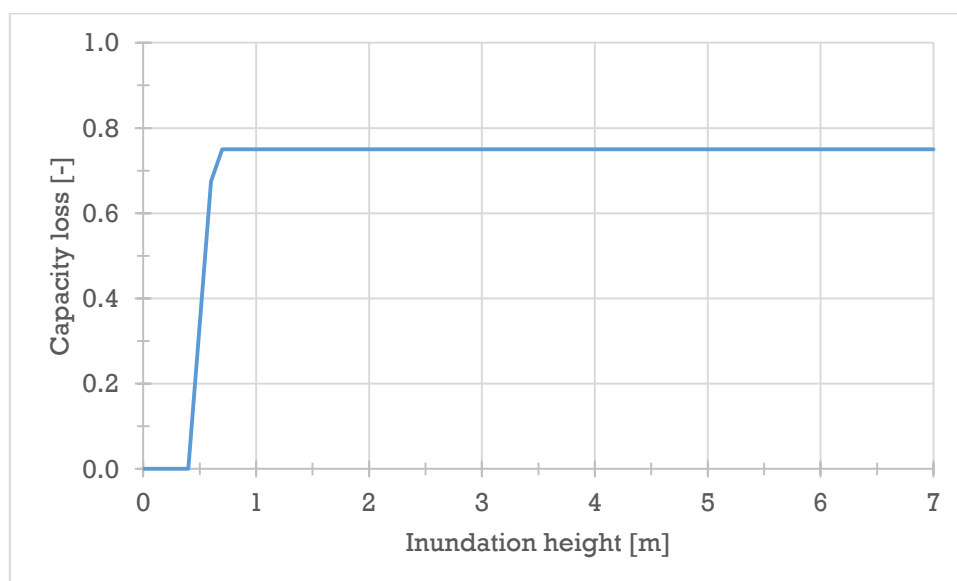


Figure App D-5: Capacity loss function electric substations

Table App D-3: Downtime structure electric mainstation

Section	Downtime [months]
Inspect	1.00
Construct	2.00
Transport ^[1]	0.50
Install	1.00
Total:	4.50

Table App D-4: Downtime structure electric substations

Section	Downtime [months]
Inspect	1.00
Construct	1.00
Transport ^[1]	0.50
Install	1.00
Total:	3.50

D.3 Ground transport

This Appendix begins with the capacity loss reduction, leading to the container crane variables, after which the remaining ground transport variables (i.e. straddle carriers, reach stackers, terminal trucks) are determined.

D.3.1 Capacity loss reduction

In a simplification of the process can be said that the amount of equipment out of order is equal to the loss of capacity, e.g., half of the straddle carriers is out of order, means 50% capacity loss of the straddle carriers. Within the simplification, the capacity loss is named direct capacity loss (Equation App D-1).

$$DCL = \frac{A_{e, ofo}}{A_{e, tot}}$$

Equation App D-1: Direct capacity loss

DCL	[factor]	Direct capacity loss
$A_{g, ofo}$	[amount]	Equipment out of order
$A_{e, tot}$	[amount]	Total equipment

In reality, the amount of equipment out of order is not necessarily equal to the loss of capacity. Imagine that one of the sixteen container cranes is out of order, the other fifteen cranes could be used efficiently to reduce the actual capacity loss on the transshipment. However, there is a limit to this reduction, in this container terminal is estimated that a capacity reduction will take place in the first 25% equipment out of order, from there the actual capacity loss cannot be reduced and is equal to the direct capacity loss (Equation App D-1). From here, the actual capacity loss is named capacity loss and could be calculated via Equation App D-2. This estimation is visualized in Figure App D-6.



Figure App D-6: Capacity loss in relationship to the factor equipment out of order

$$\text{If } DCL < 0.25 \text{ then } CL = (2 * DCL)^2$$

$$\text{If } DCL \geq 0.25 \text{ then } CL = DCL$$

Equation App D-2: Capacity loss

CL	[factor]	Capacity loss
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Until this phase, the same procedure is used for each individual ground transport asset (i.e. container cranes, straddle carriers, reach stackers and terminal trucks), however, from here different steps will be taken to determine the contribution of the different equipment on the transshipment capacity loss. The reasoning behind this is, because container cranes and flexible equipment belong to a different fault event (Figure 5-5), meaning that there is no interaction between the two, besides that, because the reach stackers and terminal trucks are not crucial to execute the ground transport, in contrast with the container cranes and straddle carriers (as explained in Paragraph 4.3 and visualized in the fault tree in Figure 4-26).

Container cranes

Container cranes, having an extensive downtime (Table App D-5), and are essential for the ground transport of the container terminal. This means that the capacity loss on the transshipment reaches up to 100%, in case all container cranes are out of order. This in combination with the given that the container cranes belong to another fault event, then the flexible equipment, the capacity loss, due to container cranes can be calculated through Equation App D-2 with the same terms as Equation App D-2. This leads to the capacity loss function of the container crane, drawn in Figure App D-7.

Table App D-5: Downtime structure complete cranes

Section	Downtime [months]
Inspect	1.50
Construct ^{[3][4]}	15.00
Transport ^{[1][3][4]}	1.00
Install ^{[3][4]}	0.50
Total:	18.00

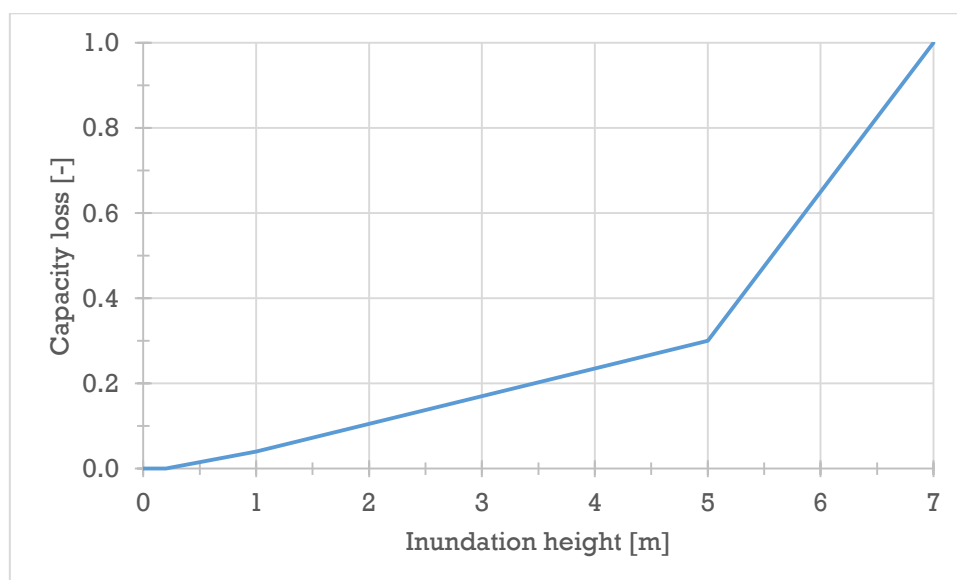


Figure App D-7: Capacity loss function container cranes

$$CL_{cc} = (2 * DCL_{cc})^2 \vee DCL_{cc}$$

Equation App D-3: Capacity loss by container cranes

CL_{cc}	[factor]	Capacity loss by container cranes
DCL_{cc}	[factor]	Direct capacity loss by container cranes

D.3.2 Flexible equipment

The determination of the capacity loss caused by flexible equipment is more complicated than the container cranes, through the interactions between the equipment (visualized in Figure 5-5). In order to calculate the interactions and its effect on the capacity loss, each equipment shall be added stepwise. Starting with the straddle carriers, followed by the interaction of the reach stackers on the straddle carriers, and the influence of the terminal trucks on the determination.

Table App D-6: Downtime structure straddle carriers

Section	Downtime [months]
Inspect	1.50
Construct ^{[3][4]}	17.00
Transport ^{[1][3][4]}	1.00
Install	-
Total:	19.50

Straddle carriers

Firstly, the *straddle carriers* are, just like container cranes, essential for the ground transport of the container terminal and cannot be replaced. In case all straddle carriers are out of order, the capacity loss (Figure App D-8, showing the same as Figure 5-8) reaches up to 100% leading to Equation App D-4 with the same terms as Equation App D-2. The downtime structure is shown in Table App D-6, identical to Table 5-3.

$$CL_{sc} = (2 * DCL_{sc})^2 \vee DCL_{sc}$$

Equation App D-4: Capacity loss straddle carriers

CL_{sc} [factor] Capacity loss by straddle carriers
 DCL_{sc} [factor] Direct capacity loss by straddle carriers

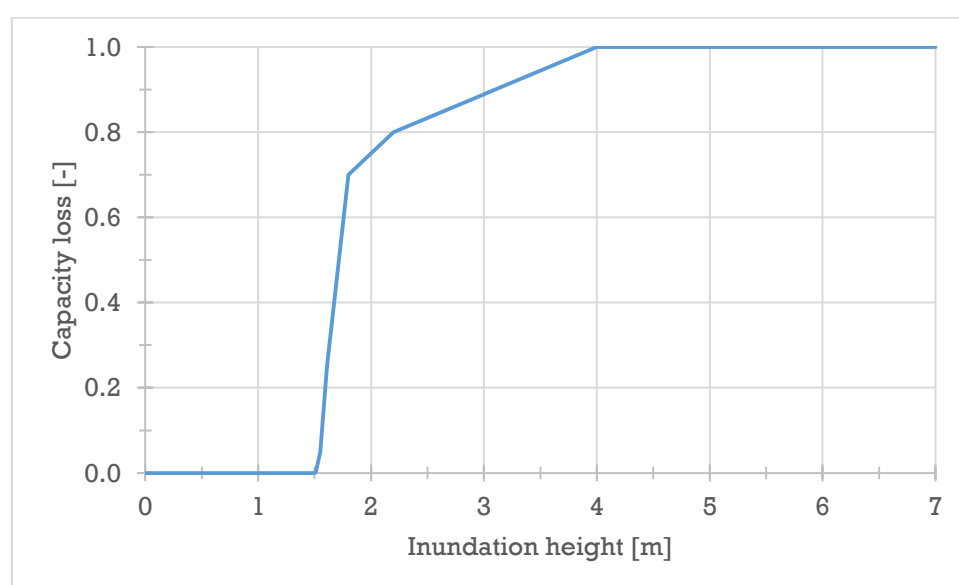


Figure App D-8: Capacity loss function straddle carriers

Reach stackers

Secondly, *reach stackers* are used to transport empty containers in and outside the stack and have above average downtimes (Table App D-7). In case all reach stackers become out of order, the straddle carriers will be used to place empty containers. Apart from the full container stack capacity loss, the straddle carriers will stack the empty containers with more space between each other and at a lower height than the reach stackers. Therefore, can be said that the capacity loss of reach stackers on the transshipment is significant, but not completely, because the process could be continued on a lower scale. The estimation is made that the capacity loss of the reach stackers (Figure App D-9) on the ground transport is equal to the distribution of empty containers on the total dwell time, which could be found by using a cross-multiplication (Equation App D-5) on the traffic (Figure 4-5) and dwell times (Figure 4-20).

Table App D-7: Downtime structure reach stackers

Section	Downtime [months]
Inspect	1.50
Construct ^{[3][4]}	9.00
Transport ^{[1][3][4]}	1.00
Install	-
Total:	11.50

$$MCL_{rs} = D_{empty} = \frac{DT_{empty}}{DT_{all}} \Rightarrow \frac{12,942}{25,526} = 0.51$$

Equation App D-5: Maximum capacity loss reach stackers

MCL_{rs}	[factor]	Maximum capacity loss by reach stackers
D_{empty}	[factor]	Distribution of empty containers on total dwell time
DT_{empty}	[days]	Dwell time empty containers (Figure 4-20)
DT_{all}	[days]	Dwell time all containers (Figure 4-20)

The cross-multiplication results in 0.51 or 51% distribution of empty containers on the total dwell time, meaning that 51% corresponds to the capacity loss on the transshipment in case all reach stackers are out of order. This distribution factor should then be multiplied by the capacity due to the reach stackers (Equation App D-6).

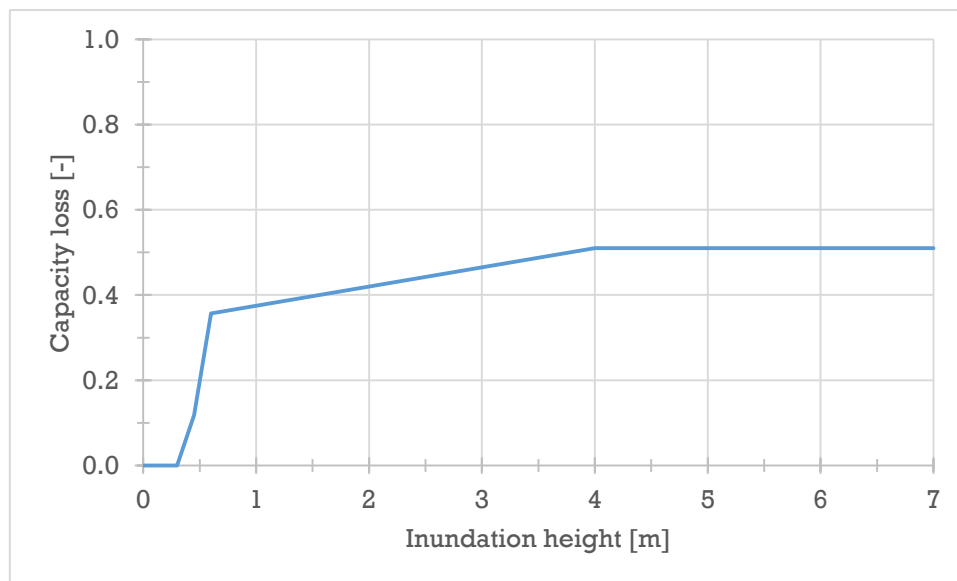


Figure App D-9: Capacity loss function reach stackers

$$CL_{rs} = MCL_{rs} * ((2 * DCL_{sc})^2 \vee DCL_{sc}) \Rightarrow 0.51 * ((2 * DCL_{sc})^2 \vee DCL_{sc})$$

Equation App D-6: Capacity loss reach stackers

CL_{rs}	[factor]	Capacity loss by reach stackers
DCL_{rs}	[factor]	Direct capacity loss by reach stackers

The interaction between the straddle carriers and the reach stackers on the capacity loss of the transshipment is estimated by multiplying the capacities of both (Equation App D-7).

$$CL_{scrs} = 1 - (1 - CL_{sc}) * (1 - CL_{rs})$$

Equation App D-7: Capacity loss straddle carriers and reach stackers

CL_{scrs}	[factor]	Capacity loss by straddle carriers and reach stackers combined
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Table App D-8: Downtime structure terminal trucks

Section	Downtime [months]
Inspect	1.50
Construct ^{[3][4]}	5.00
Transport ^[1]	1.00
Install	-
Total:	7.50

Terminal trucks

Thirdly, however, the contribution of *terminal trucks* (Table App D-8) on the ground transport is little, though the capacity will decrease in case all terminal trucks will be out of order. Given the fact that terminal trucks partly execute the function of straddle carriers (explained in Paragraph 4.3 and visualized in Figure 5-5). Therefore, the distribution of terminal trucks in combination with an efficiency factor becomes the cross-multiplication to determine the influence of the terminal trucks on the capacity loss of the transshipment (Equation App D-8).

$$MCL_{tt} = EF * \frac{A_{tt}}{A_{sc} + A_{tt}} \Rightarrow 0.5 * \frac{8}{62 + 8} = 0.06$$

Equation App D-8: Maximum capacity loss terminal trucks

MCL_{tt}	[factor]	Maximum capacity loss by terminal trucks
EF	[factor]	Efficiency factor terminal trucks compared to straddle carriers
A_{tt}	[-]	Total amount of terminal trucks
A_{sc}	[-]	Total amount of straddle carriers

The result of Equation App D-8 is 0.06, meaning that the capacity will decrease (Figure App C-10) with 6% in case all terminal trucks are out of order. The estimation is made that the loss in capacity is in ratio with the capacity loss of the straddle carriers and reach stackers. Therefore, in case the terminal trucks capacity is lower than the combined capacity, the trucks capacity loss becomes negligible. In case the terminal trucks capacity is higher or even than the combined capacity, the loss of tow trucks capacity is determined according to Equation App D-10. In order to use this calculation, the calculable capacity loss due to tow trucks on the ground transport needs to be determined via Equation App D-9 with the same terms as Equation App D-2.

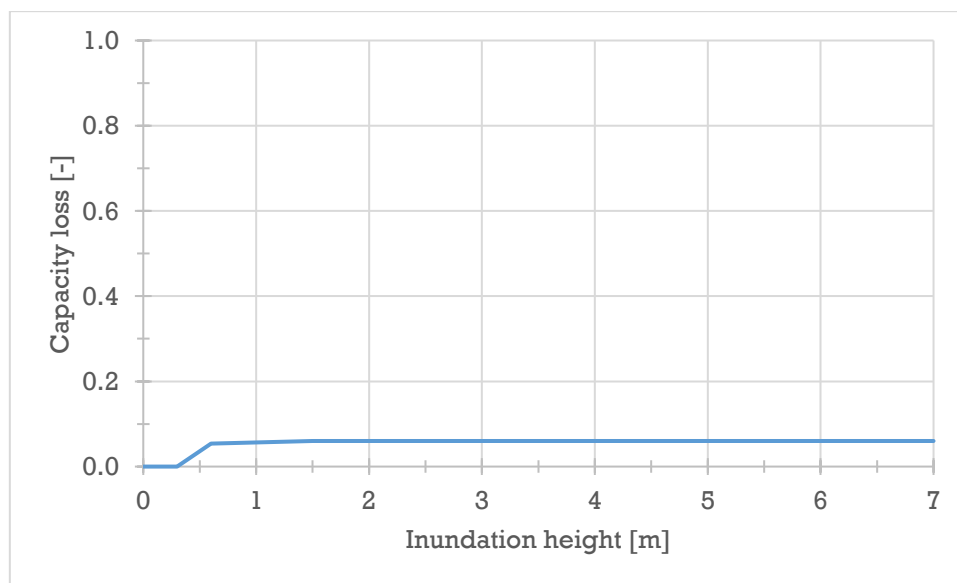


Figure App D-10: Capacity loss function terminal trucks

$$CCL_{tt} = (2 * DCL_{tt})^2 \vee DCL_{tt}$$

Equation App D-9: Calculable capacity loss terminal trucks

CCL_{tt}	[factor]	Calculable capacity loss by terminal trucks
DCL_{tt}	[factor]	Direct capacity loss by terminal trucks

If $CCL_{tt} \leq CL_{sc}$ then CL_{tt} is negligible

If $CCL_{tt} > CL_{sc}$ then $CL_{tt} = MCL_{tt} * (CCL_{tt} - CL_{sc}) \Rightarrow 0.06 * (CCL_{tt} - CL_{sc})$

Equation App D-10: Capacity loss terminal trucks

CL_{tt}	[factor]	Capacity loss by terminal trucks
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Combined

By combining the capacity loss calculations of the straddle carriers, reach stackers and terminal trucks the total capacity loss on the transshipment due to flexible equipment could be found through the Equation App D-11 (identical to Equation 5-2).

$$CL_{flex} = CL_{scrs} - CL_{tt}$$

Equation App D-11: Capacity loss flexible equipment

CL_{flex}	[factor]	Capacity loss by flexible equipment
-------------	----------	-------------------------------------

D.4 Containers

The assets full dry, empty and refrigerated containers fall under the container group. A distinction between the different container types are made through the cargo and need of electricity, however, the fault event that occurs via the containers does not rely on the cargo or the electricity. By looking to the fault event tree (Figure 5-5), there could be seen that the terminal becomes unpassable, something that will happen through floating containers. There is a direct relationship between the weight of the containers and the point where they start floating, as elaborated in Appendix C.4. Therefore, the lowest weighing containers, which are the empty ones, become decisive. The capacity loss function of the containers corresponds to the damage factor of the empty containers, as drawn in Figure App D-11. The downtime structure is displayed in Table App D-9.

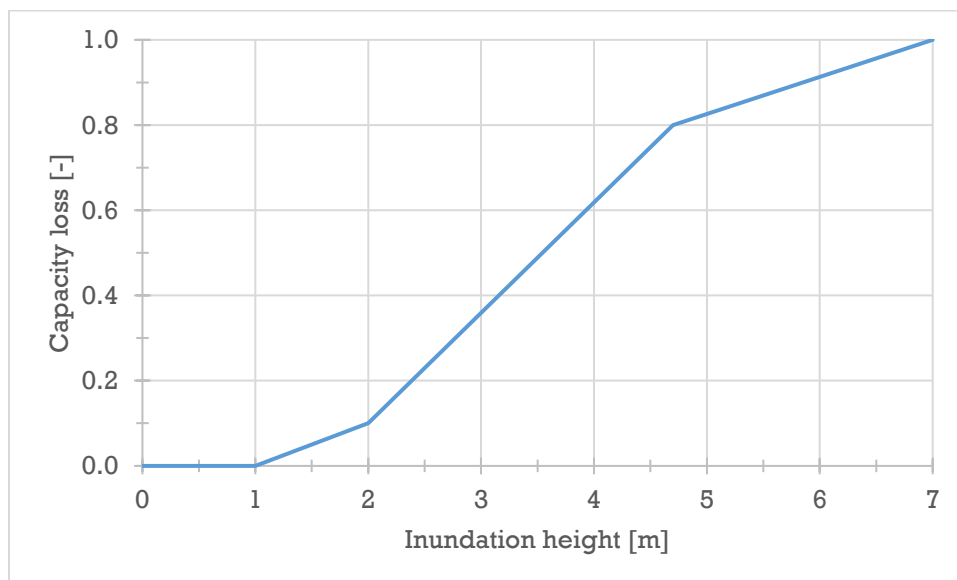


Figure App D-11: Capacity loss function containers

D.5 Fundamental

Assets boxed in the group others have a capacity loss function similar to the damage function (Figure App D-14). The capacity loss function of the pavements (Figure App D-12) is based on the point the other assets start floating, making the pavement unpassable. Quay walls trigger the fault event container crane rails unpassable, which eventually lead to the capacity loss of the entire terminal. Depending on the occurring direct damage on the quay wall, therefore, the same linear function is assumed. However, for this fault event, the capacity loss goes to 1.0 in the case of 7-meter inundation height (Figure App D-13) leading to a downtime of eleven months Table App D-11. The other downtime structures relative to the fundamental fault events can be found in Table App D-10 and Table App D-12.

Table App D-9: Downtime structure containers

Section	Downtime [months]
Inspect	0.50
Construct	-
Transport ^[1]	0.50
Install	0.50
Total:	1.50

Table App D-10: Downtime structure pavements

Section	Downtime [months]
Inspect	1.50
Construct	1.00
Transport ^[1]	0.50
Install	1.00
Total:	4.00

Table App D-11: Downtime structure quay walls

Section	Downtime [months]
Inspect	2.00
Construct ^[5]	2.00
Transport ^{[1][5]}	1.00
Install ^[5]	6.00
Total:	11.00

Table App D-12: Downtime structure others

Section	Downtime [months]
Inspect	1.00
Construct	0.50
Transport ^[1]	0.50
Install	0.50
Total:	2.50

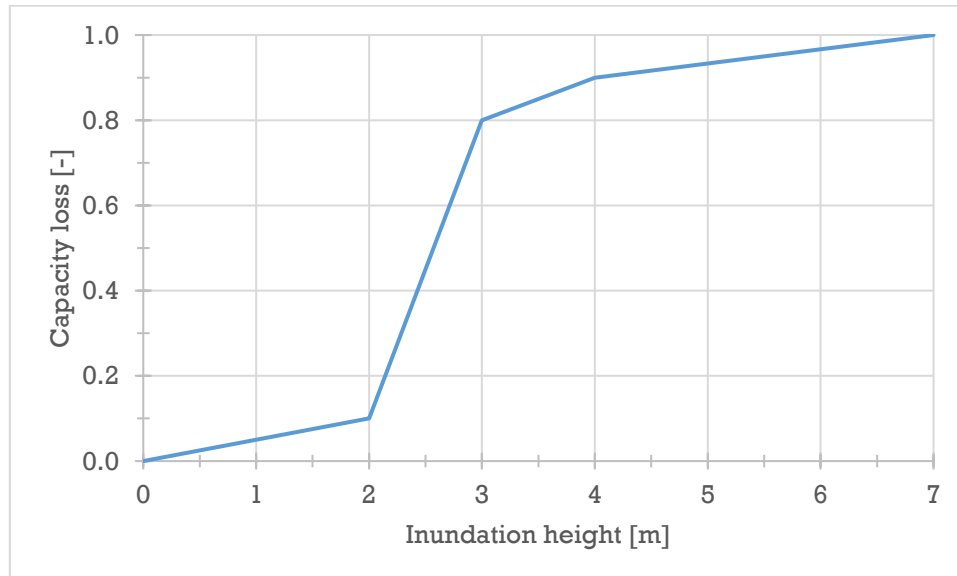


Figure App D-12: Capacity loss function pavements and power supply

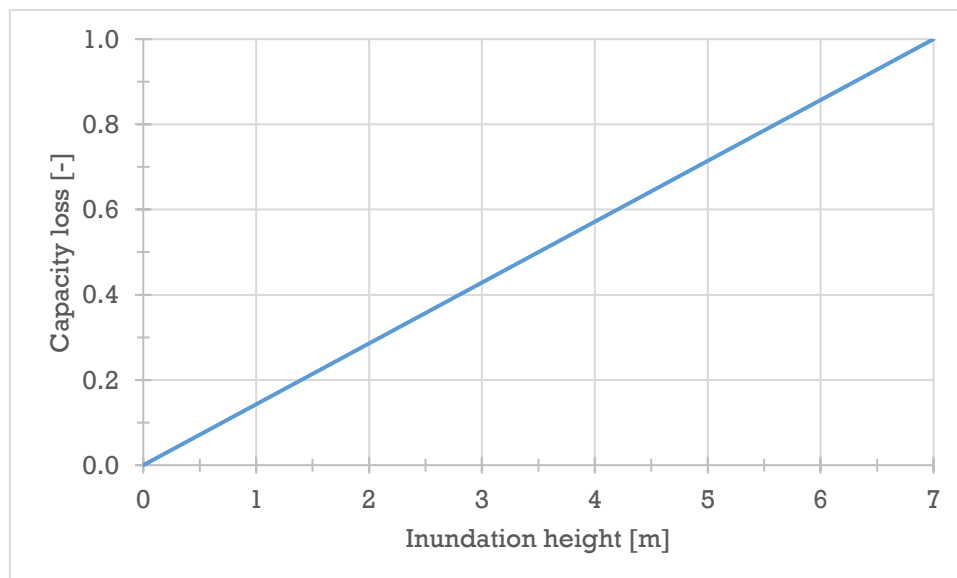


Figure App D-13: Capacity loss function quay walls

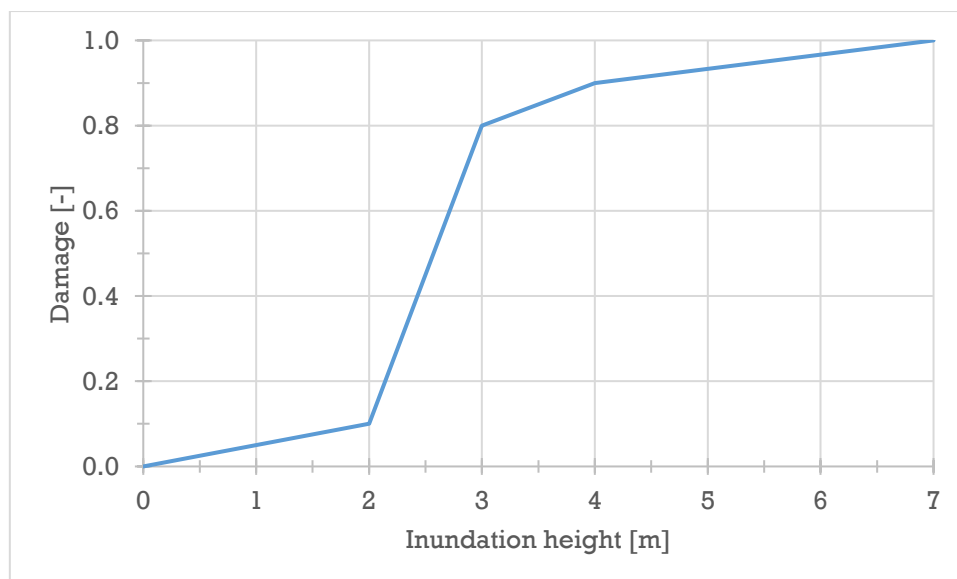


Figure App D-14: Damage function others

D.6 External

Power supply

As mentioned in Paragraph 4.3, the container terminal receives external power supply through two power plants, which are linked through the electric mainstation to the terminal via electric cables attached to wooden poles. In case the wooden poles cannot resist the receiving force, the power supply will be lost. The receiving force becomes too high in case other materials will start floating, therefore, the capacity loss function is similar to the pavements (Figure App D-12).

Table App D-13: Downtime structure power supply

Section	Downtime [months]
Inspect	0.50
Construct	-
Transport ^[1]	0.50
Install	1.00
Total:	2.00

Table App D-14: Downtime structure waterway

Section	Downtime [months]
Inspect	0.50
Construct	-
Transport	3.00
Install	0.50
Total:	4.00

Waterway

The container terminal is attainable via the vessels through the waterway and the access road can be used by trucks (Figure 4-2). Whereby containers will not be transported land in-land out, that movement shall not be executed via the terminal. Since the container terminal is a transshipment HUB (Paragraph 4.2), the movement water in-water out will occur, just like the movements land in-water out and water in-land out. Therefore, can be concluded that if the waterway becomes not passable, the entire capacity will be lost. An access road that is not passable leads to the loss of

land in containers (elaborated further in this Appendix and described in Paragraph 4.2). The capacity loss function of the waterway is an interaction between the draft and frequency of the vessels on the one hand and the sediment accretion on the other. The executed steps in order to calculate the interaction will be explained in this Appendix. The downtime can be found in Table App D-14, a similar table to Table 5-4.

Firstly, the share per vessel type is calculated by using the data from the vessel sizes and frequencies (Figure 4-4). Where the amount per week is a multiplication between the size and the frequency of the vessel type. The share is then the amount per week expressed in a factor (Table App D-15).

Table App D-15: Share per vessel type

Vessel type	Size [TEU]	Frequency [per week]	Amount per week [TEU]	Share [factor]
B1	3500	4	14,000	0.09
B2	4000	3	12,000	0.08
C	5000	9	45,000	0.30
D	9000	9	81,000	0.54
Total:			152,000	1.00

Secondly, the *drafts* per vessel type are identified. Because container vessels will most of the time not be fully loaded, there is a distinction made between the lowest, average, and highest draft, whereby the highest draft indicates a fully loaded vessel. In Figure App D-15 are the vertical lines all possible draft heights of the vessel types, the vertical ones stand for the lowest (short lower line), average (long center line), and highest drafts. (short upper line).

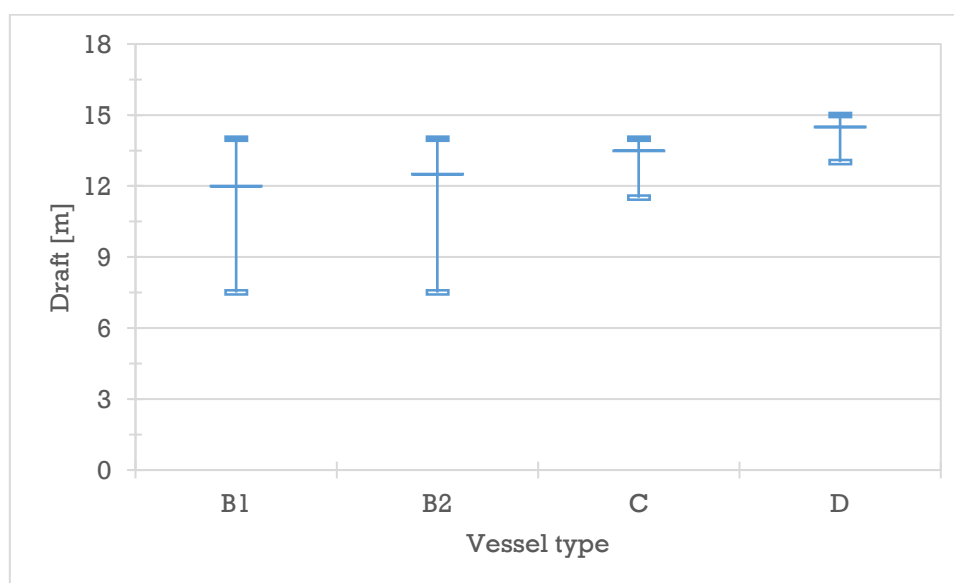


Figure App D-15: Drafts per vessel type (based on Rodrigue et al., 2013)

Thirdly, the *under keel clearance* coefficient of 0.10 is added to the vessel drafts (Figure App D-16). The height of the coefficient is common applied, especially for harbor and bay areas, and originates from Marine Exchange of Southern California (2016) and Expert group (2014).

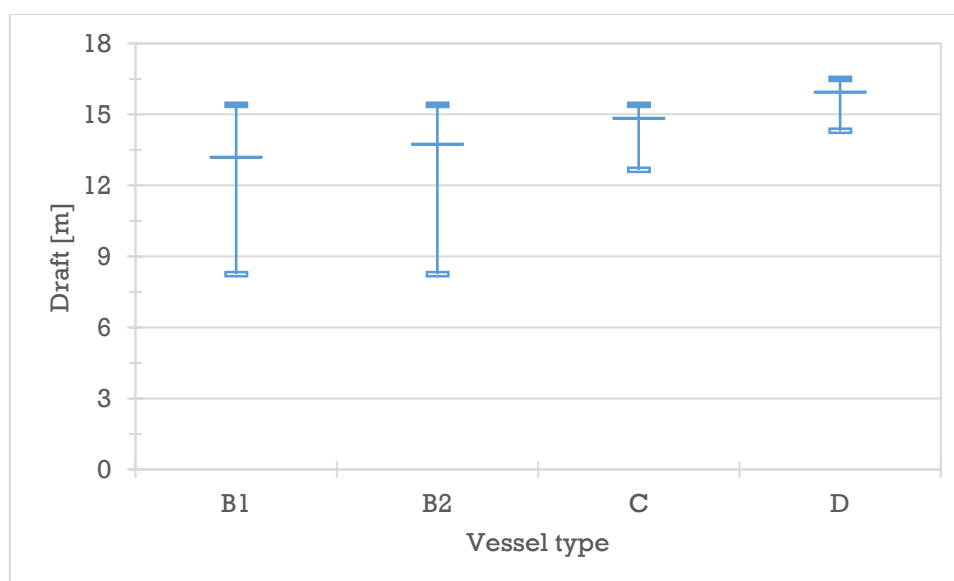


Figure App D-16: Drafts per vessel type including under keel clearance

Fourthly, the interaction between the shares and drafts per vessel type is elaborated in order to find which *waterway depth* belongs to which *capacity loss* (Figure App D-17). The depth of the waterway is equal to the draft of the vessels, including under keel clearance. The capacity loss is the inverse of the summed shares corresponding to that particular waterway depth.

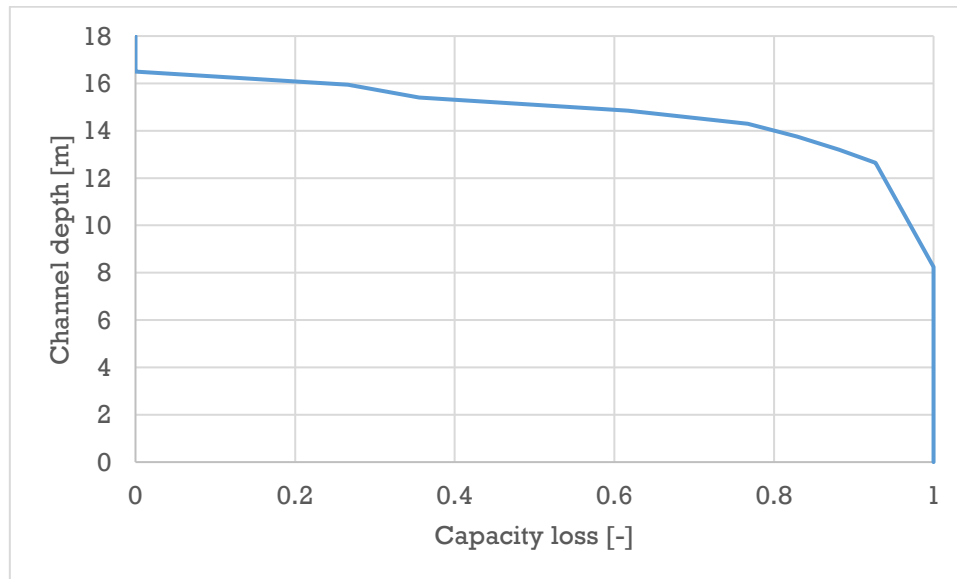


Figure App D-17: Capacity loss per waterway depth

Fifthly, the *accretion of sedimentation* per storm surge is determined via data of measured sedimentation through different storms. The data originates from a study on the case by Confidential (2012), whereby four sedimentation measures have been executed of four different storm surges and the local inundation heights could be read, after which the used storm surges are linked to corresponding return periods (Confidential, 2005 and Confidential, 2008). This leads to the sedimentation height per storm surge (Figure App D-18).

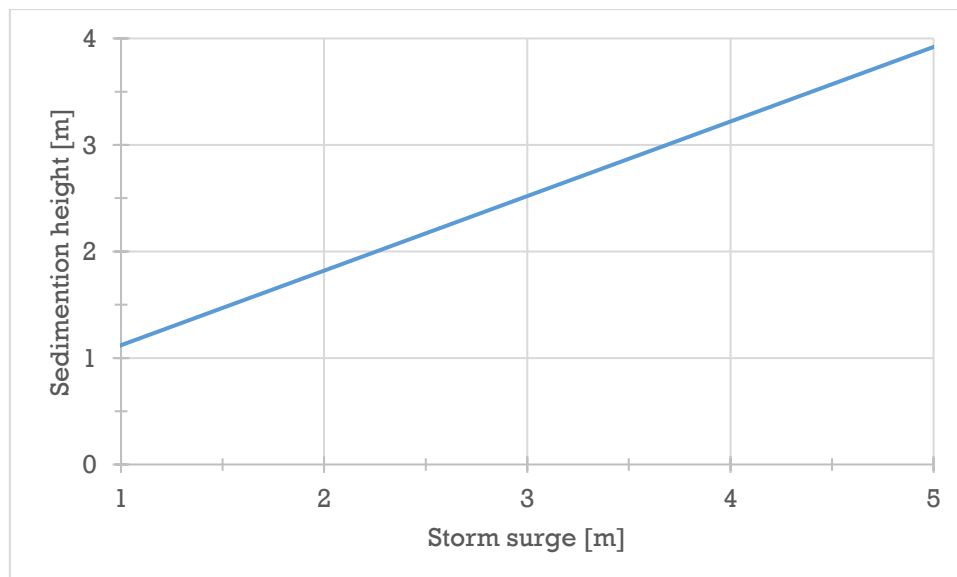


Figure App D-18: Sedimentation per return period

Lastly, the different data (i.e. vessel draft and sedimentation height) are linked, whereby the *capacity loss function* of the waterway is determined. In order to link both data, the sedimentation data needs to be expressed in channel depth, which could be done by subtracting the sedimentation accretion from the channel depth without sediment (18 meters, as mentioned in Paragraph 4.2). In that way, the capacity loss could be expressed per storm surge, which is equal to a known inundation height (as shown in Figure App D-19, similar to Figure 5-9).

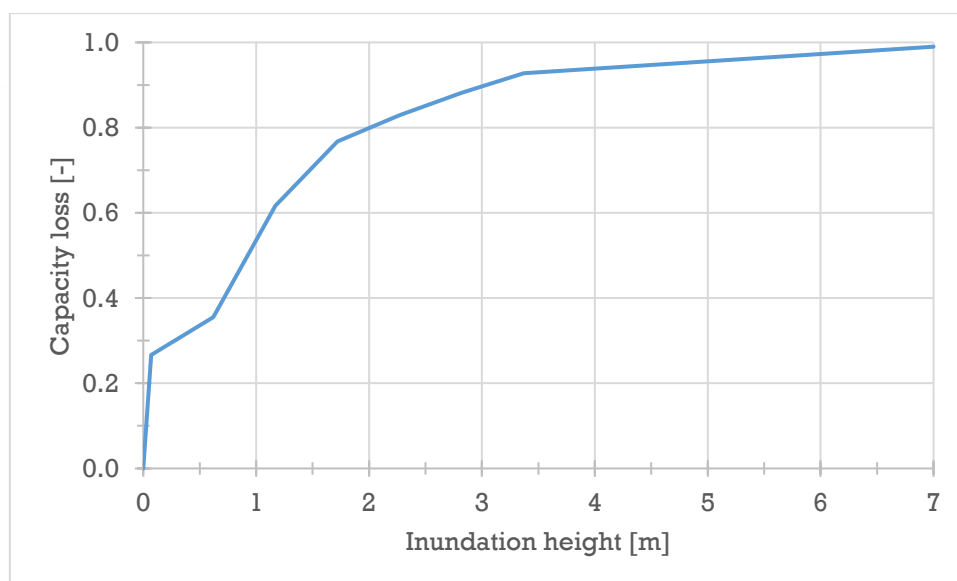


Figure App D-19: Capacity loss function waterway

Access road

The access road is a hurricane and earthquake constructed road (Confidential, 2016a), whereby is assumed that the access road will not need to be repaired after a flood. On the other hand, after a reasonable flood the access road will contain several materials that need to be removed before the access road becomes fully accessible. The estimation is made that this recovery process will take over two weeks. Before the recovery can start, an inspection is needed (Table App D-16).

Table App D-16: Downtime structure access road

Section	Downtime [months]
Inspect	0.25
Construct	0.50
Transport	-
Install	-
Total:	0.75

As mentioned in the previous Appendix, an access road which is not passable leads to the loss of land in containers. Therefore, the consequences of an unpassable access road will be determined in this Appendix, where is started with mapping and calculating data (Equation App D-12) in order to determine any conclusions.

Table App D-17: Calculation outcomes of the capacity loss through an unpassable access road

	Land		Water		Total
	In	Out	In	Out	
Full container traffic [kTEU/year] ^[1]	28	174	997	997	2,196
Full container traffic [TEU/day]	77	<u>477</u>	2,731	2,731	6,016
Dwell time [days] ^[2]	8	8	6	6	-
Traffic * dwell time [TEU]	617	3,819	15,020	15,020	34,477
1,5 stack [TEU]	<u>325</u>	<u>2,010</u>	7,907	7,907	<u>18,150</u> ^[3]
Double stack [TEU]	433	2,681	10,543	10,543	<u>24,200</u> ^[4]
Stack increase [TEU]	108	670	2,636	2,636	<u>6,050</u>

^[1] = originating from Figure 4-5

^[2] = originating from Figure 4-20

^[3] = $GS_{fc} * SH = 12,100 * 1.5 = 18,150$

^[4] = $GS_{fc} * SH = 12,100 * 2 = 24,200$

GS_{fc} [GS] Ground slots full containers (Table 4-1)
 SH [TEU] Average stack height

Secondly, the capacity loss when losing the *land in containers* is calculated (Figure App D-20).

$$CL = \frac{TEU_{li}}{TEU_l} = \frac{77}{6,016} = 0.01$$

Equation App D-12: Capacity loss when losing land in-water out containers

TEU_{li}	[TEU/day]	Land in containers per day (table)
TEU_l	[TEU/day]	Land containers per day (table)

Thirdly, with an unpassable access road, the land out containers will be stacked on the terminal and shall not be transported away until the access road becomes passable. Therefore, is calculated how long it takes until the *additional stack capacity* is fully occupied by land out containers (Equation App D-13).

$$DA_{lo;0.5} = \frac{TEU_{t;0.5} + TEU_{li;1.5}}{T_{lo}} = \frac{6,050 + 325}{477} = 13 \text{ days}$$

Equation App D-13: Moment the increased 0.5 stack consists of land out containers

$DA_{lo;0.5}$	[days]	Moment the increased 0.5 stack consists of land out containers
$TEU_{t;0.5}$	[TEU]	Total containers at 0.5 (2-1.5) stack (Table App D-17)
$TEU_{li;0.5}$	[TEU]	Land in containers at 1.5 stack (Table App D-17)
TEU_{lo}	[TEU/day]	Land out containers per day (Table App D-17)

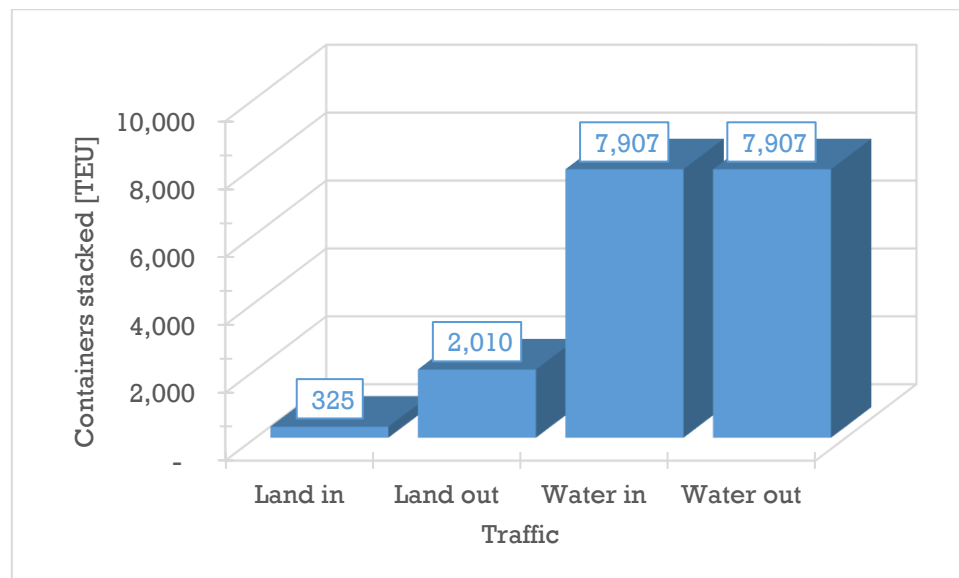


Figure App D-20: Stacked containers at regular situation

In the regular situation, the containers will be 1.5 stacked (Paragraph 4.3) as shown in Figure App D-20. This situation is manageable until the stack gets full, which is the case at the point the average stack height becomes two is assumed (Figure App D-21).

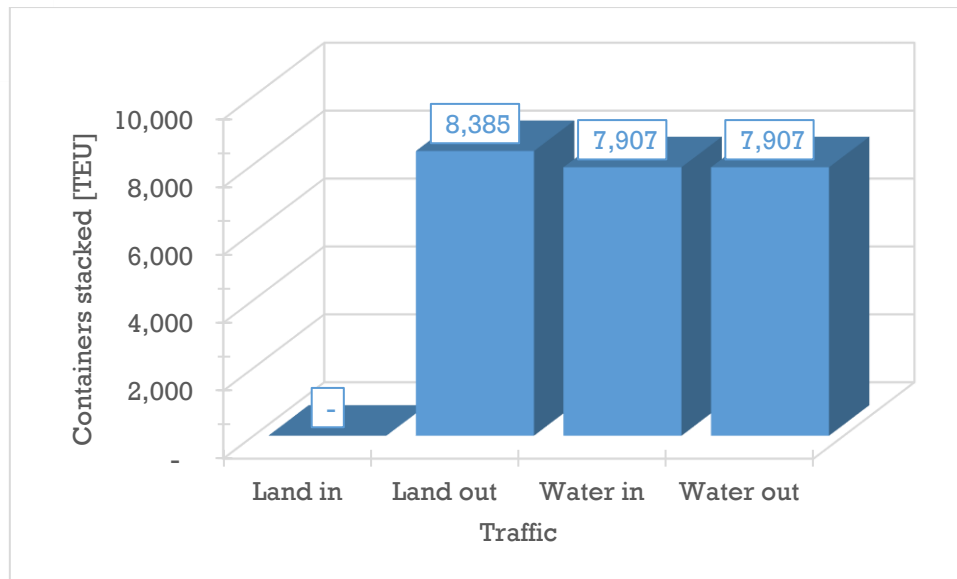


Figure App D-21: Stacked containers after 13 days without land transport

After 13 days without land transport, the water in and water out containers remain the same as the regular situation, the land in containers will all be gone, and the rest of the slots consist of land out containers (Figure App D-21).

Fourthly, is calculated how long it takes until the *entire double stack* consists completely of land out containers. During this phase, the capacity will decrease because the land out containers will be put into the workable 1,5 stack. The estimation is made that the decrease took place linearly, but first determination needs to be made how many containers of the current stack (i.e. the stack after 13 days) are land out containers. Therefore, is looked to the original 1,5 stack (Equation App D-13), because the other 6050 containers are all land out containers (Equation App D-13).

$$TEU_{w;1.5} = TEU_{t;1.5} - TEU_{lo;1.5} = 18,150 - 2,010 = 16,140 \text{ containers}$$

Equation App D-14: Water containers at 1.5 stack

$TEU_{w;1.5}$	[TEU]	Water containers at 1.5 stack
$TEU_{t;1.5}$	[TEU]	Total containers at 1.5 stack (Table App D-17)
$TEU_{lo;1.5}$	[TEU]	Land out containers at 1.5 stack (table)

The time it takes to fill the entire 1.5 stack with land out containers is 33 days (Equation App D-15).

$$DA_{lo;1.5} = \frac{TEU_{w;1.5}}{T_{lo}} = \frac{16,140}{477} = 33 \text{ days}$$

Equation App D-15: Time until 1.5 stack consists of land out containers

$DA_{lo;1.5}$	[days]	Time until the 1.5 stack consists of land out containers
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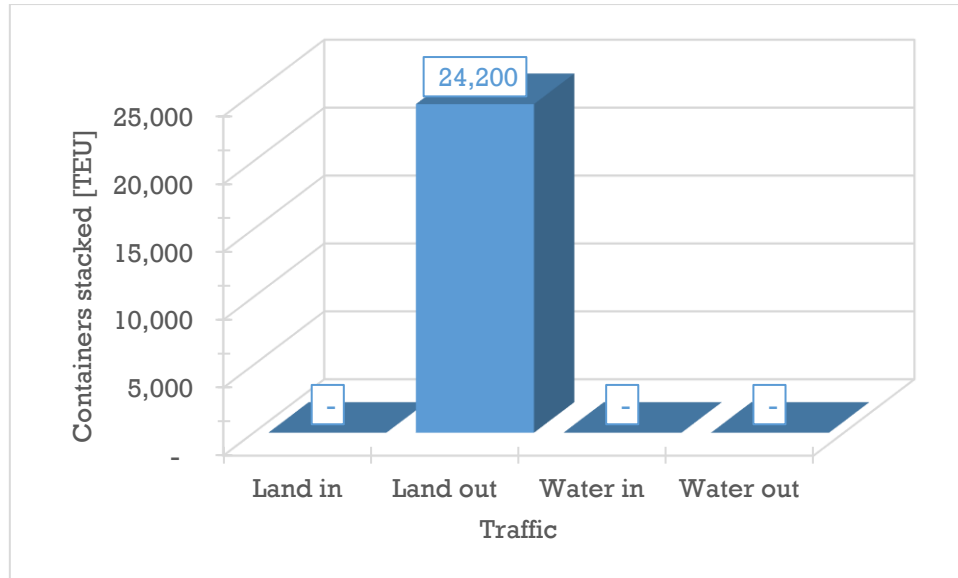


Figure App D-22: Stacked containers after 47 days without land transport

From this moment the capacity will be completely lost (Figure App D-22). This moment can be checked by determining the moment the entire double stack will be filled with land out containers (Equation App D-15).

$$DA_{lo;2} = DA_{lo;0.5} + DA_{lo;1.5} = 13.3 + 33.8 = \frac{TEU_{t;2} - TEU_{lo;1.5}}{T_{lo}} = \frac{24,200 - 2,010}{477} = 47 \text{ days}$$

Equation App D-16: Time until the entire double stack consists land out containers

$DA_{lo;2}$ [days]
 $TEU_{t;1.5}$ [TEU]

Time until the entire double stack consists land out containers
 Total containers at double stack (Table App D-17)

The outcomes of this Appendix until now leads to the ratio of the occurring capacity loss when the access road is not passable (Figure App D-23).

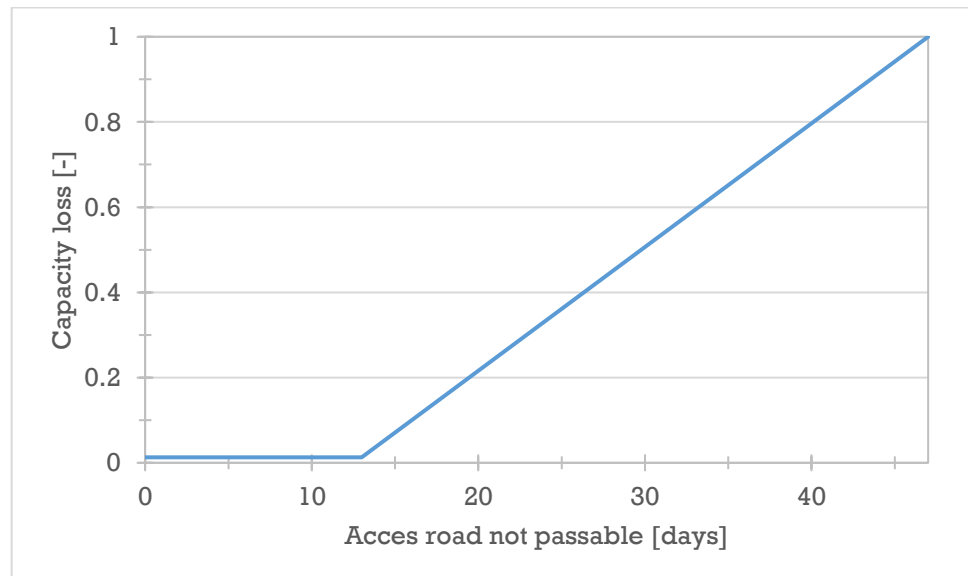


Figure App D-23: Capacity loss in case of an unpassable access road

When the downtime (Table App D-16) and capacity loss (Figure App D-23) of the access road are combined, the conclusion can be made that the capacity loss during the first 13 days is 0.01, after which the capacity loss gradually increases up until day 23 (0.75 months). This is the time the access road will be fully recovered and passable. The capacity loss of that moment is 0.29 (Equation App D-17). Therefore, the average capacity loss caused by an unpassable access road is 0.07 (Equation App D-18).

$$CL_{AR;23} = (CL_{AR;47} - CL_{AR;13}) * \frac{DA_{recovery} - DA_{lo;0.5}}{DA_{lo;2} - DA_{lo;0.5}} = (1 - 0.01) * \frac{23 - 13}{47 - 13} = 0.29$$

Equation App D-17: Capacity loss access road after 23 days

$CL_{AR;23}$	[factor]	Capacity loss access road after 23 days
$CL_{AR;13}$	[factor]	Capacity loss access road during the first 13 days
$CL_{AR;47}$	[factor]	Capacity loss access road after 47 days
$DA_{recovery}$	[days]	Time until access road recovered

$$CL_{AR;average} = \frac{DA_{lo;0.5} * CL_{AR;13} + (DA_{recovery} - DA_{lo;0.5}) * \frac{CL_{AR;23}}{2}}{DA_{recovery}} = \frac{13 * 0.01 + (23 - 13) * \frac{0.29}{2}}{23} = 0.07$$

Equation App D-18: Average capacity loss access road

$CL_{AR;average}$	[factor]	Average capacity loss access road
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These estimations, in combination with the assumption that during inundation heights lower than 0.5 meters the entire downtime, would not be needed to recover the access road after a flood, lead to the capacity loss function graph of the access road (Figure App D-24).

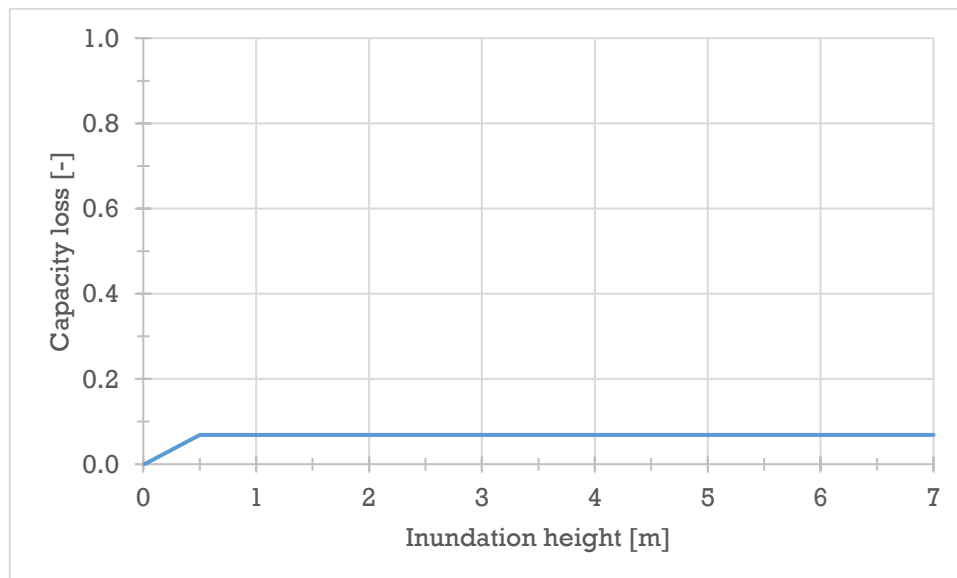


Figure App D-24: Capacity loss function access road

Appendix E Individual interventions

There are 27 different individually applied interventions, showed in Table App E-1. Each intervention will be elaborated and simulated if the intervention can perform individually and the potential damage reduction is higher than the needed investment (elaborated in Paragraph 3.1). The yellow marked interventions meet this condition, and therefore, are simulated through the MLS-Model. All simulation outcomes can be read in this Appendix, according to the same principle as the most cost-beneficial intervention option (S2b), which is elaborated in Paragraph 6.2.

No simulation is executed on the flood interventions pre-order and rental contracts (i.e. D2a, D2b, D3a, D3b, D4a and D4b). Within the current set-up of the MLS-Model, it is hard to determine the exact flood damage reduction, because the damage reduction will be much higher in case one big storm hits and the assets will have one long-lasting downtime. In case several smaller storms hit the terminal, the downtimes will appear rarely and for shorter downtimes. The reason for this huge variations lies in the delivery time and rent price. However, the spatial planning interventions (layer 2) showed enormous benefits, whereby these interventions result in also direct flood damage reduction and layer 3 interventions only reduce the indirect damages. Interventions S2b even showed a higher direct damage reduction than investment needed. Therefore, the conclusion is made that these interventions (i.e. D2a, D2b, D3a, D3b, D4a and D4b) are less beneficial than layer 2 interventions, and because, the most cost-beneficial solution wants to be found, it is unnecessary to dig into the simulation.

Apart from the flood interventions altering the waterway (i.e. D1a and D1b), no interventions are included to reduce the flood damage on external assets. The reason for the backup data server lies in the fact that the server is located on higher grounds on the hinterland (Paragraph 4.3), so could not be damaged by flood. In case the power supply will be lost, the container terminal is one of the first that shall go back online because resources are easily received via the terminal (Paragraph 4.2). The access road is already earthquake proof constructed and will have a relatively short downtime (Paragraph 4.2).

Table App E-1: Flood interventions overview

#	Intervention	
P	Prevention layer	
1 P1a	Entire terminal	Heighten
2 P1b		Enclose
3 P2a	Sectional terminal	Heighten
4 P2b		Enclose
5 P3	Coastline	Flood defenses
S	Spatial planning layer	
6 S1a	Entire Terminal A	Heighten
7 S1b		Enclose
8 S2a	Sectional Terminal A	Heighten
9 S2b		Enclose
10 S3a	Control area	Heighten
11 S3b		Enclose
12 S4a	Maintenance area	Heighten
13 S4b		Enclose
14 S5a	Electric mainstation	Heighten
15 S5b		Enclose
16 S5c		Immediate relocate
17 S5d		Relocate during replacement
18 S6a	Container cranes	Depot
19 S6b		Moveable to Terminal A
D	Disaster management layer	
20 D1a	Dredging	Vessel purchase
21 D1b		Pre-arrangement
22 D2a	Fuel facility	Pre-order contracts
23 D2b		Rental contracts
24 D3a	Electric stations	Pre-order contracts
25 D3b		Rental contracts
26 D4a	Transport equipment	Pre-order contracts
27 D4b		Rental contracts

E.1 Prevention

In this section the interventions of the prevention layer are elaborated, however, these interventions are not simulated because the investments to realize the interventions appeared much higher than the occurring damage throughout the 30 year concession period. This means that they not meet the criteria (i.e. damage reduction > needed investment). In case the concession period was longer or the case not only contained the container terminal (but e.g. the entire harbor bay), it is recommended to involve the prevention interventions into the simulation process.

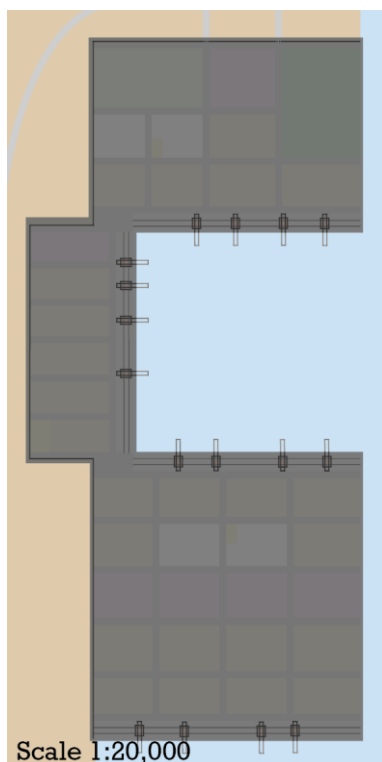


Figure App E-1: Illustration entire terminal heightening

Entire terminal heightening

Increasing the surface level of the entire container terminal (Figure App E-1), whereby the pavements, buildings, quay walls, etc., need to be removed and rebuilt to make the applying of an increased foundation possible. The simulation outcomes are shown in Table App E-2.

Table App E-2: Simulation outcomes entire terminal heightening

	P1a	P1b	P2a	P2b	P3		
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b
	S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a	D4b
Damage reduction: "high"			Investment: "very high"			Cost-benefit: "negative"	

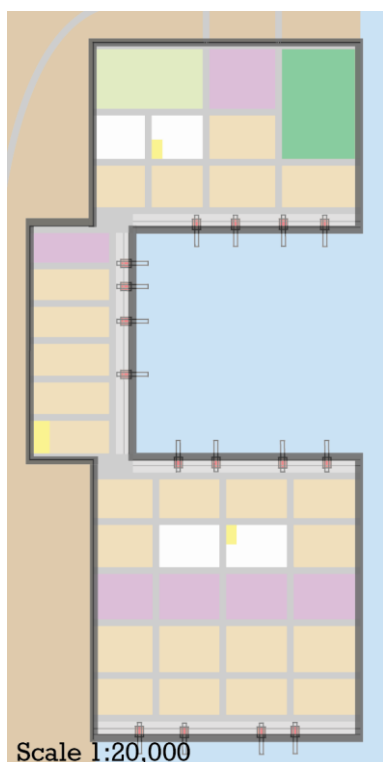


Figure App E-2: Illustration entire terminal enclosure

Entire terminal enclosure

Enclosing the entire terminal consist of an increased wall around the borders of the terminal (Figure App E-2). The quay walls need to be reconstructed on a higher level, and several flat slopes will be built to transport containers from the quay wall to the stacks. At the entrance and exit gates will be no wall, instead of a sizeable unit that could be placed in the gap of the wall in case of a flooding threat. A flooding threat will be known several days up front and is expected to occur once every few years, based on the storm surge data (Appendix B). Simulation indication of this intervention can be found in Table App E-3.

Table App E-3: Simulation outcomes entire terminal enclosure

		P1a	P1b	P2a	P2b	P3		
 S1a	 S1b	 S2a	 S2b	 S3a	 S3b	 S4a	 S4b	
		 S5a	 S5b	 S5c	 S5d	 S6a	 S6b	
 D1a	 D1b	 D2a	 D2b	 D3a	 D3b	 D4a	 D4b	
Damage reduction: “high”			Investment: “very high”			Cost-benefit: “negative”		

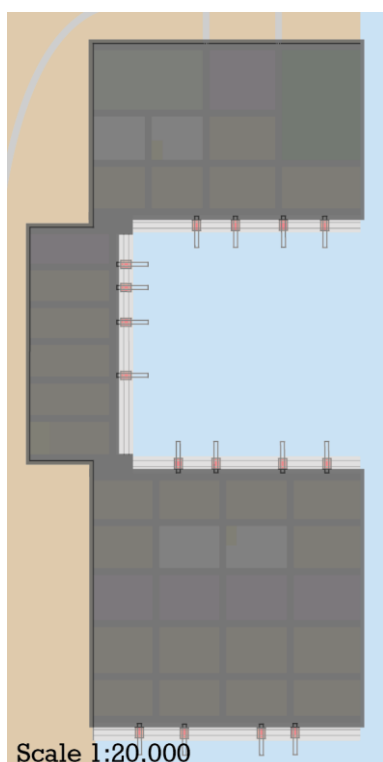


Figure App E-3: Illustration sectional terminal heightening

Sectional terminal heightening

The difference between sectional and entirely heighten of the terminal is the reconstruction of the quay walls. Increasing the height of the quay wall basically means that the current quay wall needs to be removed and rebuilt because e.g. the changing foundation and ground forces (Arcadis, 2016a). A costly process which could be excluded from the intervention by realizing multiple flat slopes from the quay wall to the rest of the terminal (Figure App E-3).

Table App E-4: Simulation outcomes sectional terminal heightening

		P1a	P1b	P2a	P2b	P3		
 S1a	 S1b	 S2a	 S2b	 S3a	 S3b	 S4a	 S4b	
 S5a		 S5b	 S5c	 S5d	 S6a	 S6b		
 D1a	 D1b	 D2a	 D2b	 D3a	 D3b	 D4a	 D4b	
Damage reduction: “high”			Investment: “very high”			Cost-benefit: “negative”		

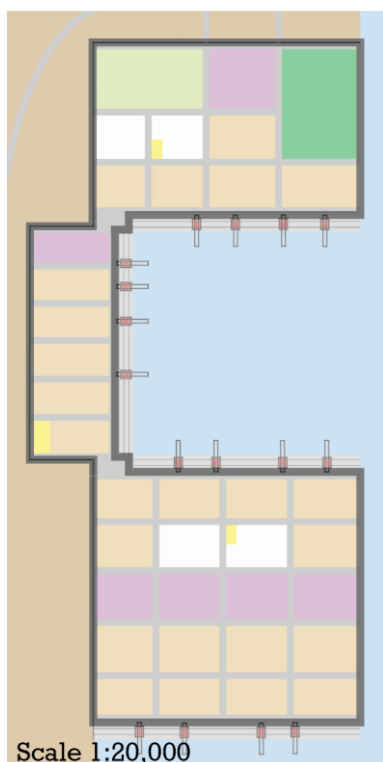


Figure App E-4: Illustration sectional terminal enclosure

Sectional terminal enclosure

The wall borders the entire terminal except for the quay walls (Figure App E-4). In order to transport containers from the stacks to the quay walls, several gaps in the wall will behold.

Table App E-5: Simulation outcomes sectional terminal enclosure

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: "high"			Investment: "very high"		Cost-benefit: "negative"	

Coastline flood defenses

Improve the current blocks wall surrounding the harbor bay and construct a storm surge barrier (Figure 7-2). Due to this flood intervention, the harbor bay will be completely protected and still accessible for shipping.

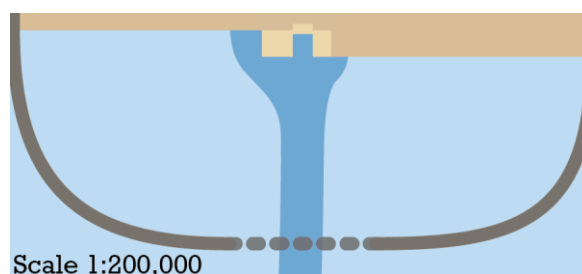


Figure 7-2: Illustration coastline flood defenses

Table App E-6: Simulation outcomes coastline flood defenses

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: "high"			Investment: "very high"		Cost-benefit: "negative"	

E.2 Spatial planning

Spatial planning interventions will be elaborated in this Appendix. After a brief description, the outcomes of the simulations are mentioned by the investment table, intervention impact and simulation outcomes. Prices used to estimate the investment originate from the asset value structures (Appendix CC.6).

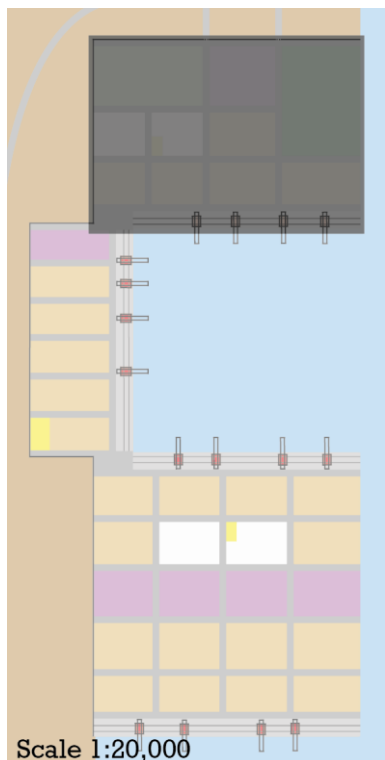


Figure App E-5: Illustration entire terminal A heightening

Entire terminal A heightening

Terminal A is located in the northern section of the container terminal, where the control and maintenance area could be found (Paragraph 4.3). Therefore, the damage through a flood is reduced more, especially the indirect damage, than other areas of the terminal, when flood interventions were applied. The principle of heightening remains the same as the previous interventions, only this time slopes were realized at the entrance, exit and passage to terminal B (Figure App E-5), leading to an estimated average loss during the concession period of \$ 63.2 M (Figure App E-6). The intervention impact, forming the translation in the MLS-Model, of this intervention is shown in Table App E-7, whereas the investment structure is displayed in Table App E-8.

	Pl a	Pl b	P2 a	P2 b	P3	
▲ S1 a	▲ S1 b	▲ S2 a	▲ S2 b	▲ S3 a	▲ S3 b	▲ S4 a
	▲ S5 a	▲ S5 b	▲ S5 c	▲ S5 d	▲ S6 a	▲ S6 b
○ D1 a	○ D1 b	○ D2 a	○ D2 b	○ D3 a	○ D3 b	○ D4 a
Damage reduction: \$ 104.3M		Investment: \$ 167.5M		Cost-benefit: \$ -63.2M		

Figure App E-6: Simulation outcomes entire terminal A heightening

Table App E-7: Intervention impact entire terminal A heightening

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100	S1 a				
Maintenance area	100					
Electric substations	50					
Generators	73					
Container cranes	25					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	33					
Quay walls	17					
Others	33					

Table App E-8: Investment structure entire terminal A heightening

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Buildings [%]	90	10.00	9.00
Electric substations [%]	50	5.00	2.50
Underground equipment [%]	33	15.30	5.10
Pavements [%]	33	76.50	25.50
Pavements removal [ha]	34	0.30	10.20
Quay walls [m]	500	0.07	35.00
Quay walls removal [m]	500	0.02	7.50
Capacity loss [months]	3.0	19.93	59.78
Total fixed investment:			154.58
Component	Height [m]	Price per m [M\$]	Total [M\$]
Foundation [m]	1.90	6.80	12.92
Total investment:			167.50

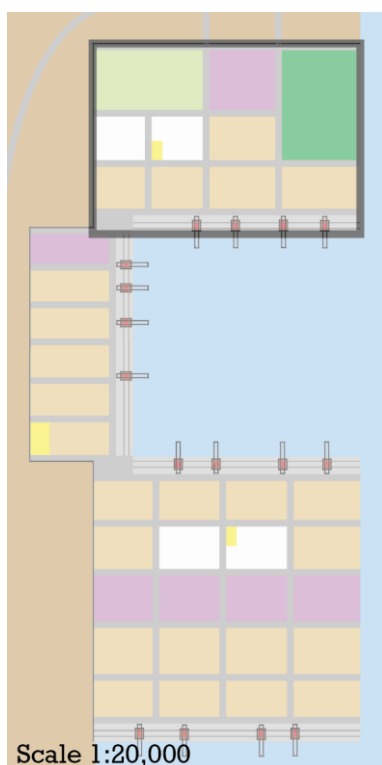


Figure App E-7: Illustration entire terminal A enclosure

Entire terminal A enclosure

Enclosing Terminal A (Figure App E-7) means that walls are realized at the borders of the terminal and the quay wall is reconstructed. On the same locations at the slopes are openings in the wall created. This means an investment structure shown in Table App E-10, and a benefit of \$ 40.7 M (Figure App E-8).

		P1a	P1b	P2a	P2b	P3		
								
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b	
								
S5a		S5b	S5c	S5d	S6a	S6b		
								
D1a		D1b	D2a	D2b	D3a	D3b	D4a	
D4b								
Damage reduction: \$ 104.8M			Investment: \$ 64.1M			Cost-benefit: \$ 40.7M		

Figure App E-8: Simulation outcomes entire terminal A enclosure

Table App E-9: Intervention impact entire terminal A enclosure

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		Slb			
Maintenance area	100					
Electric substations	50					
Generators	73					
Container cranes	25					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	33					
Quay walls	17					
Others	33					

Table App E-10: Investment structure entire terminal A enclosure

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	3.6	15.30	0.55
Quay walls [m]	500	0.07	35.00
Quay walls removal [m]	500	0.02	7.50
Total fixed investment:			42.50
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.40	8.70	20.89
Three regular passages [m]		0.30	0.72
Total variable investment:			21.61
Total investment:			64.11

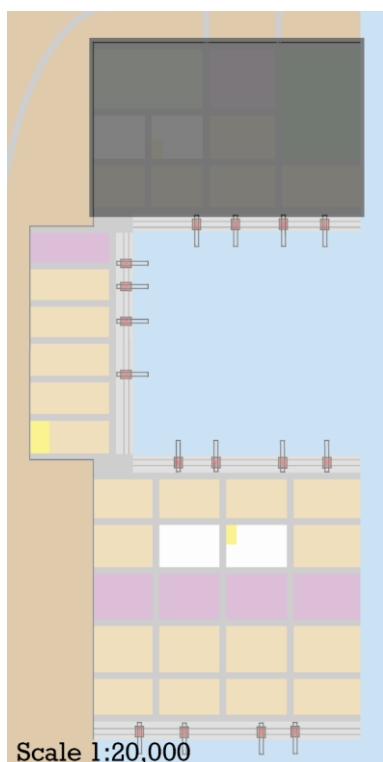


Figure App E-9: Illustration sectional terminal A heightening

Sectional terminal A heightening

As could be seen in Table App E-8 and Table App E-10, the investment on quay walls is high. Therefore, it might be interesting to simulate the situation where terminal A is protected, except the quay wall (Figure App E-9). Via this way, several slopes need to be realized between the stack and quay wall, resulting in a total estimated benefit over the concession period of \$ 39.1 M (Figure App E-10).

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 102.9M			Investment: \$ 63.8M		Cost-benefit: \$ 39.1M	

Figure App E-10: Simulation outcomes sectional terminal A heightening

Table App E-11: Intervention impact sectional terminal A heightening

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100	S2a				
Maintenance area	100					
Electric substations	50					
Generators	73					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	32					

Table App E-12: Investment structure sectional terminal A heightening

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Buildings [%]	90	10.00	9.00
Electric substations [%]	50	5.00	2.50
Underground equipment [%]	33	15.30	5.10
Pavements [%]	32	76.50	24.75
Pavements removal [ha]	33	0.30	9.90
Total fixed investment:			51.25
Component	Height [m]	Price per m [M\$]	Total [M\$]
Foundation [m]	1.90	6.60	12.54
Total investment:			63.79

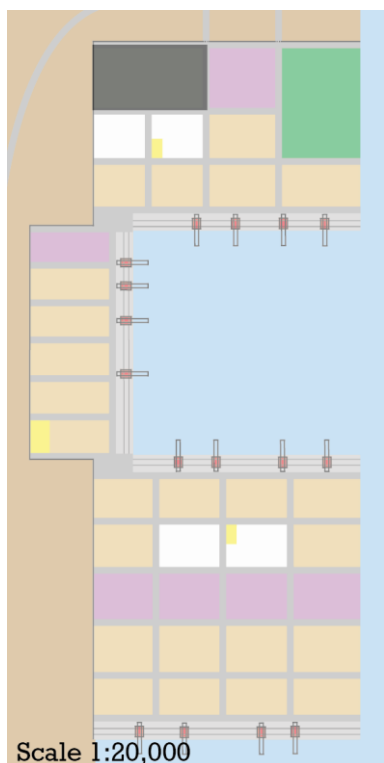


Figure App E-11: Illustration control area heightening

Control area heightening

Protecting smaller areas leads to lower investments, as could be concluded by comparing different investment tables (e.g. Table App E-8 with Table App E-12). Out of the simulations appeared that reducing the indirect damage is more favorable than focusing on the direct damage reduction, which means that focusing on reducing the indirect damage is more beneficial. In this process, the direct damage will also be reduced. Therefore, it is interesting to determine the impact of relative smaller interventions as heightening the control area.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 18.9M		Investment: \$ 11.1M		Cost-benefit: \$ 7.8M		

Figure App E-12: Simulation outcomes control area heightening

Table App E-13: Intervention impact control area heightening

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100	S3a				
Generators	18					
Straddle carriers	25					
Reach stackers	25					
Terminal trucks	25					
Pavements	4					
Others	4					

Table App E-14:: Investment structure control area heightening

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Buildings [%]	40	10.00	4.00
Underground equipment [%]	3.9	15.30	0.60
Pavements [%]	3.9	76.50	3.00
Pavements removal [ha]	4.0	0.38	1.50
Total fixed investment:			9.10
Component	Height [m]	Price per m [M\$]	Total [M\$]
Foundation [m]	2.00	1.00	2.00
Total investment:			11.10

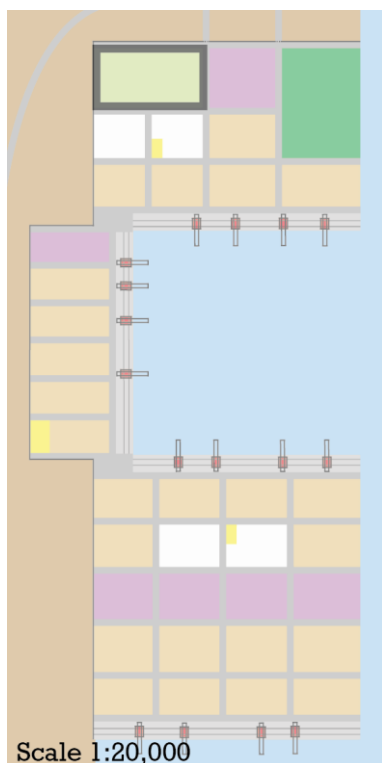


Figure App E-13: Illustration control area enclosure

Control area enclosure

Constructed with three passages, one at the entrance and two directed to the terminal, an expected benefit of \$ 13.9 M is achieved by enclosing the control area (Figure App E-13).

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
		S5a	S5b	S5c	S5d	S6a
						S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
						D4b
Damage reduction:		Investment:		Cost-benefit:		
\$ 18.5M		\$ 4.7M		\$ 13.9M		

Figure App E-14: Simulation outcomes control area enclosure

Table App E-15: Intervention impact control area enclosure

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S3b			
Generators	18					
Straddle carriers	25					
Reach stackers	25					
Terminal trucks	25					
Pavements	4					
Others	4					

Table App E-16: Investment structure control area enclosure

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	0.69	15.30	0.11
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.31	1.60	3.70
Three regular passages [m]		0.38	0.87
Total variable investment:			4.56
Total investment:			4.67

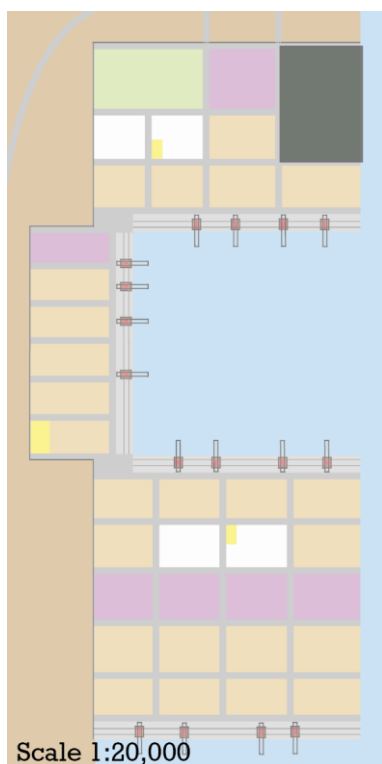


Figure App E-15: Illustration maintenance area heightening

Maintenance area heightening

Containing three slopes, one situated at the exit gate and two on the asphalted lanes of the terminal, heighten the maintenance area has an expected benefit of \$ 40.2 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
D4b						
Damage reduction:		Investment:		Cost-benefit:		
\$ 55.9M		\$ 15.7M		\$ 40.2M		

Figure App E-16: Simulation outcomes maintenance area heightening

Table App E-17: Intervention impact maintenance area heightening

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Maintenance area	100	S4a				
Generators	36					
Straddle carriers	75					
Reach stackers	75					
Terminal trucks	75					
Pavements	6					
Others	6					

Table App E-18: Investment structure maintenance area heightening

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Buildings [%]	50	10.00	5.00
Underground equipment [%]	5.9	15.30	0.90
Pavements [%]	5.9	76.50	4.50
Pavements removal [ha]	6.0	0.38	2.25
Total fixed investment:			12.65
Component	Height [m]	Price per m [M\$]	Total [M\$]
Foundation [m]	2.00	1.50	3.00
Total investment:			15.65

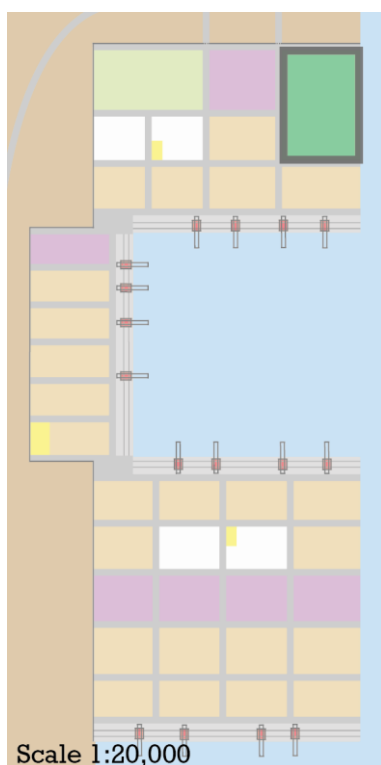


Figure App E-17: Illustration maintenance area enclosure

Maintenance area enclosure

With three passages, on similar spots as the slopes as described at the previous intervention, enclosing the maintenance area has an expected benefit of \$ 46.9 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction:		Investment:		Cost-benefit:		
\$ 55.2M		\$ 8.3M		\$ 46.9M		

Figure App E-18: Simulation outcomes control area enclosure

Table App E-19: Intervention impact maintenance area enclosure

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Maintenance area	100		S4b			
Generators	36					
Straddle carriers	75					
Reach stackers	75					
Terminal trucks	75					
Pavements	6					
Others	6					

Table App E-20: Investment structure maintenance area enclosure

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	0.83	15.30	0.13
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.40	3.04	7.30
Three regular passages [m]		0.38	0.90
Total variable investment:			8.20
Total investment:			8.33

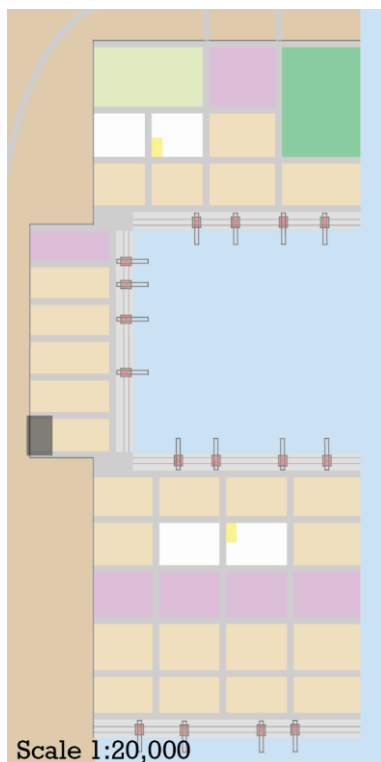


Figure App E-19: Illustration electric mainstation heightening

Electric mainstation heightening

Another crucial asset in the process is the electric mainstation. With an expected benefit of \$ 7.2 M, heightening the electric mainstation is profitable. Where one small and steeper slope is realized, to fulfill regular checks and maintenance.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
D4b						
Damage reduction:		Investment:		Cost-benefit:		
\$ 13.8M		\$ 6.5M		\$ 7.2M		

Figure App E-20: Simulation outcomes electric mainstation heightening

Table App E-21: Intervention impact electric mainstation heightening

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Electric mainstation	100	S5a				
Generators	9					
Others	1					

Table App E-22: Investment structure electric mainstation heightening

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Electric mainstation [%]	100	6.00	6.00
Underground equipment [%]	1.2	15.30	0.18
Total fixed investment:			6.18
Component	Height [m]	Price per m [M\$]	Total [M\$]
Foundation [m]	2.03	0.18	0.37
Total investment:			6.55

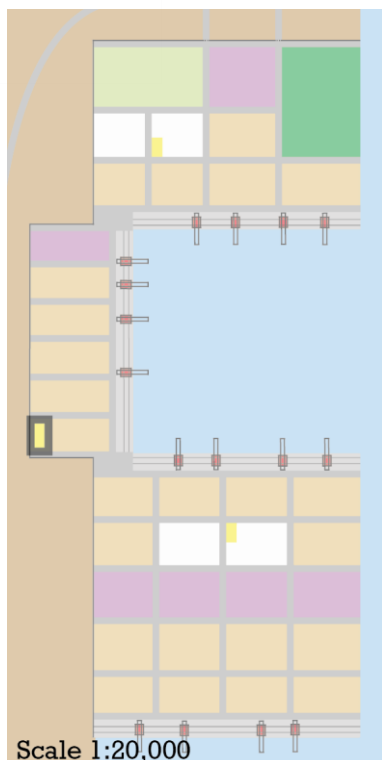


Figure App E-21: Illustration electric mainstation enclosure

Electric mainstation enclosure

The expected benefit contains \$ 12.9 M in case the electric mainstation is enclosed, where a narrow passage is situated at the same location as the slope.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 13.8M		Investment: \$ 0.9M		Cost-benefit: \$ 12.9M		

Figure App E-22: Simulation outcomes electric mainstation enclosure

Table App E-23: Intervention impact electric mainstation enclosure

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Electric mainstation	100		S5b			
Generators	9					
Others	1					

Table App E-24: Investment structure electric mainstation enclosure

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	1.2	15.30	0.18
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.40	0.22	0.54
One narrow passage [m]		0.08	0.18
Total variable investment:			0.72
Total investment:			0.90

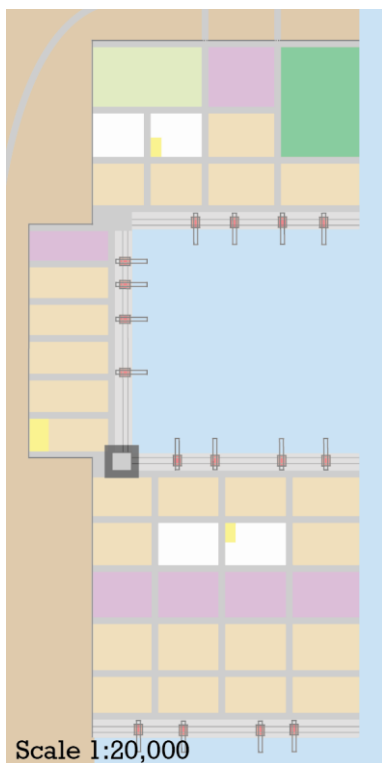


Figure App E-23: Illustration container cranes depot

Container cranes depot

Apart from the straddle carriers, reach stackers and terminal trucks, which are protected via interventions S1a until S4b, the container cranes form a crucial part of the ground transport (Figure 5-5). In case no quay walls are heightened, all container cranes will get. This means an extensive direct damage, but also an indirect damage, due to the capacity of the entire terminal will be lost up until the cranes are repaired and fully operative again. Therefore, a depot is realized at the corner of the quay walls of terminal B and C. The depot is basically a wall, accessible during the entire time, so no interruption in the process will occur. Only in times of flooding threat, when the terminal will be shut down, the crane will drive into the depot, after which the passages will be closed. The crane depot intervention lead to a loss \$ 1.5 M as expected outcome. Therefore the protection height in the investment structure is 0, increasing this height will result in a bigger loss.

		P1a	P1b	P2a	P2b	P3			
									
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b		
									
		S5a	S5b	S5c	S5d	S6a	S6b		
									
D1a		D1b		D2a		D2b			
D3a		D3b		D4a		D4b			
Damage reduction: \$ 0.0M				Investment: \$ 1.5M			Cost-benefit: \$ -1.5M		

Figure App E-24: Simulation outcomes container cranes depot

Table App E-25: Intervention impact container cranes depot

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Electric substations	50		S6a			
Container cranes	75					
Pavements	0.1					
Others	0.1					

Table App E-26: Investment structure container cranes depot

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Electric substation [%]	50	2.50	1.25
Crane rails [km]	0.10	1.50	0.15
Underground equipment [%]	0.44	15.30	0.07
Total fixed investment:			1.47
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	-	0.27	-
Two wide passages [m]	-	0.60	-
Foundation [m]	-	0.06	-
Total variable investment:			-
Total investment:			1.47

E.3 Disaster management

Both disaster management interventions (i.e. D1a and D1b) lead to improvements in the waterway and its water depth, as marked in Figure App E-25.

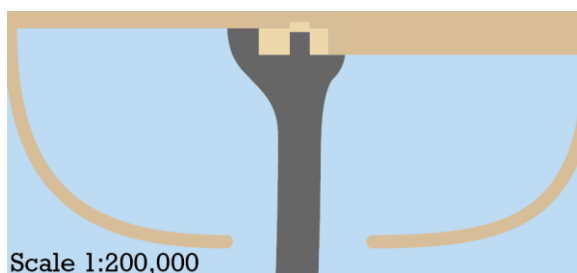


Figure App E-25: Illustration waterway interventions

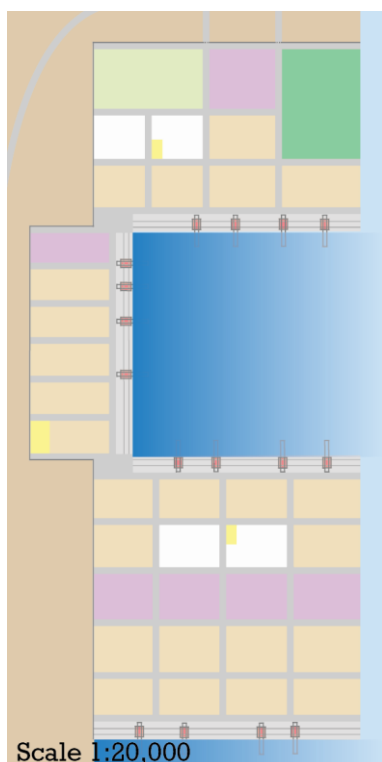


Figure App E-26: Illustration dredging vessel purchase

Dredging vessel purchase

That the municipality is responsible for maintaining the waterway and will dredge when necessary (Paragraph 4.2), does not mean that buying dredging vessel is not an option. By showing the potential benefit for the entire harbor bay, in case a dredging vessel is purchased, this might convince the municipality to obtain one. This leads to a more consistent water depth, illustrated by the darker blue water (Figure App E-26). However, in case the municipality requests a contribution from the different companies located in the harbor bay, 10% of the purchase cost is reserved (Table App E-28). Making the expected benefit \$ 1.7 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 1.9M		Investment: \$ 0.2M		Cost-benefit: \$ 1.7M		

Figure App E-27: Simulation outcomes container cranes depot

Table App E-27: Intervention impact container cranes depot

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Waterway						3.25

Table App E-28: Investment structure dredging vessel purchase

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Purchase dredging vessel [%]	10	1.50	0.15

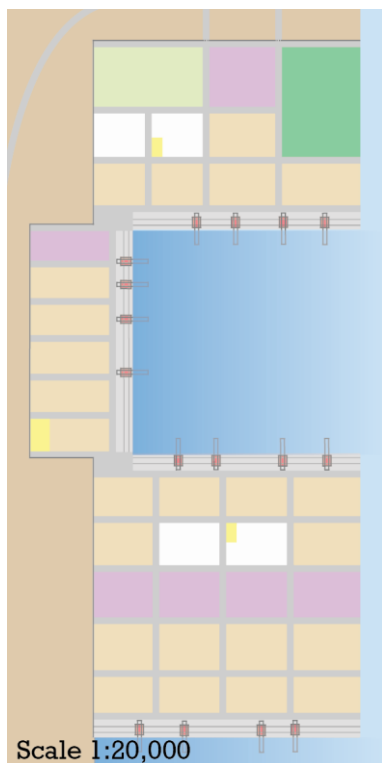


Figure App E-28: Illustration dredging contract

Dredging contract

Making an arrangement on the forehand, in case the waterway becomes inaccessible through sedimentation and dredging is required, results in an expected benefit of \$ 1.0 M. Though will the downtime be higher than via purchasing a dredging vessel, illustrated by the slightly darker blue water (Figure App E-28).

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 1.0M	Investment: \$ 0.0M			Cost-benefit: \$ 1.0M		

Figure App E-29: Simulation outcomes dredging contract

Table App E-29: Intervention impact dredging contract

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Waterway						1.75

Table App E-30: Investment structure dredging contract

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Set-up	160	70.00	0.01
Updates	400	70.00	0.03
Total investment:			0.04

Appendix F Combined interventions

The process of finding the most cost-beneficial option, when a combination of interventions is applied, is described in this Appendix. After each application is considered if the combination has the potential to become the most cost-beneficial option or can be a part of this solution. Via this method, several interventions are excluded and the most cost-beneficial intervention combined will be found. The final outcome (i.e. most cost-beneficial intervention combination) is elaborated in 6.3, the way to determine this option is described step by step in this Appendix.

F.1 Sectional terminal replacement

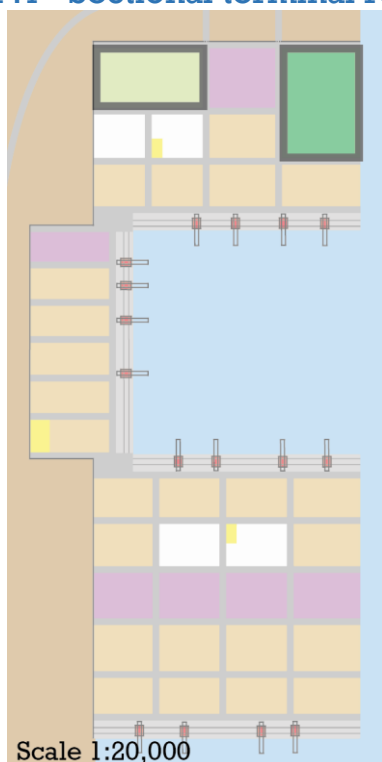


Figure App F-1: Illustration interventions S3b & S4b

Interventions S3b & S4b

Intervention S2b (enclosing sectional terminal A) results in the highest cost-benefit, considering single interventions (Paragraph 6.2). However, replacing this intervention by multiple similar ones could potentially lead to better results. Since intervention S2b is aimed at terminal A, similar interventions are studied, as combining interventions S3b & S4b. The control area and maintenance area will be enclosed by this combination because these had better outcomes than heightening. S3b and S4b result in an expected benefit throughout the concession period of \$ 56.6 M.

		P1a	P1b	P2a	P2b	P3		
 S1a	 S1b	 S2a	 S2b	 S3a	 S3b	 S4a	 S4b	
 S5a		 S5b	 S5c	 S5d	 S6a	 S6b		
 D1a	 D1b	 D2a	 D2b	 D3a	 D3b	 D4a	 D4b	
Damage reduction: \$ 64.2M			Investment: \$ 7.6M			Cost-benefit: \$ 56.6M		

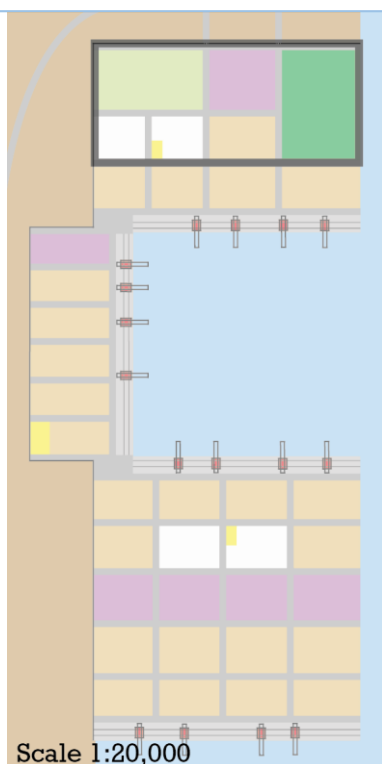
Figure App F-2: Simulation outcomes interventions S3b & S4b

Table App F-1: Intervention impact interventions S3b & S4b

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S3b & S4b			
Maintenance area	100					
Generators	55					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Pavements	10					
Others	10					

Table App F-2: Investment structure interventions S3b & S4b

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	1.5	15.30	0.23
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall control area [m]	2.31	1.44	3.33
Three regular passages [m]		0.34	0.78
Wall maintenance area[m]	2.40	2.74	6.57
Three regular passages [m]		0.34	0.81
Total variable investment:			7.38
Total investment:			7.61


Figure App F-3: Figure 7 20:
Illustration interventions S3b & S4b +

Interventions S3b & S4b +

Another intervention alternative that could replace S2b is simulated (S3b & S4b +), containing enclosing the control and maintenance area, electric substation, and full dry, empty, and reefer container stack. Leading to a benefit of \$ 54.9 M.

	P1a	P1b	P2a	P2b	P3		
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b
	S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a	D4b
Damage reduction: \$ 84.6M			Investment: \$ 29.6M			Cost-benefit: \$ 54.9M	

Figure App F-4: Simulation outcomes interventions S3b & S4b +

Table App F-3: Intervention impact interventions S3b & S4b +

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S3b & S4b +			
Maintenance area	100					
Electric substations	50					
Generators	73					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	9					
Empty containers	20					
Reefers	44					
Pavements	10					
Others	10					

Table App F-4: Investment structure interventions S3b & S4b +

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	3.8	15.30	0.58
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.40	11.51	27.63
Six regular passages [m]		0.60	1.44
Total variable investment:			29.07
Total investment:			29.65

F.2 Add electric mainstation protection

After other flood intervention combination seemed less beneficial than intervention S2b (Paragraph 6.2), this intervention will form the basis for finding the most beneficial combination, due to the MLS-Model appeared that the highest indirect flood damage reduction could be achieved via electric mainstation interventions (S5b, S5c, S5d). Therefore, flood intervention S2b is combined with these intervention alternatives. Intervention S5a (heightening the electric mainstation) is excluded because the benefit of this interventions appeared lower than intervention S5b (enclosing).

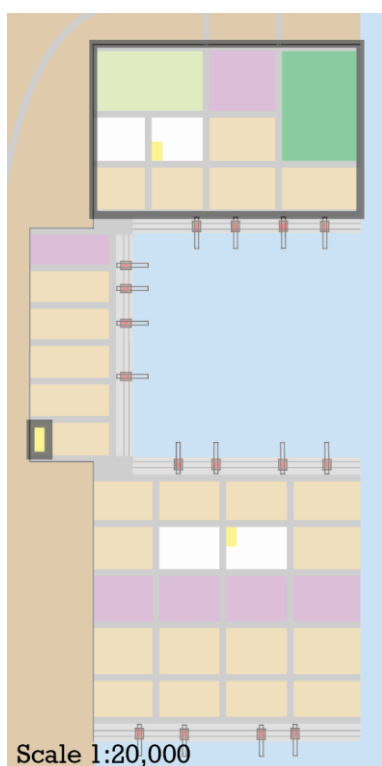


Figure App F-5: Illustration interventions S2b & S5b

Interventions S2b & S5b

Firstly, the combination of S2b & S5b (i.e. enclosing of sectional terminal A and the electric mainstation) is simulated, resulting in an expected cost-benefit throughout the concession period of \$ 94.1 M.

		P1a	P1b	P2a	P2b	P3			
									
S1a	S1b	S2a	S2b	S3a	S3b	S4a	S4b		
									
		S5a	S5b	S5c	S5d	S6a	S6b		
									
D1a		D1b		D2a		D2b		D3a	
D3b		D4a		D4b					
Damage reduction: \$ 125.5M				Investment: \$ 31.4M			Cost-benefit: \$ 94.1M		

Figure App F-6: Simulation outcomes interventions S2b & S5b

Table App F-5: Intervention impact interventions S2b & S5b

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b			
Maintenance area	100					
Electric mainstation	100					
Electric substations	50					
Generators	82					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					

Table App F-6: Investment structure interventions S2b & S5b

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	6.4	15.30	0.99
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Wall electric mainstation [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Total variable investment:			30.39
Total investment:			31.38

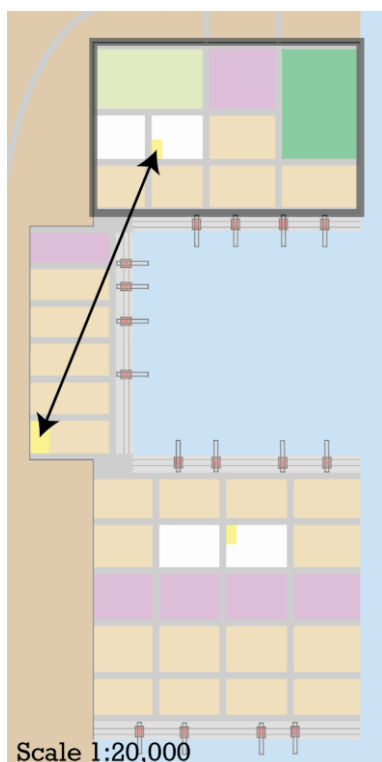


Figure App F-7: Illustration interventions S2b & S5c

Interventions S2b & S5c

Secondly, interventions S2b and S7a (i.e. enclosing sectional terminal A and immediate relocate electric mainstation) are simulated resulting in a benefit of \$ 87.1 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 122.2M			Investment: \$ 35.1M		Cost-benefit: \$ 87.1M	

Figure App F-8: Simulation outcomes interventions S2b & S5c

Table App F-7: Intervention impact interventions S2b & S5c

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5c			
Maintenance area	100					
Electric mainstation	100					
Generators	73					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	32					

Table App F-8: Investment structure interventions S2b & S5c

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Electric mainstation [%]	50	6.00	3.00
Electric substation [%]	50	2.50	1.25
Pavements [%]	0.59	76.50	0.45
Underground equipment [%]	6.4	15.30	0.99
Total fixed investment:			5.69
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.32	12.19	28.29
Seven regular passages [m]		0.50	1.16
Total variable investment:			29.45
Total investment:			35.13

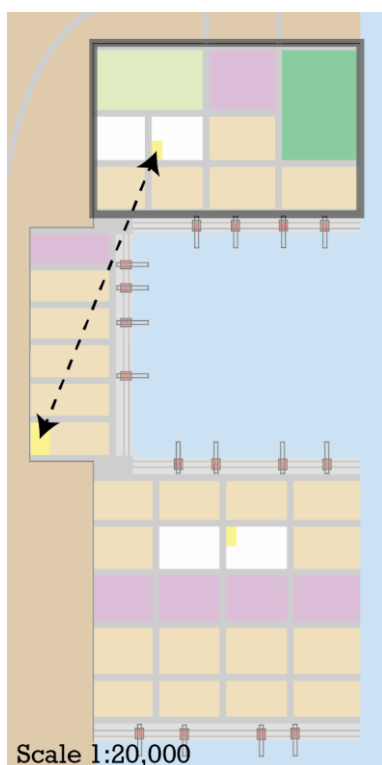


Figure App F-9: Illustration interventions S2b & S5d

Interventions S2b & S5d

Thirdly, interventions S2b & S7b (i.e. enclosing sectional terminal A and relocate during replacement electric mainstation) lead to a benefit of \$ 93.2 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
S5a	S5b	S5c	S5d	S6a	S6b	
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 124.5M			Investment: \$ 31.3M		Cost-benefit: \$ 93.2M	

Figure App F-10: Simulation outcomes interventions S2b & S5d

Table App F-9: Intervention impact interventions S2b & S5d

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5d			
Maintenance area	100					
Electric mainstation	50					
Electric substations	25					
Generators	73					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	32					

Table 7-1: Investment structure interventions S2b & S5d

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Pavements [%]	0.59	76.50	0.45
Underground equipment [%]	6.4	15.30	0.99
Total fixed investment:			1.44
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Total variable investment:			29.91
Total investment:			31.35

F.3 Add dredging

Via the simulation process of the MLS-Model appeared that interventions affecting the waterway had the highest potential in reducing the indirect flood damage, which going to be combined with S2b & S5b, due to these combination has the highest cost-benefit until now (Appendix F.2).

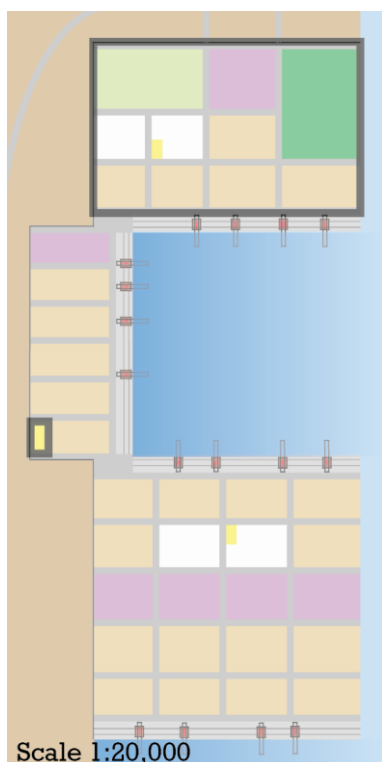


Figure App F-11: Illustration interventions S2b & S5b & D1b

Interventions S2b & S5b & D1b

The interventions S2b & S5b & D1b (i.e. enclosing sectional terminal A & enclosing electric mainstation & pre-arrangement dredging) resulted in a benefit of \$102.2 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 133.6M		Investment: \$ 31.4M		Cost-benefit: \$ 102.2M		

Figure App F-12: Simulation outcomes interventions S2b & S5b & D1b

Table App F-10: Intervention impact interventions S2b & S5b & D1b

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b			
Maintenance area	100					
Electric mainstation	100					
Electric substations	50					
Generators	82					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					
Waterway	100					D1b

Table App F-11: Investment structure interventions S2b & S5b & D1b

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Underground equipment [%]	6.4	15.30	0.99
Set-up	160	70.00	0.01
Updates	400	70.00	0.03
Total fixed investment:			1.02
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Wall electric mainstation [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Total variable investment:			30.39
Total investment:			31.42

F.4 Add crane protection

Interventions on the container cranes seemed reducing the indirect flood damages similar to the dredging interventions. Therefore, crane protecting interventions are added to S2b & S5b.

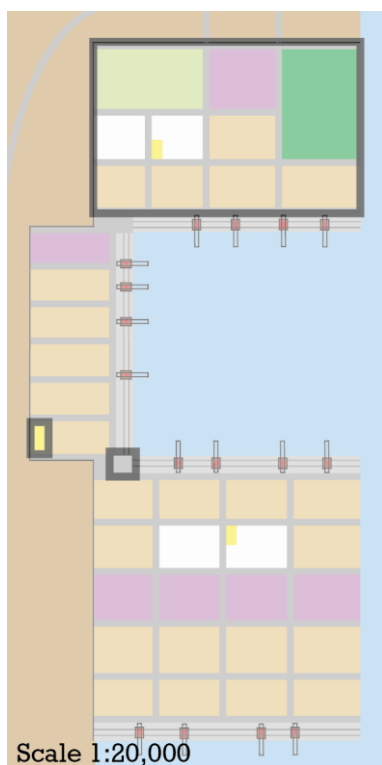


Figure App F-13: Illustration interventions S2b & S5b & S6a

Interventions S2b & S5b & S6a

Firstly, interventions S2b & S5b & S6 (i.e. enclosing sectional Terminal A & enclosing electric mainstation & depot container cranes) result in a benefit of \$ 98.5 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 130.0M			Investment: \$ 31.5M		Cost-benefit: \$ 98.5M	

Figure App F-14: Simulation outcomes interventions S2b & S5b & S6a

Table App F-12: Intervention impact interventions S2b & S5b & S6a

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b & S6			
Maintenance area	100					
Electric mainstation	100					
Electric substations	100					
Generators	82					
Container cranes	75					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					

Table App F-13: Investment structure interventions S2b & S5b & S6a

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Electric substation [%]	50	2.50	1.25
Crane rails [km]	0.10	1.50	0.15
Underground equipment [%]	5.3	15.30	0.81
Total fixed investment:			2.21
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	10.82	25.10
Seven regular passages [m]		0.70	1.62
Wall electric mainstation [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Wall container depot [m]	2.32	0.46	1.06
Two wide passages [m]		0.40	0.93
Foundation [m]	1.90	0.04	0.08
Total variable investment:			29.27
Total investment:			31.47

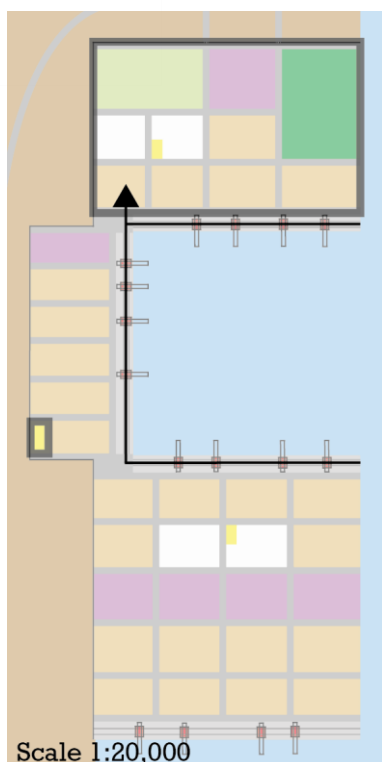


Figure App F-15: Illustration interventions S2b & S5b & S6b

Interventions S2b & S5b & S6b

Secondly, interventions S2b & S5b & S8 (i.e. enclosing sectional terminal A & enclosing electric mainstation & moveable to terminal A container cranes) scored beneficial with \$ 95.1 M.

	P1a	P1b	P2a	P2b	P3	
S1a	S1b	S2a	S2b	S3a	S3b	S4a
	S5a	S5b	S5c	S5d	S6a	S6b
D1a	D1b	D2a	D2b	D3a	D3b	D4a
Damage reduction: \$ 126.9M			Investment: \$ 31.8M		Cost-benefit: \$ 95.1M	

Figure App F-16: Simulation outcomes interventions S2b & S5b & S6b

Table App F-14: Intervention impact interventions S2b & S5b & S6b

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b & S6b			
Maintenance area	100					
Electric mainstation	100					
Electric substations	50					
Generators	82					
Container cranes	25					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					

Table App F-15: Investment structure interventions S2b & S5b & S6b

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Crane rails [km]	0.10	1.50	0.15
Underground equipment [%]	5.3	15.30	0.81
Total fixed investment:			0.96
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	12.19	28.29
Six regular passages [m]		0.70	1.62
One wide passages [m]		0.20	0.46
Wall container depot [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Total variable investment:			30.86
Total investment:			31.81

F.5 Add dredging and crane protection

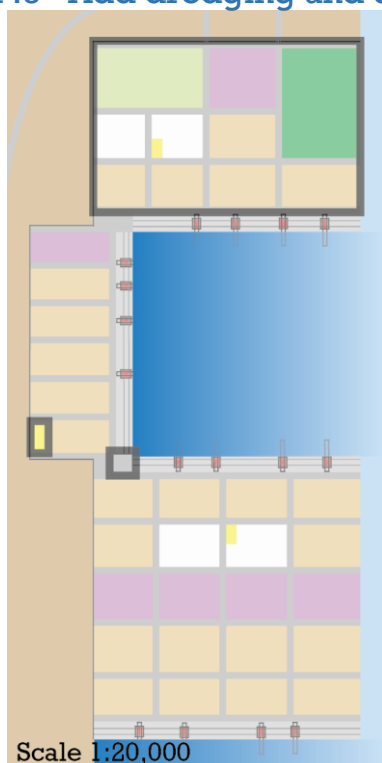


Figure App F-17: Illustration interventions S2b & S5b & S6a & D1a

By knowing the impact of dredging and crane protection interventions when combined with the interventions S2b & S5b, all most beneficial interventions combinations could be put together.

Interventions S2b & S5b & S6a & D1a

The interventions S2b & S5b & S6 & D1a (i.e. enclosing sectional Terminal A & enclosing electric mainstation & vessel purchase dredging & moveable to terminal A container cranes) are simulated and lead to an expected cost-benefit throughout the concession period of \$ 107.4 M.

	P1a	P1b	P2a	P2b	P3		
 S1a	 S1b	 S2a	 S2b	 S3a	 S3b	 S4a	 S4b
	 S5a	 S5b	 S5c	 S5d	 S6a	 S6b	
 D1a	 D1b	 D2a	 D2b	 D3a	 D3b	 D4a	 D4b
Damage reduction: \$ 142.5M			Investment: \$ 35.0M		Cost-benefit: \$ 107.4M		

Figure App F-18: Simulation outcomes interventions S2b & S5b & S6a & D1a

Table App F-16: Intervention impact interventions S2b & S5b & S6a & D1a

Asset	Partial protection [%]	Heighten surface [m]	Heighten enclosure [m]	Improved protection [%]	Downtime reduction [%]	Downtime reduction [months]
Control area	100		S2b & S5b & S6a			
Maintenance area	100					
Electric mainstation	100					
Electric substations	100					
Generators	82					
Container cranes	75					
Straddle carriers	100					
Reach stackers	100					
Terminal trucks	100					
Fully dry containers	23					
Empty containers	20					
Reefers	44					
Pavements	32					
Others	33					
Waterway	100					D1a

Table App F-17: Investment structure interventions S2b & S5b & S6a & D1a

Component	Amount [-]	Price per amount [M\$]	Total [M\$]
Electric substation [%]	50	2.50	1.25
Crane rails [km]	0.10	1.50	0.15
Underground equipment [%]	6.8	15.30	1.04
Purchase dredging vessel	10	1.50	0.15
Total fixed investment:			2.59
Component	Height [m]	Price per m [M\$]	Total [M\$]
Wall terminal A [m]	2.32	12.19	28.29
Seven regular passages [m]		0.70	1.62
Wall electric mainstation [m]	2.40	0.15	0.36
One narrow passage [m]		0.05	0.12
Wall container depot [m]	2.32	0.46	1.06
Two wide passages [m]		0.40	0.93
Foundation [m]	1.90	0.04	0.08
Total variable investment:			32.46
Total investment:			35.05