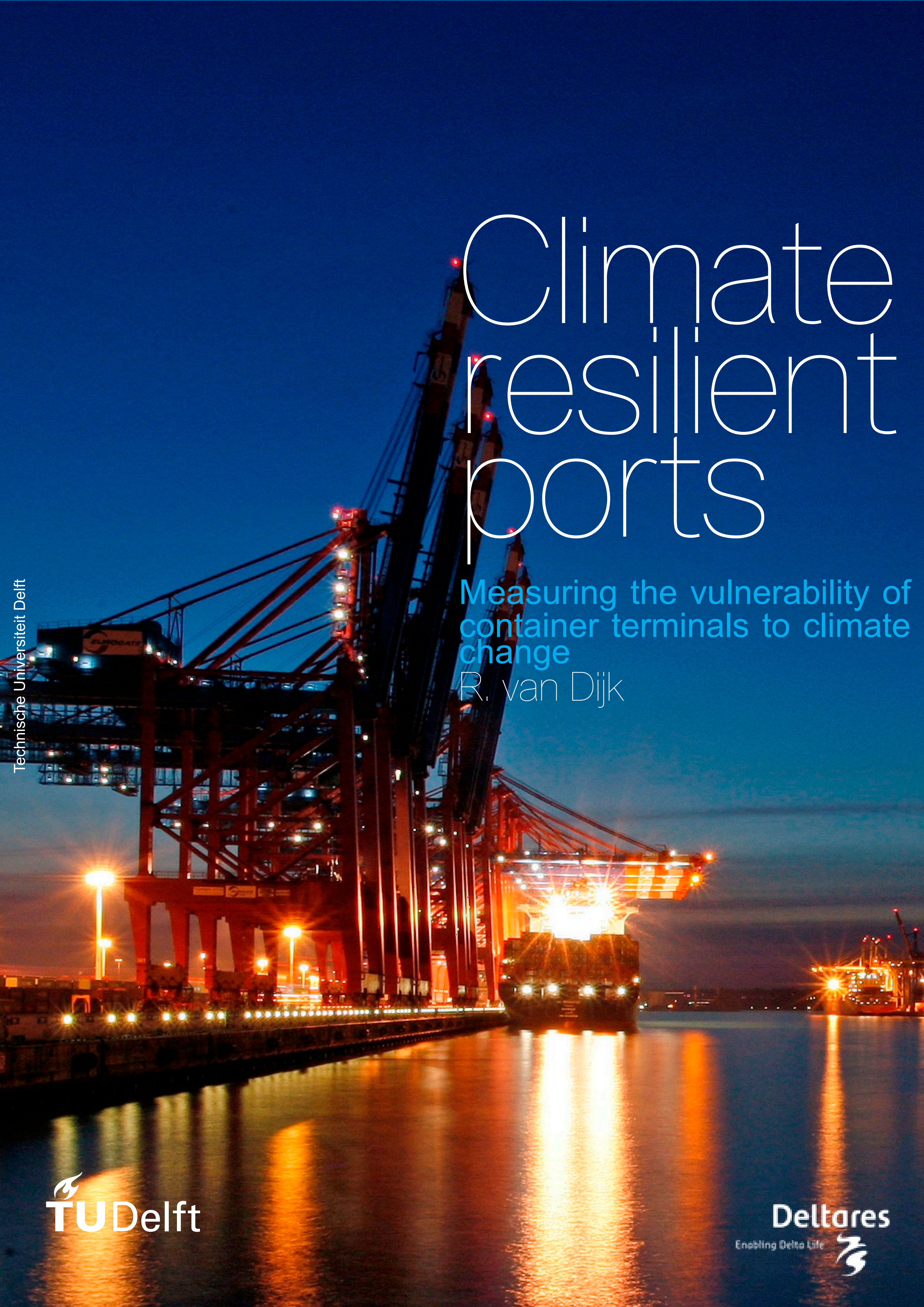

Technische Universiteit Delft

Climate resilient ports

Measuring the vulnerability of container terminals to climate change

R. van Dijk

TU Delft

Deltares
Enabling Delta Life

Climate resilient ports

Measuring the vulnerability of container terminals to climate change

by

R. van Dijk

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TU Delft

Preface

2016 has been a year full of big significant happenings. V&D went bankrupt, multiple terrorist attacks hit Europe, Max Verstappen wins it's first GP, BREXIT, Johan Cruijff passed away, Steven Kruijswijk *almost* wins the Giro d'Italia, Bauke Mollema *Almost* won the Tour the France, Tom Dumoulin *almost* won the olympic timetrial, Muhammad Ali died, and Donald Trump was elected as president of the United States. Although many may describe 2016 as a bad year, my 2016 was frankly nice.

At the beginning of the year, I realized that 2016 was going to be important to me and it made me pumped with energy. Firstly, 2016 would be my last year at the university of Delft. Although I have enjoyed the years in Delft, I would be relieved when this chapter is closed. Closing this chapter would mean searching for a job (or creating your own job of course), and eventually also buying a house for my own.

Another big red circle on my calender was located at the 24th of July. I would dedicate approximately fifteen hours per week in preparing for that single day; The qualifier event for 2017's Triathlon World Championships. although I already trained quite intensive for triathlons for over 2 years now, this was the first time that I dedicated myself to such a goal. To qualify for the World Championships, I had to finish in the top-15 of my age-group (25-29). Although I really had no clue what my chances on qualifying are, I at least wanted to have a shot, and participate with the idea that I did all I could.

So, we are now at the end of 2016. Although the road was bumpy sometimes, I can look back to this year with much Joy. These are my last hours at the Technical University in Delft, with a as good as finished MSc thesis. Also, I signed a contract at EY, to start at the first of January, 2017. In the meantime, my girlfriend (Loena) and I are negotiating over the price of a house we both like. If all goes well, we should be able to live there next February! Also, the qualifier for the World Championships went extraordinary well; I finished second in my age-group, and thus qualified for 2017's World Championships in Rotterdam! Although I again have no idea of the competition that I will face there, I am looking forward to the preparation period. Next to these, I became a qualified trainer for Triathlon, and also became board-member for our triathlon-association. Altogether, a lot of positive energy was received last year!

Enough about me for now. All of those achievements could of course not been realized without support of others. For my thesis, there are some people that were important to my progress and outputs. Firstly, my direct supervisors from both the Technical University in Delft (Frans Klijn, Jan Kwakkel, Rob Stikkelman), as my supervisors from Deltares (Monica Altamirano and Martijn de Jong). All of my supervisors provided me with feedback on the reports and contents that I delivered. Especially Jan Kwakkel, with whom I had a weekly discussion, was able to push me back on track when I struggled with balancing my work for this thesis.

Also special thanks to Arvid, Hugo and Clotilde, who often accompanied me at the coffee-machine, and with whom I could discuss any problems in the process. They were a huge support during the entire process. Erwanda, who was also part of that group, deserves even more thanks. The first half of my thesis were parallel to Erwanda's thesis. Many useful discussions with him have taken place concerning choices in the thesis; Thanks a lot Erwanda! Next to the few students I mentioned as individuals, there were many more contributing to my thesis in different ways. Regular coffee-breaks at 3 PM in the tetra-office often provided fruitful discussions about problems we encountered in our researches.

Also, in the midst of my process, I received quite some help from Sofia Caires, an expert from Deltares. She helped me a lot with gathering the data about climate. I also owe to Philipp Schwarz, who helped me out with the programming for Exploratory Modeling. Without him, my thesis would definitely have looked different. Lastly, I would like to thank Loena, for always being ready for me, and my family and family in law for supporting me in this adventure.

Have fun reading!

R. van Dijk
Delft, July 2016

Abstract

Climate is changing. Ports, which are critical for economies all over the world, are affected by these changes in climate. Climate change may have negative effects on the performance of a port, such as more frequent storms but may also face positive effects as a result of climate change, such as less frost. The world bank currently requires a climate stress test before an investment.

Although scientists in general agree upon the average global direction of climate change, the regional variations are vast. This situation results in deep uncertainty for decision makers in ports, and specifically, container terminals. Although methods to plan under deep uncertainty are available, the input for these methods is often not available. To generate this input, very costly and lengthy studies must be performed.

To enable policy makers to estimate the impact of climate change on a container terminal, a new method should be developed. The research question that should be answered with this method is: *"What is the effect of different climate scenarios on the operational performance of container terminals"*

Firstly, a system dynamics model is created to simulate the development of ports in relation to climate change. To understand the deep uncertainty of climate risks in ports, scenario discovery is applied. Then, robust decision-making is used to analyse the measures that can be applied in the development of a port.

Summary

The climate is changing, and large infrastructures face risks related to climate change. For new investments, a climate stress test is required. The most recent studies of the vulnerability of container terminals to climate change has been either qualitative, based on the subjective values from stakeholders, been focused on assessing the impact from a single weather event, or related to the effectiveness of a resilience measure. State of the art research to assess the vulnerability of container terminals to climate change is expensive and time consuming. Furthermore, since the models should face deep uncertainty related to climate change, it is questionable whether it is possible to validate any of the given scenarios. In such situations, exploratory modeling studies can be used to analyze the behavior of the system under a large set of scenarios. Also, it is not always desired to perform an in-depth study for every container terminal. Therefore, there is social demand for a more generic tool, which can be used for screening of container terminals.

To screen for vulnerability of container terminals, an exploratory method should be developed, that can be used to estimate the operational impact of climate change for a given container terminal. The main question to be answered with such a tool is: *"What is the effect of different climate scenarios on the operational performance of a container terminals?"*.

Measuring performance of container terminals

To answer the main question, the operational performance of container terminals must be measurable. Different key performance indicators are found in a literature study. Three key performance indicators are selected for this study.

1. Level of service
2. Terminal capacity
3. Terminal utilization

These three key performance indicators are used to represent the operational performance of a container terminal. The performance indicators are related to each other via several variables. The relations between these indicators are visualized with help of system diagrams. An excel model is created, which is used to calculate the values of the key performance indicators, given the settings of a specific container terminal.

Effect of weather on a terminal's performance

To estimate the effect of climate scenarios on a container terminal, the terminal's behavior on different weather types must be identified. A list of 12 events influencing the operational performance of a container terminal is identified. The events all relate to four weather variables.

1. Wind speed
2. Temperature
3. Wave height
4. Precipitation volume

With these four weather variables the occurrence of all 12 weather events can be determined. In other words, certain combinations of the weather variables result in one or more of the weather events. So far, the operational performance of a container terminal under each of the 12 weather events can be estimated.

Weather distributions

Since the terminal's behavior on climate is required rather than it's behavior on a single weather event, the weather events must be related to climate. With statistical distribution functions, the probability that the weather variables reach a certain state can be determined. Hence can the number of hours that a weather variable is above or below a certain value. With these functions, an estimation of the number of hours that a weather event occurs during a year can be made. With this information, the operational performance of a container terminal during one year is estimated, given a set of weather distribution functions.

Exploratory modeling

By shifting the weather distribution functions, the change in climate is simulated. To compute the effect of these changes on the operational performance, exploratory modeling is used. Exploratory modeling uses computational experiments to explore uncertainties in the context, the system model and different perspectives. Through performing 10.000 replications of the experiment, a large variety in different climate change scenarios is covered. For each of these replications, the terminal's level of service, terminal capacity and terminal utilization is measured. With these steps, the performance of a container terminal under a diverse set of climate change scenarios can be generated.

Scenario discovery

With scenario discovery, the results from the exploratory modeling is analyzed. With the outcomes of this analysis, scenarios are identified for which the container terminal is vulnerable.

Through following the steps in this thesis, the vulnerability of a container terminal to climate change can be analyzed.

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1

WELCOME TO THE NEW CLIMATE

Wednesday the first of June, 2016. Extreme precipitation occurred in the north-west of Europe. Over 20.000 citizens had to be evacuated in France, streets were submerged, schools closed, dikes were at the point to break, and over 15 people lost their lives. [18] [9] [7]. Gerrit Hiemstra, a Dutch weatherman from the NOS responded on these events by making the following statement on the national television: ”Welkom in het nieuwe klimaat”, which means ”Welcome in the new climate” [27]. According to Hiemstra, these situations will most likely occur more often in the future. The consequences of this new climate are among other things melting glaciers, more precipitation, more extreme weather events and shifting seasons [56]. Next to that, There might be an increase in regional human health risk [60], flooding risks all over the world is increasing [59], and 15- 37% of all species may be subjected to extinction in 2050 [65]. Climate change is fully into the picture these days. To mitigate the risks imposed by climate change we need to adapt.

1.1. The change in climate

In the coming decades, we can expect climate to continue to change as a result of human influence [63]. Although the exact changes of climate characteristics are very uncertain, there is a certain consensus on the direction of the change. There is for instance plenty of scientific proof for global warming. According to the Intergovernmental Panel on Climate Change (IPCC), Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level [1]. The exact average surface temperature that we will face in 2100 is however very uncertain and dependent on human actions. The IPCC forecasts the global temperature to rise between 0.3 degrees Celsius, and 4.8 degrees Celsius in in this century [59]. Figure 1.1 shows the estimations made by the IPCC. Both the blue and red field follows a certain scenario, which depends on a lot of uncertainties and human influence.

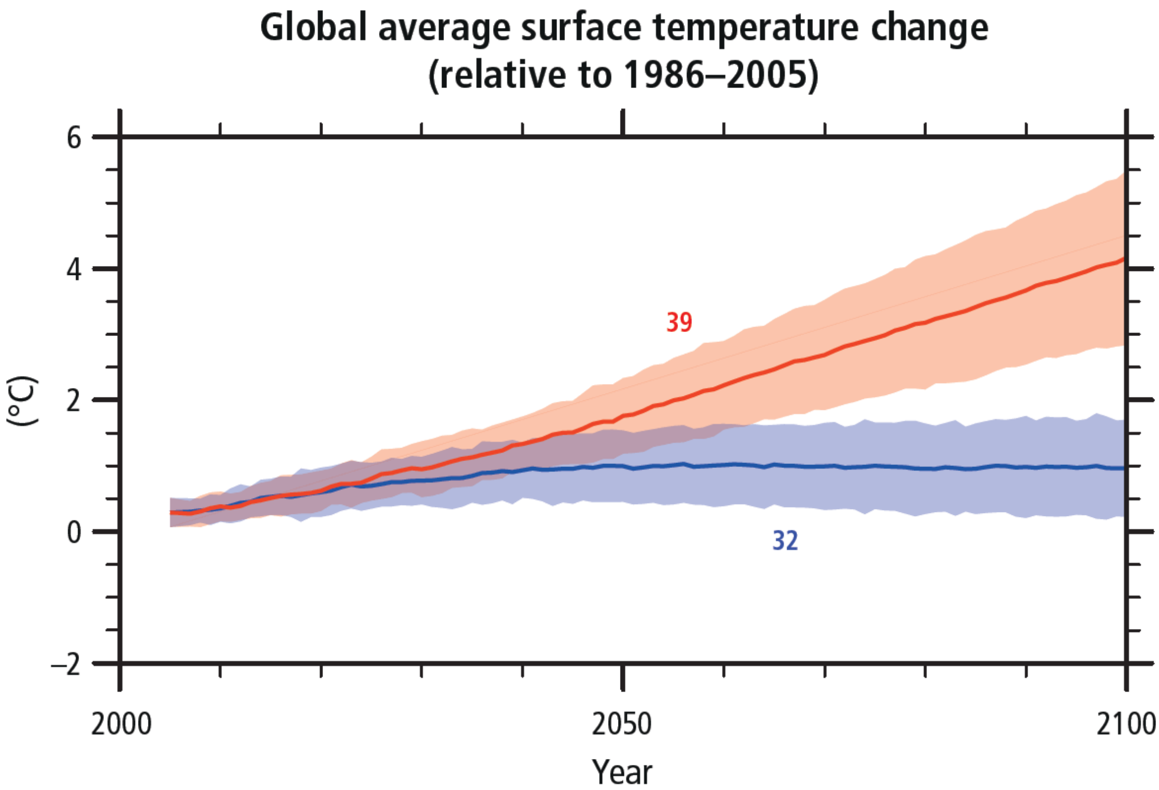

Figure 1.1: The forecast of global average surface temperature change, obtained from [59]. The vertical axis represents the change in temperature compared to the average between 1986 and 2005. The horizontal axis represents the years from 2000 to 2100. The red and blue line each represent a climate scenario. The bandwidth around it represents the uncertainty in this scenario.

Strongly linked to this prediction of global average surface temperature are the predictions concerning sea-level rise. Over the last decades an increase in sea-level is observed, which can be explained by global warming. Firstly, sea-level is rising due to the expansion of water under heat and secondly, due to the addition of water as a result of melting ice [4]. According to the International Panel on Climate Change (IPCC) the global mean sea-level rise is likely to be within 0.28m-0.61m to 0.53-0.98m in 2100, dependent on the scenario [48]. This already indicates that there is quite some uncertainty, for the sea level rise might turn out to be 0.28m, as well as 0.98m. Next to that, a recent study published in nature revealed that the contribution of Antarctica to sea-level rise might be highly underestimated. One of the main conclusions of the report - ”Antarctica alone has the potential to contribute to more than a meter of sea-level rise by 2100 and more than 15 meters by 2500” [41].

According to Munich Reinsurance Company, their database clearly indicates a sharp rise in the number of weather-related natural catastrophes per year, in terms of overall and insured losses [11]. Their database backs the statement made by Gerrit Hiemstra. Examples show that there has been a threefold increase of floods since 1980, windstorm losses are increasing, and Atlantic hurricanes are becoming more destructive. Their statement is as follows : ”Climate change cannot be identified from individual events but our figures, backed by verifiable changes in meteorological data, indicate a trend towards an increase in extreme weather events that can only be fully explained by climate change.” The trends in extreme weather events may have severe consequences for many sectors.

1.2. Vulnerability of port operations to climate change

Among all that can be impacted by climate change, are ports. Ports are vital for trade, and serve an important role in the global economy. The locations of sea-ports are crucial to their success, but at the same time make them vulnerable to many hazards [34]. Aside from operational-, security-, technical and organizational risks, there are many hazards applying to seaports. Examples of these are earthquakes, heavy rainfalls, flooding, snow, hurricanes and lightning [51]. In Australia, 2009’s heat wave had massive impact on port operations; rail-tracks and roads were deformed, engines overheated and workers were entitled to stop working above certain temperatures [61]. In the United States, hurricane Katrina inflicted over 100 billion U.S. dollars of economic damage in 2005 [47], and hurricane Sandy effectively closed the ports of New York and New Jersey due to debris in the channels, blocked roads and damage to the gates and terminals. Impact of extreme events can be severe to ports, as can the rise in sea-level. Since ports usually have a long lifetime, the ports will face long-term climate changes. If ports don't adapt to climate change, the impact on port performance can be massive.

1.3. The role of ports in the global economy

"*The transportation sector is a strong factor in terms of economic and regional balanced development, as well as also having a great influence on national integration to the world economic market*" [42]. Since over 90% of global trade is currently carried by sea [49], seaports are crucial for trade carried by sea, and are thus vital for global trade and the local, regional as well as the global economy [34]. According to Global Insight [35] the worldwide containerized trade is expected to double in 13 years. This would imply that ports are even becoming more important than they are currently. The economy's dependency on sea-ports will increase even further. If the performance of these ports are harmed by the change in climate, the development of economies will be harmed, as will global trade.

1.4. Adaptation of ports is lagging behind

To reduce the vulnerability of ports, ports should adapt to climate change. 81% of the port operators find that impact of climate change is something that needs to be addressed by the port community, while only 31% feels sufficiently informed about how climate change influenced port operations. [33]. This indicates that there indeed is a lot of uncertainty about what future climate will look like. Another research described it as following: "most ports do not appear to be thinking about, let alone actively preparing to address, the effects of climate change" [46]. Ports are likely to become more vulnerable to extreme weather events, while at the same time ports are not taking actions to reduce these vulnerabilities. The climate is inevitably changing, and with it should our way of planning the development of ports.

2

RESEARCH DESIGN

This chapter recaps the research problem, the importance of the study, the research questions and the methods that are used to come up with the answers to each of the research questions. At the end of this chapter a reader's guide is included. In this guide a short description on the contents of each of the coming chapters is provided.

2.1. Research problem

Ports are vulnerable to the weather conditions. As the current climate is subjected to change, the impact of weather on container terminal operations is changing as well. Weather-related risks are subjected to change. Policy makers must make short and long-term decisions to cope with these risks, and make ports climate-resilient. The factors on which they base their decisions are however very uncertain.

There are some methods available to deal with deep uncertainty. Examples of these are *assumption based planning*, *adaptive policy making*, *adaptation tipping points*, *adaptation pathways* and *dynamic adaptive policy pathways*. These methods are not fit for all policy problems. According to Walker, Haasnoot and Kwakkel Walker et al. 66 a method may fit to a policy making problem according the dynamic nature and uncertainty in the system. Figure 2.1 presents the outcomes of this comparison. The vertical axis indicates the dynamic nature of the adaptation. Static indicates that timing of measures is not taken into account, static robust indicates that measures are anticipatory, and dynamic indicates that the adaptation can be anticipatory, reactive and concurrent. The horizontal axis describes the degree of uncertainty that the adaptation can deal with.

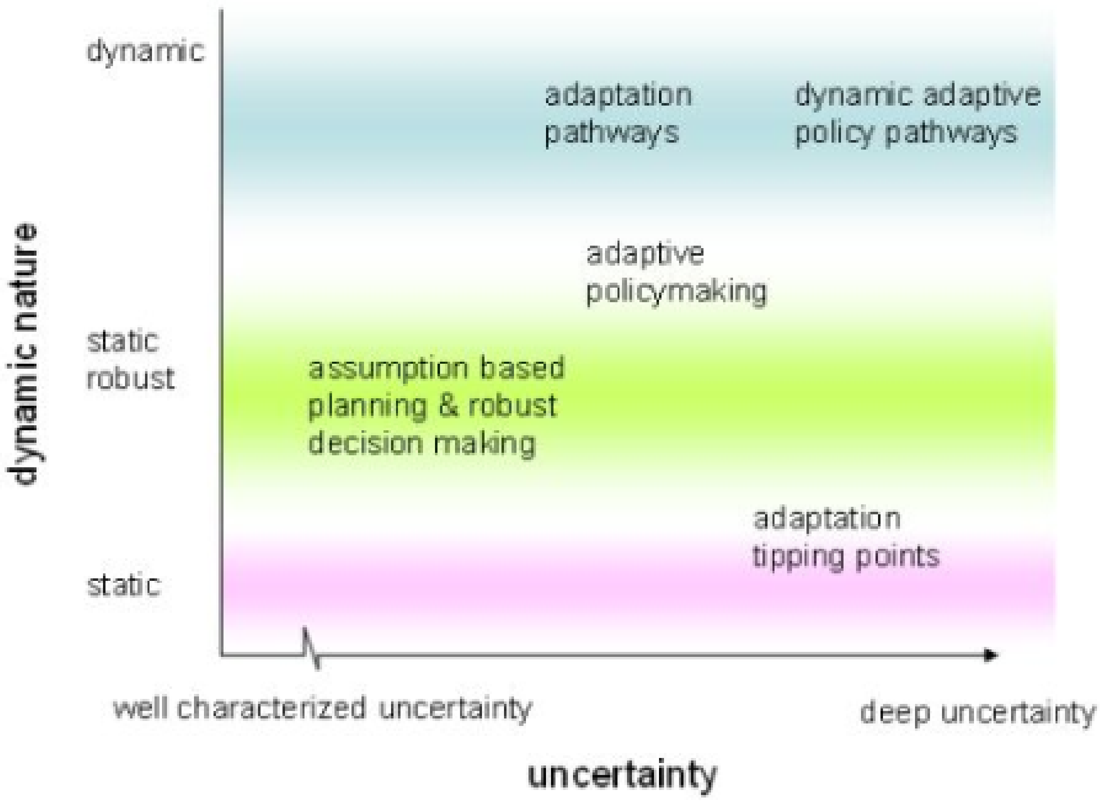

Figure 2.1: Policy making methods in relation to the dynamic nature and uncertainty of the system. Adopted from Walker et al. 66

These methods could be used to improve policy making in container terminals. However, to make these plans, quantitative data about the influence of climate change on container terminals is required. This information is often not available. Recent studies have been focusing on finding vulnerabilities in container terminals, and estimating the effect of single events on a terminal [38] [57] [37] [39] [50]. In the literature study no research has been found that yet incorporated the uncertainty in climate scenarios in their models.

2.2. Research objective

With these uncertainties in future container terminal performance, it is important to understand how different climate scenarios influence the performance of container terminals. The objective of this thesis is to develop a method that can be used to estimate the operational impact of climate change for a given container terminal. With this method, policymakers could screen container terminals according to their vulnerability to climate change, and generate information that can be used for policy making under deep uncertainty.

2.3. Research questions

One main question and five sub-questions are used to reach this research objective. The main questions should be related to the desired outcome of the method that will be produced. The main question thus becomes:
”What is the effect of different climate scenarios on the operational performance of a container terminals?”

Four sub-questions are used to support the main question. Each sub question plus a short elaboration on why this question is chosen are mentioned below.

1. How do container terminals operate?
   (a) What are the performance indicators of a container terminal
   (b) Which terminal operations are related to these performance indicators?
   (c) How do these operations affect the performance indicators?

   To select the indicators with which the performance of the system can be measured, the system itself must be understood. By identifying the indicators that describe the performance of the container terminal, we can elaborate on how these performance indicators are calculated. These performance indicators, and how these are calculated, provide a basis framework that can be used to build the model on.

2. Which weather events influence container terminal operations, and what is their effect?

   To describe the effects of climate on the operations of a port, a list of weather events has to be created. Each of these events has an effect on the key performance indicators identified in sub-question 1.

3. Under which climate conditions can weather events be expected?

   As we now understand which events influence the operations of a container terminal, we need to know the conditions under which these events occur. If this information is present, the only remaining gap in data is the likelihood that these events occur.

4. How likely are these events in the future?

   So, the last knowledge gap is related to the likelihood that the events occur. Not merely the likelihood in the present time, but particularly in future climate scenarios. In that way, we can estimate the impact of several climate scenarios on the terminal operations.

2.4. Methodology

By applying several methods in five different topics, each of the research questions can be answered. Figure 2.2 provides a schematic representation of the different topics that will be investigated during this research. A further explanation of every topic is provided in this subsection.

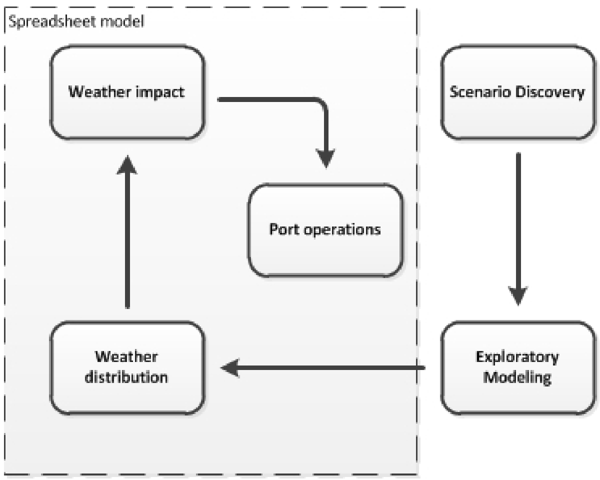

Figure 2.2: A schematic representation of how the research is conducted.Five blocks are shown. Each block represents a big chunk of this research. The arrows do not show the flow of the research, but show that the block is related to the other.

In the first topic, ”port operations”, the main goal is to identify the operations in a container terminal, and how the performance of these operations can be measured. This is essentially the backbone of the research. The outcome of this topic should be a framework that can be used to measure the operational performance of a container terminal. Sub-question 1, ”*How do container terminal operate*”, is answered with this topic.

The goal of the second topic, the ”weather impact” is to find a way to relate the weather to the operational performance of container terminals. The arrow between weather impact and port operations indicate that the weather impact should somehow be connected to the framework that has been created in the first topic. The outcome of this topic should be a list of weather events, with the impact of every event on the operations of a container terminal. Sub-question 2, ”*Which weather events influence container terminal operations?*” is answered in this topic.

The third topic, ”Weather distribution” has as goal to identify how often the weather events occur. The arrow between weather distribution and weather impact indicate that the weather distributions determine how often the weather events occur. Although probability distributions are used, the occurrence of weather events is not considered as a stochastic value. Instead, the expected values are used. The outcome of this topic should be a distribution of weather events or weather variables. By understanding the distribution of weather, the yearly impact of weather can be determined. This topic provides an answer to sub-question 3, ”*Under which climate conditions can weather events be expected?*”.

Topic one, two and three together are merged in a spreadsheet model. This model will be used to calculate the outcomes of the port operations under different weather distributions.

The goal of the fourth topic ,”exploratory modeling analysis”, is to determine a set of climate scenarios, which can be used to simulate the effects of climate change on container terminals. This topic determines how the distribution functions from the third topic change through the years. This is indicated by the arrow. Through the weather distributions, weather impacts and port operations framework, the effects of climate change on container terminals can be estimated. This outcomes of this topic should be a range of different climate change scenarios. Sub-question 4, ”*How likely are these events in the future?*” is answered in this topic.

The last topic, is the ”Scenario Discovery”. The other topics combined provide a method that can measure the range of port performances under the range of different climate change scenarios. The last step would be to identify the climate change scenarios for which the container terminal is vulnerable. This is the goal of the last topic. For this, we use a method called PRIM-Analysis. The PRIM-analysis is applied to the data produced in the other topics. Eventually, the PRIM-analysis should result in a set of climate change characteristics for which a container terminal is vulnerable. This last topic should answer the main question ”*What is the effect of climate change scenarios on the operational performance of container terminals?*”.

2.5. Exploratory modeling and analysis

The central method in this research is exploratory modeling and analysis (EMA). EMA shall be used to explore the effects of climate change on the operational performance of container terminals. EMA has been used to analyze on climate change and flooding and drought before. However, in the literature review, no other research was related to large infrastructures.

In consolidative modeling techniques, a researcher should be able to create a model with ”adequate knowledge about both the system characteristics and initial conditions” [31]. The reliability of the outcomes of such a model relies heavily on the validation of the model. If there is deep uncertainty in the model, validation is not possible. For situations where deep uncertainty exists, exploratory modeling can be used. Exploratory modeling is not built on a single model that can be validated, but rather a large amount of very diverse plausible models. It is not possible to validate these models, but it is nevertheless possible to argue about the behavior of the system with these models. In this case, it is not possible to validate any of the possible climate change scenarios, but it is nevertheless possible to argue on the behavior of the system in a very diverse set of different climate change scenarios.

With an exploratory modeling research, a model is constructed, with a very diverse set of scenarios. For this case, a model describing the operational performance of a container terminal is constructed. Then, a space of uncertainty influencing the model is described. For this research, the climate change is the plane of uncertainty that affects the operational performance of the container terminal. With this field of uncertainty, a number of experiments are selected. The larger the number of experiments, the larger the coverage of the uncertainty space.

The results from the computational experiments need to be analyzed to gain insights in the behavior of the system. Figure 2.3 provides an example of how PRIM analysis works. With the PRIM analysis, a set of boxes is generated. Each box covers a fraction of the outcomes, and is shaped in the uncertainty space. The figure shows the shape of the boxes in a 2 dimensional space, plus the outcomes of the runs. The grey dots are the runs of which the outcome did not result in a state of interest, while the black ones resulted in an outcome of interest. The boxes that are generated contain 2 characteristics; Density and Coverage. The density is the ratio between the number of outcomes of interest in the box, over the number of outcomes which are not of interest in that same box. The coverage is the number of outcomes of interest in the box, over the total number of outcomes of interest in the entire experiment.

Consider Peel 3, Box 1. All of the outcomes within this box are outcomes of interest; all of them are black. The density of this box, is thus 100%. The coverage is high; a lot of outcomes of interest lie within the box, whereas only a few outcomes of interest are not situated in the box. The coverage for this box is approximately 80%.

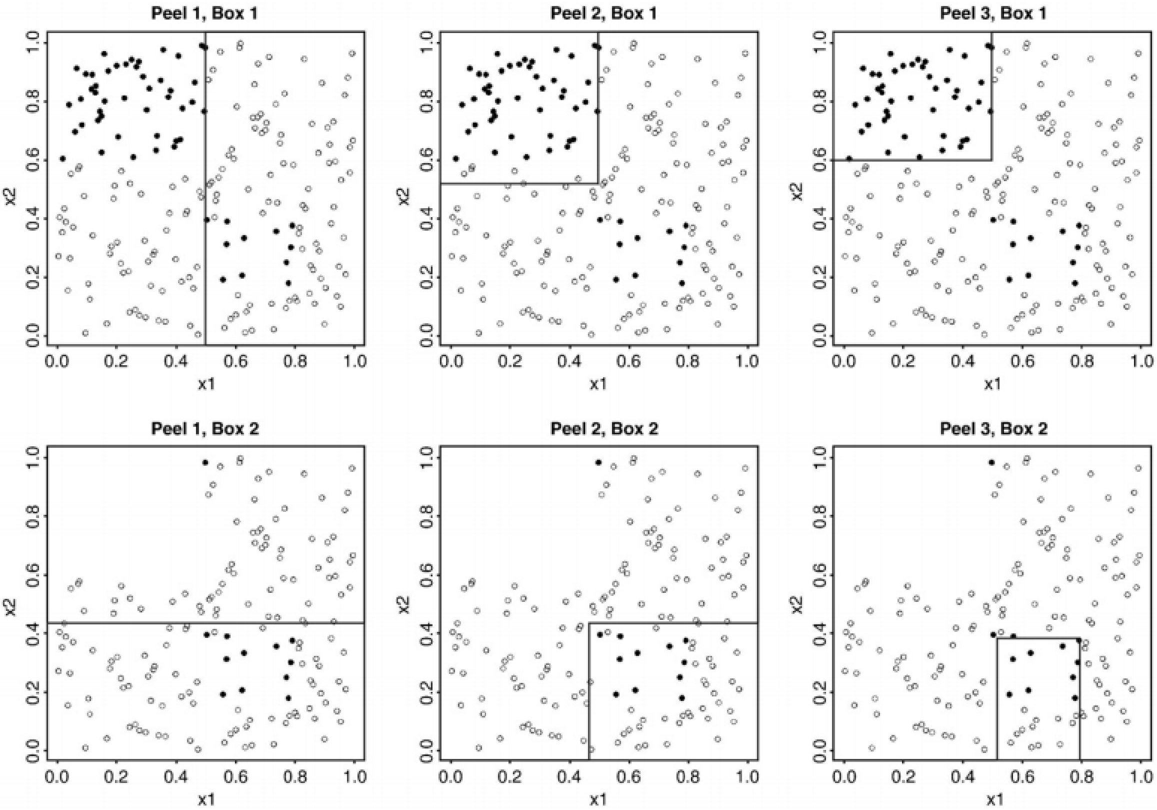

Figure 2.3: An example of PRIM-Analysis. Black dots indicate that the result is an outcome of interest. Grey dots indicate that the result is not an outcome of interest. Adopted from Bryant and Lempert (2009).

2.6. Scope

This section contains the most important boundaries of this research. Note that the research objective is ”to develop a method that can be used to **estimate** the **operational impact** of **climate change** for a given **container terminal**” The objective by itself already defines a part of the scope. The four most important boundaries defined in the research objective are discussed here.

Type of method

This thesis aims at developing an exploratory method rather than a predictive one. This implies that the accuracy of the model is not fit to use it for predictions. The method can thus not be used to determine when certain events are occurring. The model can merely be used to show vulnerabilities in the system.

System to be analyzed

The system that is being analyzed in this thesis is the container terminal at open sea. Other terminals like bulk or roll-on/roll-off are not taken into account. Also, this research is dedicated to container terminals that are located at open sea, not those which are based at a river, or inland.

Which external factors that influence the system performance will be taken into account?
The vulnerability of container terminals to climate change is assessed. Many external factors influence the performance of container terminals. Container terminals are for instance subjected to geopolitical influences, but also to economic development, technological developments and supply and demand curves. In this thesis, the only external factor that will be analyzed is the change in climate. All other external factors will be ignored. Also, a demarcation can be made between operational and extreme climate. Extreme climate consists of these events that occur once in a very long period, for example once in 1000 years. Operational climate is the climate that can normally be expected during a year. This thesis focuses on operational climate rather than extreme climate.

How is the effect measured?
To measure the influence of climate change on a container terminal, many different aspects can be taken into account. Examples are : cascading effects, operational impact, financial impacts, structural damages, etc. In this research, the only effect that is measured is the operational impact. As a result of climate change the operational performance is changing. Although the other effects may be more severe, they are not within the scope of this research.

2.7. Reader's guide

The report is mainly structured around the methodology. this section provides a short abstract of what is discussed in each chapter, as a guide for the reader. Chapter 1 and 2 should be finished reading already, so the first abstract here starts at chapter 3.

- **Chapter 3**
  This chapter provides an introduction in how container terminals operate. This chapter summarizes the basics of container terminal operations, and is used to create a foundation of understanding on which the other chapters are built. For those who are familiar with how ports operate, this chapter can be skipped.
- **Chapter 4**
  Chapter four is the core of the research. This chapter describes how the operational performance of container terminals is measured. Furthermore, this chapter describes how these measurements can be calculated.
- **Chapter 5**
  Chapter five provides a list of all weather events that may affect the operations in a container terminal. The impact from these events are used to determine the operational performance if the weather events occur.
- **Chapter 6**
  Chapter six is the first chapter with case-specific information. It provides the distributions of sealevel, wave height, precipitation volume, temperature and wind speed in Manzanillo. These distributions are used to determine how often the weather events occur.
- **Chapter 7**
  Chapter seven discusses the experimental setup. The settings for the experiments are discussed, as well as the number of runs.
- **Chapter 8**
  Chapter eight presents the results, and discusses the outcomes of the analysis.
- **Chapter 9**
  Chapter nine discusses on the social and scientific relevance of the thesis.
- **Chapter 10**
  Chapter ten concludes on all of the research questions formulated in this chapter.
- **Chapter 11**
  Chapter eleven consequently provides a reflection on the process. This chapter contains no additional information on this topic.

3

HOW CONTAINER TERMINALS OPERATE

This chapter gives a short and simplified explanation on how container terminals operate. The contents of this chapter are used to create a fundamental understanding of the system that we analyse: the container terminals. Although the contents of this chapter are merely a summary of other people's works, the chapter has a right of existence due to its contribution to the understanding of the system, and providing basis knowledge for the reader that is not familiar with container terminals. Figure 3.1 highlights the topic to which this chapter belongs. This topic is part of the port operations-topic, as identified in chapter 2.

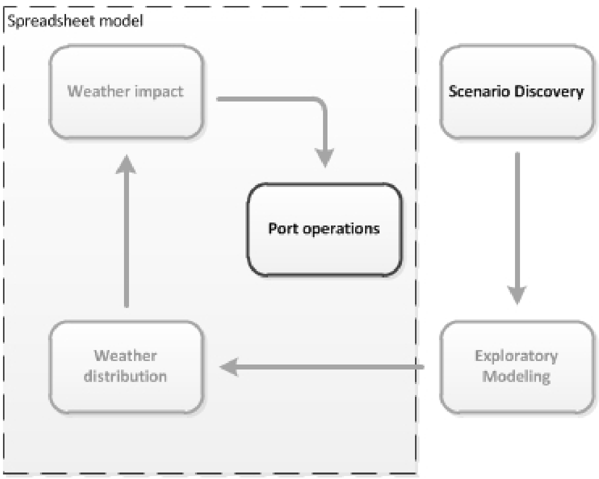

Figure 3.1: The position of chapter 3 and 4 in this research. The highlighted box refers to the part of the research that is described in this chapter. The other boxes represent the parts of the research that need to be done in the coming chapters.

Firstly, an elaboration about how all actors are involved in ports is presented. In that same section, a first idea of operations is provided through the different business models, the roles of these actors and their interests. Then, the different operations in a container terminal are briefly mentioned. The assets and structures involved in these operations are presented thereafter.

3.1. How actors relate to container terminals

A port is an assembly of all sorts of assets, organizations and operations that all contribute to the function of a port: transportation. The assembly of organizations that is involved in a container terminal depends on the applied port business model. The business model determines how some different organizations are related to each other.

3.1.1. Port business models

Very much dependent on the region and institutional setting where to port is located, different port business models might be used. Most of the ports can be categorized in any of these 3 different typologies of business models [36].

1. **Landlord ports**. In this model, the port authority is the owner of the entire core port infrastructure like the land, berths, etc. All marine services, cargo handling and equipment (cranes, vehicles, etc.) are owned by private operators. The port operators are given a concession for a certain amount of time, and hire the core infrastructure for that period from the port authority.

2. **Mixed ports**. The port authority provides the infrastructure and provides operational services in competition with private companies. The port authority acts as port operator, but also allows other port operators in the port.

3. **Full-service ports**. In full-service ports the port authority owns and operates the full spectrum of port activities. The authority is monopolist in this case, and hires all labor to perform the activities. The port authority is the only port operator.

3.1.2. Services and actors in ports

There are many organizations involved in ports. In the port of Rotterdam for instance, over 1500 organizations are involved [5]. Fortunately, not all of these are important for this research. Instead, only eight different types of actors are described here, which are involved in most of the ports with container terminals. These eight types represent most of the actors that are important for this research. while this sections briefly describes the involvement of each of these actors, the next sections further delineate their purpose, roles and goals in ports.

Figure 3.2 is a schematic representation of how actors and services are related in landlord ports. One of the central actors involved in this system is the port authority. The port authority provides the terminal structure and the maritime access in the port. For this, it receives payments from shipping companies, who use the maritime access, and from the port operators, who lease the terminal structure from the port authority. The other central actor is the port operator. They exploit the terminal structure from the port authority, and pay for the lease-contract. It does all the container handling in the port, and receives payments from both the shipping companies and the freight forwarders. The shipping companies and freight forwarders also pay for the maritime access or inland access, to either the port authority (for maritime access) or the national government (for inland access). The regional government provides the regional infrastructure, which is necessary for transport to the hinterland. For this, it receives a percentage of the port tariffs. The port security is responsible for the protection and inspection in the port and marine areas. The harbormaster enforces all regulations and optimizes port logistics.

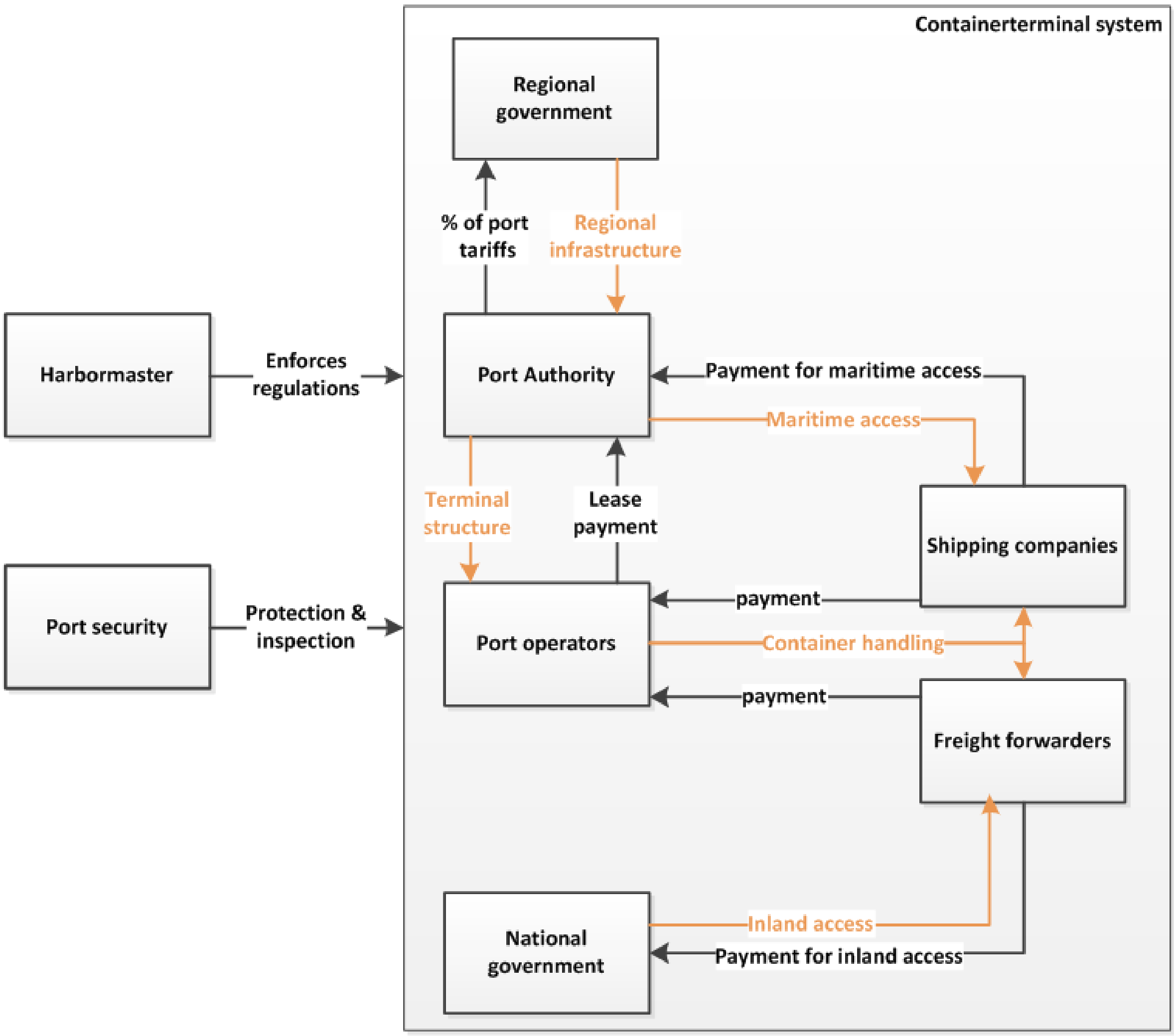

Figure 3.2: A schematic representation of how actors relate to each other, based on [64]. Each block represents one actor in the system. The black arrows indicate a hierarchical relation, while the orange arrows show the function that is provided.

A **national** and/or regional government is always involved in the port, either directly, or indirectly. They may have given a permit for construction, and are often shareholders of the port authority. Thus, the port authority should always act in line with the government. In some occasions also private parties are shareholders of the port authority. However, since this is very rare, this situation is not discussed in this research. The port authority can give a concession to a port operator to operate in a area of the port, for instance with a container terminal. The port authority and operator are thus bound by a long-term bilateral contracts. Shipping companies then supply goods to these terminals, while freight forwarders transport the containers to the demand-side with ships, trucks, trains or other vehicles. The shipping companies and freight forwarding companies pay per container to the port operator. A harbormaster is normally involved in enforcing regulations in order to ensure safety of navigation, security of the port and correct operations. The harbormaster works in name of the port authority, and enforce the rules and regulations to the port operators, shipping companies and freight forwarding companies. The regional and national government indirectly inherits these powers, since they are the shareholders of the port authority. A port security is involved in the port to apply the rules and regulations from the International Maritime organization [16]. The port security is sometimes merged with the harbormaster, and is responsible for the protection of the port, maritime security and the protection and inspection of the cargo. The port security is bound by the IMO, and it's powers are inherited by the national /regional government as well.

3.1.3. Description of actors involved in container terminals

The eight actors introduced in the previous section are often represented in container terminals. Now that the primary contribution of these actors to the services in container terminals are known, their roles can further be described. This subsection provides an extended description of each of the organizations that are mentioned before.

Port authority
The port authority can be owned by a mix of national and regional governments, and private companies. The port of Rotterdam for instance, is 70% owned by the municipality of Rotterdam, and 30% by the Dutch government [2]. According to ESPO, about 40% of the port authorities are state-owned, 35% municipality-owned, and 4% private-owned [44]. The port authority is the governing body that is responsible for the development of the port. It's role is to manage, operate and develop the port area.The goals of the port authority are to create economic and social value for the region, to stimulate growth of the port and to earn profit. The port authority is in the larger sense responsible for all that happens in the port; operations, environmental impact; expansions, etc.

Harbormaster
The harbormaster is responsible for safe, sound and sustainable operation of the port. The harbormaster usually cooperates with all acting organizations in the port with the aim to improve the safety and efficiency of the port. The exact activities of the harbormaster vary per port however. A harbormaster for a yacht-harbor are quite different from those of the harbormaster of a large chemical port. The main goals of the harbormaster are in any case safety in the port and efficient transport of ships. The harbormaster might carry the responsibility for the port security, and is often embodied in the port authority.

Port security
The port security is often directed by the harbormaster and has full responsibility concerning all security-related issues in the port. This includes the protection of the seaports themselves, the protection and inspection of the cargo moving through the ports, and maritime security. The port security follows the regulations from the International Maritime Organization (IMO).

Port operator
The port operator is providing a service in the port. In this case, the port operator is the party that operates the container terminal. It therefore provides all services from unloading to storage, to loading. Private port operators are usually organizations with terminals all over the world. Examples of these are Hutchinson Port Holdings (HPH), Singapore Port Authority (PSA) and APM Terminals [62].

National government
The national government is responsible for supporting the economic development of the country. The ultimate goal for the national government is to maximize welfare. The economic and environmental aspect are both incorporated here.

Regional government
The goal of a regional government is to maximize regional welfare. Supporting the growth of the port often results in increased regional welfare. Their concerns also relate to the environment. The regional governments can be the province and the municipalities.

Freight forwarders
There are several types of freight forwarders. Depending on the available infrastructures that connect the port with the hinterland, there can be trucking companies, rail operators, barge operators and shipping companies. Trucking companies transport containers by trucks, rail operators transport containers by train and barge operators use inland ships to transport containers over waterways.

Shipping companies
The shipping companies are private parties with the goal to earn profits. Their function in the port is to transport containers from oversea to the terminal and vice versa. Examples of these are MAERSK Lines, HYUNDAI Merchant Marine, COSCO, MSC and Dockwise.

3.1.4. Container terminal performance

As each of the actors presented so far have different goals, tasks, means and responsibilities, they might measure performance of the port in different ways. However, the stakeholder that is considered most important for this research is the terminal operator; in the end, the terminal operator is the owner of the terminal, and is solely dependent on the performance of its terminal(s).

A study performed by Soner Esmer [43] concludes that there is little agreement between ports, international organizations concerned with ports and experts in the field over what these performance measures must be. He does however summarize a set of performance indicators that are used in multiple occasions. The indicators are divided in of four categories.

1. **Production**: These are measures used to quantify the level of activity in a business. Different words for production are used around: throughput, output, traffic, trade, etc. Examples of indicators are ship throughput and yard throughput.

2. **Productivity**: This concerns the ratio between output and input. The productivity is especially important to the port operator. Examples of indicators in this category are labor productivity and crane productivity.

3. **Utilization**: The utilization is used for determining to what extend a resource is used. Typical ones are quay utilization and storage utilization.

4. **Service**: The service measures are those of importance for the clients. The higher the level of service, the happier the shippers are. Typical indicators are the ship turnaround time and the road vehicle turnaround time.

It is important to choose the measures that fit the purpose of this research. Since this research aims to identify the impact of climate change on container terminal operations, the indicators should on the one hand reflect the impact for the problem owner - which is identified as the port operator- and on the other hand be such that it is not primarily affected by other factors than those related to the weather.

This implies that indicators that are for instance related to the added value of a port to a region are not useful, for these would reflect the interests of the governments rather than the interests of the operator. Furthermore, all indicators related to monetized value are not used either. By relating the indicator to a monetary value, like the cost per container, the indicator becomes highly dependent on the value of the money, but also on the cost of labor, etc. Since climate-change does not directly seem to influence the wages or value of money, these indicators are not useful for this research.

There are however 3 indicators that fit with this research and are also supported by the UNCTAD [53].

1. **Level of service**: In contrast to what is mentioned above, this indicator does not directly impact the port operator. But, since the port operator loses his customers if the level of service is dropping, this will indirectly impact the operator, and is therefore still important to the operator. The level of service is an indication of how happy customers are with the terminal. The higher the level of service, the better.

2. **Terminal capacity**: The capacity of the terminal is describes the maximum number of containers the terminal can process in a year. If the terminal capacity is decreasing due to the weather, this would imply that the port is negatively affected by climate change. The higher the capacity of the terminal, the higher their potential throughput - which is of course better for the operator.

3. **Terminal utilization**: The terminal Utilization indicates how far from the maximum capacity the terminal is actually operating; ”how much slack is left?”. If the port is 100% utilized, this would mean there is no waste of capacity. On the other hand, this would also mean that if peak capacity drops, a backlog is appearing.

Since these three indicators are suitable indicators of port performance, they are used as key performance indicators throughout this report. Additional performance indicators might be taken into account in another stage, but most weight is attached to these three. Chapter 4 will provide a more detailed description of the performance indicators.

3.2. Operations related to container terminals

On high level, the actors involved in container terminals have been identified in the sections above, as have their role in the ports. This section continues with the operations related to container terminals. for this study, seven operational steps are taken into account. These are 1) Navigation, 2) Berthing, 3) Unloading, 4) Vehicle transport, 5) Storage, 6) Loading and 7) Transporting. A description of these seven is provided in table 3.2. These seven are chosen as all operational steps on the highest possible level, that are directly related to the main purpose of the container terminal: transporting containers.

Table 3.2: List of operations in container terminals. In the left column, the operation is shown. A description of that operation is given in the right column

Operation	Description
Navigation	The transportation of a vessel to the berth
Berthing	positioning the vessel at the berth
Unloading	recovering the containers from the vessel, barge, train or truck
Vehicle transport	The transportation of the container on-site with a vehicle
Storage	The storing of the containers
Loading	The placement of containers on a vessel, barge, train or truck
Transporting	Transporting the containers via vessel, barge, train or truck to the hinterland

3.3. Assets in container terminals

To perform the operations mentioned in the previous section, a set of assets is used. The assets involved in the terminal's operations are separated in 2 categories; 1) The functional assets, which are part of the logistic chain and 2) The supportive structures, which are those that support the functional assets. The supportive assets do not have operational functions, but must be in place to allow the operations to take place.

3.3.1. Functional assets

The assets in the logistic chain are the assets that perform a real function in either moving or storing containers. A schematic overview of the logistic chain within a container terminal is provided in figure 3.3. Note that some assets are mentioned in the text, which are not included in the figure yet. A vessel (which can be deep-sea, or any other type) ships containers to the location of the port. A tugboat brings the vessel to the berth. When the vessel is moored to the quayside, one or more quay cranes start unloading the containers from the vessel, placing the containers on (automatic guided) vehicles. These vehicles deliver the containers to a storage crane (Rail mounted gantry crane/RMG). The storage crane unloads the vehicles, and stores the containers in a rack or other storage location. These operations are necessary to deal with the supply of containers in a terminal. To deal with the demand, some other assets are necessary. Demand from the hinterland is dealt with by rail-transport, road-transport or waterborne transport. In a Dutch terminal approximately 45% of the transport to hinterland is transported over water, 35% by road, and 20% by rail [23]. To load the containers to a train or truck, gantry cranes are commonly used. Vehicles (optionally automatic guided) transport containers from the storage location to the gantry cranes. to load containers on vessels, the quay cranes are used again.

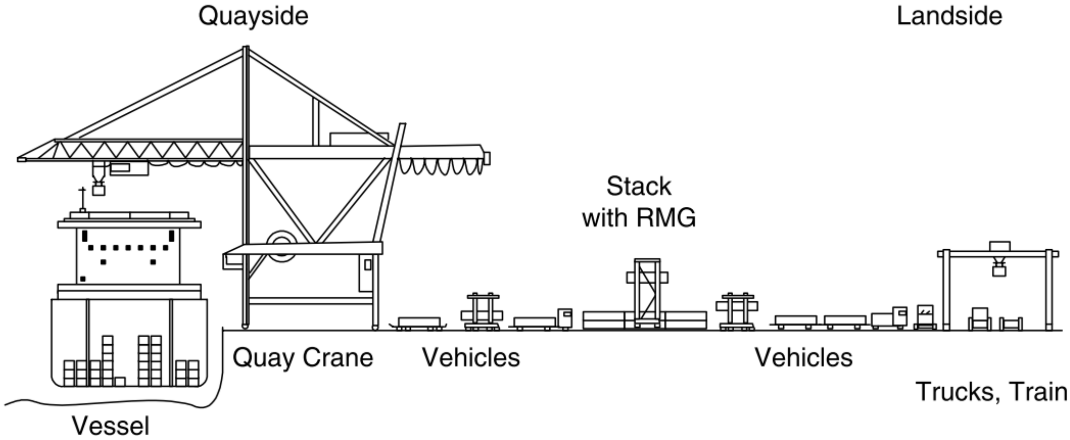

Figure 3.3: A schematic overview of the functional assets in a container terminal, obtained from [64].

The functional assets that are identified here represent those that are moving or storing containers in direct relation to the container terminal. Table 3.3 presents the functional assets in ports, along with the function the asset performs. Note that the assets are limited to those that exist on the terminal or are directly related to the container terminal. Also note that some of the assets are presented in a general term. Assets might be available in various sizes, different amounts or diverse types. A terminal might for instance have 20 gantry cranes. These can be rubber tired gantries, but also rail mounted gantries. Differences between those types will not be taken into account here.

Table 3.3: List of functional assets in container terminals. In the first column, the asset is mentioned. The function of the asset is provided in the second column.

Asset	Functions
Quay cranes	Moving containers from a ship to a (automatic guided)vehicle on the quay and vice versa
Deep sea quay cranes	Moving containers from a deep-sea vessel to a (automatic guided) vehicle on the quay and vice versa
(Automatic guided) vehicles	transporting the container from a storage crane to a rail-crane or (deep sea) quay crane and vice versa
Storage cranes	Transporting a container from a (automatic guided) vehicle to a storage-rack and vice versa
Gantry cranes	Often used for loading and unloading of trains or trucks
Trains	Trains are used to transport containers over rails to the hinterland
Trucks	Trucks are used to transport containers over the road to the hinterland
Deep-sea vessels	Deep-sea vessels are used to transport containers over the sea to ports
Inland ships	Inland ships are used to transport containers over waterways and rivers to the hinterland
Tugboat	The tugboat assists the ship while making its maneuver in the port.

3.3.2. Supportive structures

The supportive structures do not directly contribute to the logistic performance of a terminal, but are responsible for *enabling* the logistic processes. In that sense, the structures mentioned here create the boundary conditions for the processes to happen. These structures can be hard structures, like a quay, but also soft-structures like an internet connection, or a database. When the supportive structures are impacted, the logistic process might come to a halt. Say, if the quay is damaged, the cranes cannot operate, and the logistic process is halted. Table 3.4 provides an overview of the supportive structures that are present in ports, and what their use is.

Table 3.4: List of supportive structures related to container terminals. In this first column, the supportive structure is mentioned. The description of the function is provided in the second column.

Supportive structure	Functions
Power grid	Since electricity is the main power source for most terminals, the connection with a functional grid determines how reliable power supply is
Aggregate	In case the power grid fails, the aggregate is able to keep electricity running for a short while
Berths	A berth is used to moor the vessels
Utilities	Utilities like water, power and gas are necessary for port operations.
Breakwater	These are used to reduce wave impact on vessels and ports
Other coastal defenses	To prevent sea-related impacts on the port.
Internal road	This road provides the infrastructure for the vehicles
On-site rails	These rails are used by cranes
Quays	Quays are the area where quay cranes are located. Quays must support the weight inflicted by the other structures.
Telecommunication	The telecommunication connections are responsible for guiding all of the systems in the terminal. If this system fails, the operations on the terminal are terminated.
Rail	The rail connects the terminal with the hinterland
External road	These roads connect the terminal with the hinterland
Waterways	Connects the terminal with the hinterland and other ports

3.4. Recap

In this chapter the most important stakeholders in container terminals were identified. These are the national government, the regional government, the port authority, port operators, port security, harbormasters, shipping companies and freight forwarders. Each of them has a specific role in relation to the terminal. For this research, the port operators are considered the central stakeholder. Although all stakeholders have different ideas about the indicators to measure terminal performance, only three are considered as key performance indicators; level of service, terminal capacity and terminal utilization. These three are representing the terminal operations mostly from the view of the port operator. Lastly, the assets in container terminals are described. The list of assets and supportive structures provides insight in the dependency of the operations on some of the assets. These assets and performance indicators can be related to each other, such that a quantitative description of port performance can be made, dependent on these assets. This will be done in the next chapter.

4

MEASURING THE PERFORMANCE OF CONTAINER TERMINALS

This chapter builds on the knowledge extracted from the previous chapter. To describe the impact of climate change on container terminals, we must first understand how the performance of container terminals can be measured. The quantification of the impact of climate change is one of the goals of this research. Figure 4.1 shows the position of this chapter in this research. This chapter is still within the topic of port operations, building the foundation of the model.

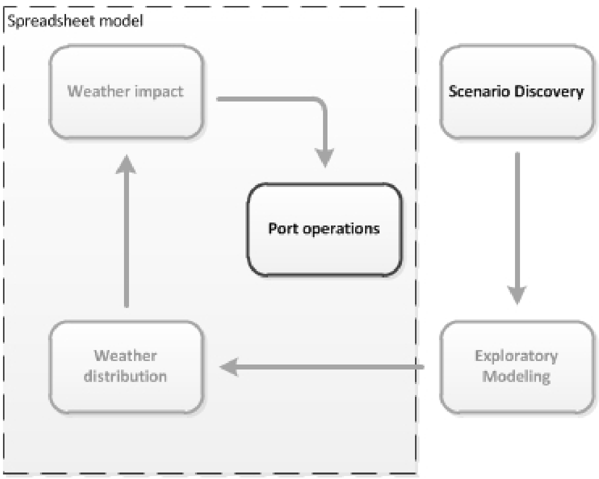

Figure 4.1: The position of chapter 3 and 4 in this research. The highlighted box refers to the part of the research that is described in this chapter. The other boxes represent the parts of the research that need to be done in the coming chapters.

In the previous chapter, some performance indicators have been mentioned briefly. The most relevant ones to this research are further specified to assess the performance of the system. The three that are the most important are the **level of service**, the **terminal capacity** and the **terminal efficiency** [53]. These three key performance indicators will be used to quantify the effects of climate change on container terminals. How these performance indicators are calculated, is presented in this chapter. To have a good overview of the origin of each of the equations, the source is mentioned at the concluding section of this chapter.

4.1. Level of service

Let's start with the level of service. The level of service is a measure of the quality by system clients and users. This thus incorporates some of the goals that these clients and users have. For the shipping companies basically two points are important.

1. They can deliver as many containers as possible.
2. This should be done in as little time as possible.

An illustration of how the level of service is measured, is provided in figure 4.2. Each of the relations shown in the illustration will be elaborated in this subsection.

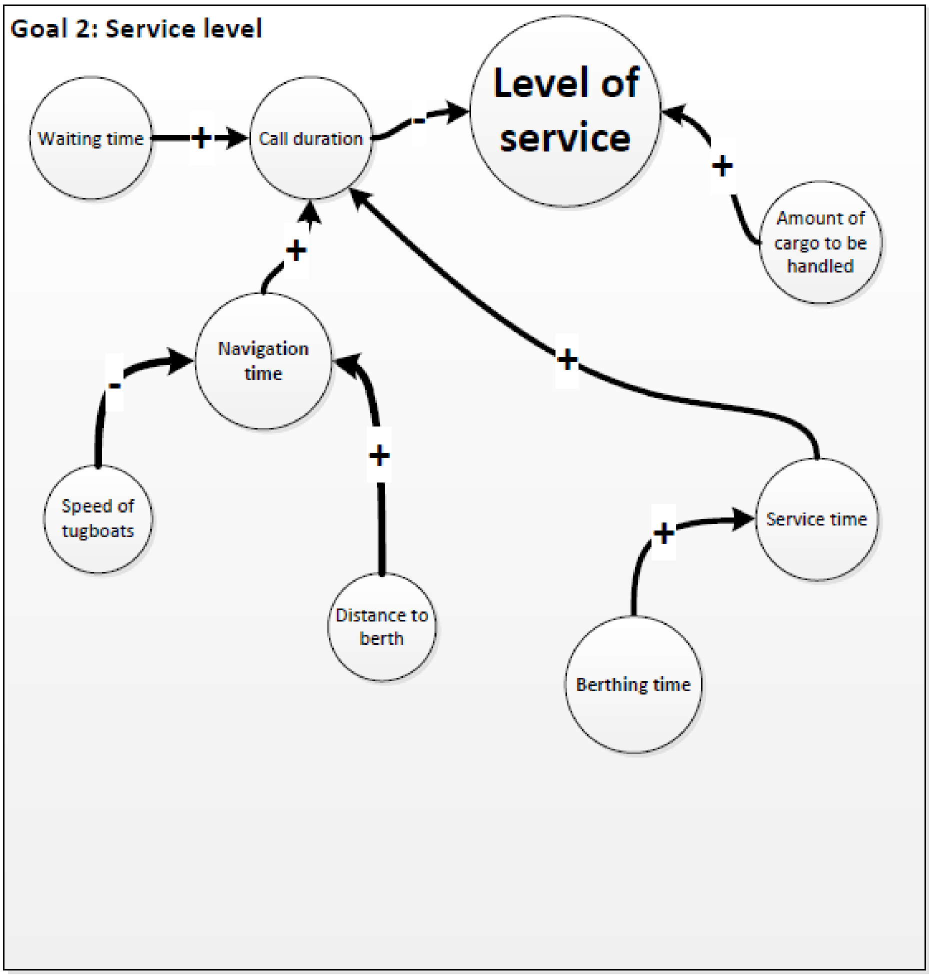

Figure 4.2: Visualization of how the level of service is measured. The big circle represents the key performance indicator. The smaller circles represent the variables needed to calculate the value of the key performance indicator.

According to the UNCTAD [53] the level of service should be measured as the call duration divided by the quantity of goods that can be delivered (as shown in equation 4.1). This implies that if the amount of goods increases, the level of service drops, just as happens when the call duration is reduced.

$$S_L = \frac{T_P}{Q} \tag{4.1}$$

S_L = level of service
T_P = vessel time at port (call duration)
Q = amount of cargo to be handled at port

This is however very counter-intuitive. You should expect that the level of service should be as high as possible, while with the equation proposed by UNCTAD, the lower the level of service, the better. Therefore, the definition of service level in this research deviates from the one used by UNCTAD. The equation is inverted to make it more intuitive. With this definition, the higher the level of service, the better.

$$S_L = \frac{Q}{T_p} \tag{4.2}$$

S_L = level of service
Q = amount of cargo to be handled at port
T_P = vessel time at port (call duration)

The vessel time at port is an addition of times that different processes take. The UNCTAD speaks of Three time-consuming processes that are important here. 1) The waiting time, which is the amount of time that a vessel spends anchored, waiting for allowance into the port. 2) The navigation time; this is the time a vessel needs to move from the entrance of the port, until the vessel is berthed. 3) The service time, which is the time that is needed at the quay. This is practically the time needed for berthing and unloading of the vessel.

$$T_P = T_w + T_n + T_s \tag{4.3}$$

T_P = vessel time at port (call duration)
T_w = waiting time
T_n = ship navigation time
T_s = service time

Waiting time only occurs when the ship cannot proceed directly into the port upon arrival. This is for instance because the berth is fully occupied, because the depth of the entry channel is too low (tidal window), or because the capacity of the tugboats available at that time is too low. The ship navigation time depends on how far the ship must navigate, and the availability of tugboats. The service time is more complex, and will be described in detail in the next sections.

4.2. Terminal capacity

The terminal capacity is the maximum yearly traffic it can handle in a given scenario. The capacity is based on the capacity of all subsystems performing in a container terminal. According to UNCTAD two processes are normally restricting the capacity of a terminal. These are the processes related to berthing & unloading the ships and the processes related to the storage of containers. The processes related to transporting the containers on site, and those related to the demand-side of the port are in most cases not restricting processes. Figure 4.3 visualizes the factors that influence the terminal capacity, in the same way as has been done for the level of service. Note that only the storage capacity and the capacity at quay are included in this image. For completeness, appendix C contains the larger model, with the factors that were not constraining the capacity of the port according to UNCTAD.

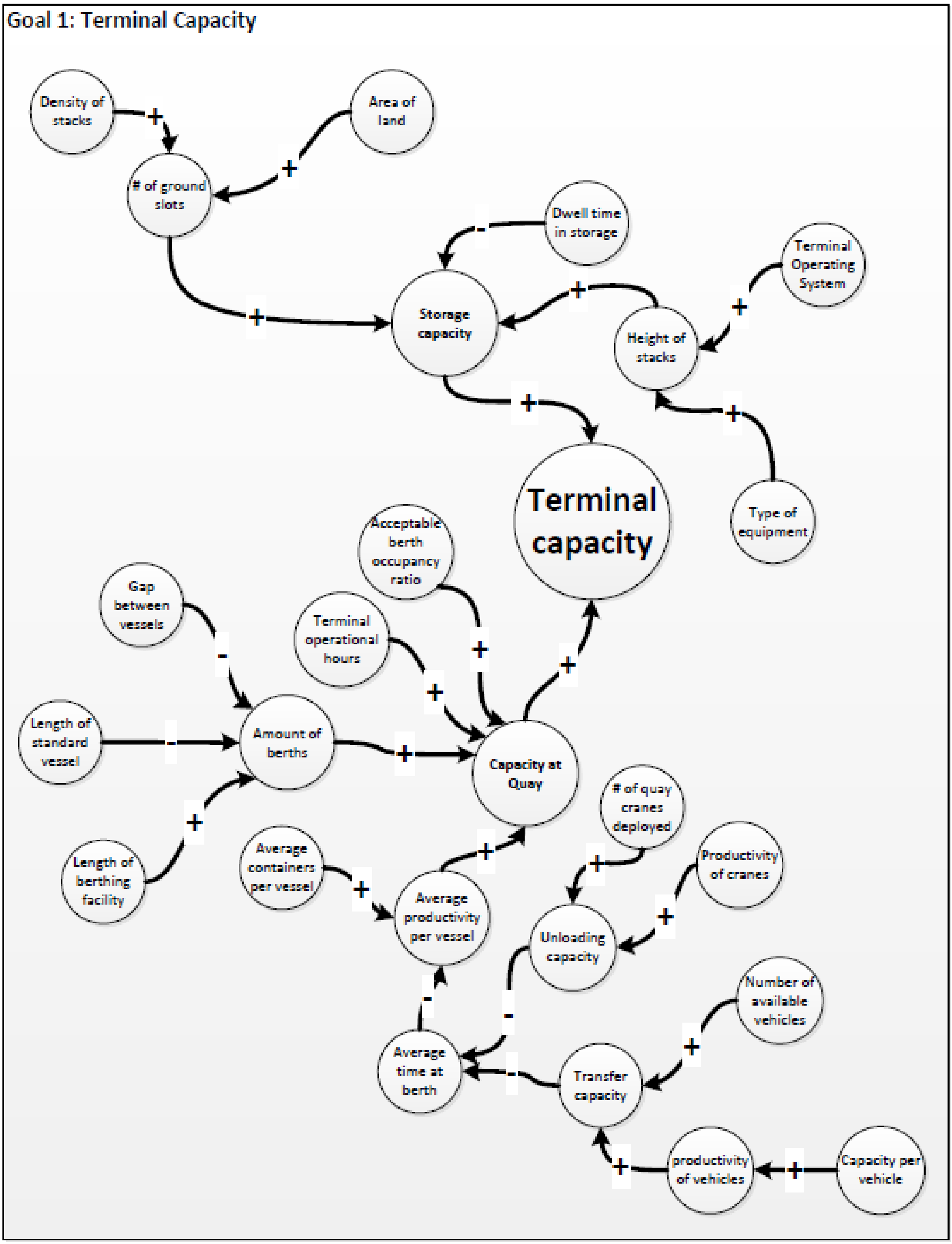

Figure 4.3: Visualization of how the terminal capacity is influenced. The big circle represents the key performance indicator. The smaller circles represent the variables needed to calculate the value of the key performance indicator.

The capacity of the port will be measured as the minimum capacity of the restricting processes. Thus; if the yearly capacity of the capacity at quay is lower than that of the storage capacity, the terminal capacity will be equal to the capacity at quay.

$$C_T = MIN(C_Q, C_S) \tag{4.4}$$

C_T = terminal capacity
C_Q = capacity at quay
C_S = storage capacity

The capacity at the quay is dependent on the availability of berthing locations, as well as the productivity at the quay. The level of service requires the call duration and the waiting time to be as low as possible. If the berth is full, this would mean that new vessels need to wait before continuing to the berth. This would result in a waiting time, which is undesirable. Due to this, the planned berth occupancy ratio is never 100%. The capacity at the quay can be described as following.

$$C_Q = n \times \phi \times t_{year} \times P \tag{4.5}$$

C_Q = capacity at quay
n = amount of berths
ϕ = acceptable berth occupancy ratio
t_{year} = hours the terminal is operational per year
P = annual average productivity of vessel at berth

The amount of berths (n) depends on 3 factors. Firstly the length of the berthing facility- the longer it is, the more vessels can berth. Secondly, the length of a standard vessel- the longer the vessels, the fewer the amount of berths available. Lastly, the gap between the vessels at the berth. If this gap is bigger, this means that less vessels can berth. The UNCTAD suggested equation 4.6 for calculating the amount of berths. However, with this equation the amount of berths calculated is lower than the actual amount of berths, since the gap between vessels do not occur before the first ship, nor does it occur behind the last ship at the berth. So, for calculating the amount of berths, equation 4.7 is proposed.

$$n = \frac{L_B}{L_V + G} \tag{4.6}$$

$$n = \frac{L_B + G}{L_V + G} \tag{4.7}$$

n = amount of berths
L_B = length of berthing facility
L_V = length of Vessel
G = gap between vessels

The annual average productivity of vessels at berth as mentioned in equation 4.5 is the average amount of containers that the vessel is delivering, divided by the average time that a vessel is at berth. Thus; the amount of containers that on average is delivered per hour.

$$P = \frac{Q_V}{T_B} \tag{4.8}$$

P = annual average productivity of vessels at berth
Q_V = average amount of containers on vessel
T_B = average time a vessel is at berth

The average time that a vessel is at berth is dependent on many factors. The time that is needed to unload the vessel is dependent on the amount of cranes that are used, the productivity of each crane, the amount of containers on the vessel, but also the capacity of the transfer vehicles. If the capacity of these vehicles is lower than the unloading capacity, the cranes cannot continue their operations.

$$T_B = \frac{Q}{MIN(C_U, C_{Tr})} \tag{4.9}$$

T_B = average time that a vessel is at berth
Q = amount of cargo to be handled at port
C_U = unloading capacity
C_{Tr} = transfer capacity

The unloading capacity is then dependent on the amount of cranes that are used for unloading and the speed at which they can unload. The more cranes that are used, the bigger the unloading capacity.

$$C_U = Q_C \times P_C \tag{4.10}$$

C_U = unloading capacity
Q_C = number of cranes used for unloading
P_C = productivity of cranes

The transfer capacity is the amount of containers that can be processed by the transfer vehicles in one hour. This depends on the number of vehicles available and the time that vehicles need to transfer a container. The more vehicles, and the shorter the time for transferring, the bigger the capacity. The time needed to transport 1 container is multiplied by 2, for the vehicles also needs to return to the crane after delivering the container to the storage.

$$C_{Tr} = Q_V \times \frac{60}{2t} \tag{4.11}$$

C_{Tr} = transfer capacity
Q_V = number of vehicles
$\frac{60}{2t}$ = productivity of vehicles
t = time needed to transport 1 container

The second factor that might be limiting the terminal capacity is the storage capacity. The storage capacity depends on three factors. These are 1) the number of ground spots, 2) the height of each stack and 3) the average dwell time. The height times the number of stacks indicates the total amount of spots that can be used for storing containers. The dwell time indicates how long containers on average stay in the storage. The longer they stay, the lower the capacity of the storage is.

$$C_S = m \times h \times \frac{365}{T_{dw}} \tag{4.12}$$

C_S = storage capacity
m = number of ground slots
h = height of the stacks
T_{dw} = average dwell time of containers

The number of ground slots is dependent on the density of the slots and the size and shape of the port. Next to that, there are several possibilities in the lay-out of the terminal site. This also influences the number of ground slots. The height of the stacks depends on the equipment the port uses as well as the Terminal Operating System (TOS). The dwelltime differs per port, and is also related to whether the port is oriented at importing or exporting. Typical dwelltimes are 4-7 days.

4.3. Terminal utilization

The terminal efficiency is not as straightforward as the other key performance indicators. Several definitions for terminal efficiency can be found throughout the literature. Examples are ”How much does it cost to handle a tonne of cargo?”, ”How much cargo is handled per employee?” [43], ”The capacity of obtaining maximum amount of output from certain inputs” and ”capacity of obtaining a given output level using the minimum amount of inputs” [68].
Using an efficiency indicator related to costs is not desired, for the costs in a terminal are subjected to a lot of factors which are not related to climate-change. By looking at cargo per employee, we also don't cover the chunk that we aim for; employees are not all that is utilized. Cargo per crane wouldn't fit for the very same reason. To represent terminal efficiency in this thesis, the terminal utilization is

used. Terminal utilization represents how many slack is left, or, how much of its capacity the terminal is actually using.

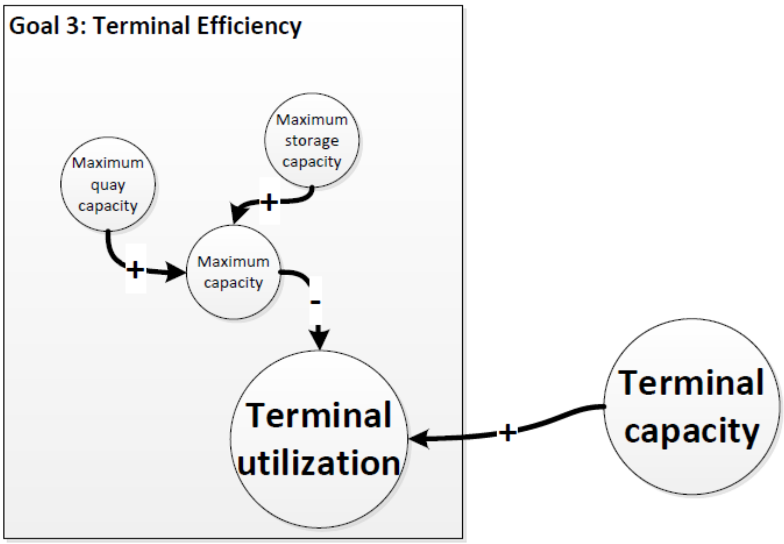

Figure 4.4: Visualization of how the terminal utilization is measured. The big circle represents the key performance indicator. The smaller circles represent the variables needed to calculate the value of the key performance indicator.

$$U_T = C_T - Q \tag{4.13}$$

U_T= terminal utilization
C_T= terminal capacity
Q= actual throughput

4.4. Recap

To measure the impact of climate-change on ports, 3 key performance indicators are used. Each of these performance indicators is subjected to a set of variables, which are used to compute the value of the key performance indicator.

1. **Level of Service**. This measures how attractive the port is for the shipping companies. It gives an indication of how much time the vessel needs for delivering a certain amount of containers. The more containers can be delivered in 1 hour, the better.

2. **Terminal capacity**. The terminal capacity defines the yearly throughput the terminal can achieve. The bigger possible throughput, the better.

3. **Terminal utilization**. The terminal utilization measures how much of the maximum capacity the terminal is actually using. If the utilization is very low, there is an overcapacity. If the utilization is very high, there is risk for losing level of service.

The equations used in this specification are either obtained from the UNCTAD [53], based on the UNCTAD, or completely argued by the author.

- Obtained from UNCTAD: 4.1, 4.3, 4.5, 4.6, 4.8, 4.10
- Based on UNCTAD: 4.2, 4.4, 4.7, 4.12,
- Own arguments: 4.9, 4.11, 4.13

5

THE EFFECTS OF WEATHER EVENTS ON CONTAINER TERMINALS

The performance of container terminals is influenced by the state of weather. This chapter relates different weather events to the key performance indicators that were described in the previous chapter. Figure 5.1 presents the position of this chapter in this research. This chapter describes the weather impacts on the port operations that were described in the previous two chapters.

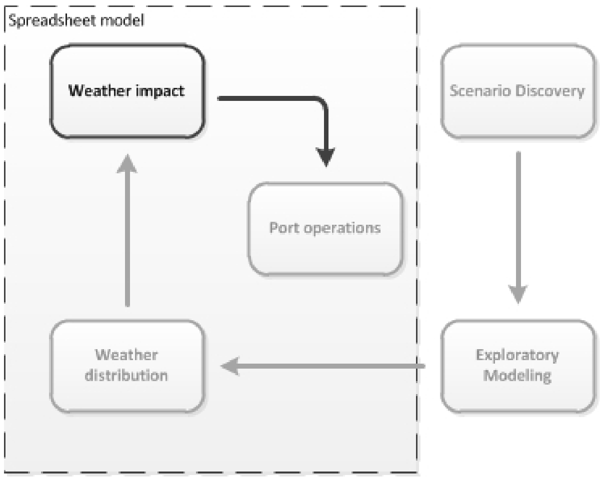

Figure 5.1: The position of chapter 5 in this research. The highlighted box refers to the part of the research that is described in this chapter. The other boxes represent the parts of the research that are already completed in the previous chapters, or need to be done in the coming chapters.

Each weather event specified in this chapter has a specific impact on the performance of the container terminal. This impact directly influences the operational performance of the container terminal.

The first section provides a classification of different types of weather. For every type of weather specified in the first section, a specific section is created. In each of these sections, a brief elaboration on that weather type is provided, along with the weather events that may occur in that weather-type. For every weather type is specified what the operational impact is, and under which conditions the event occurs. This chapter concludes with a section providing a summarized table of weather events and their impacts on the operations of a container terminal.

5.1. Weather events and their impact on container terminals

"Weather is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy." [26]. Ports are being influenced by weather. However, no research has so far been able to quantify all weather influences on container terminals. Although Chhetri et al. [38] and van den Bos [29] did some effort in closing that knowledge gap, most of the impacts are not yet quantified. To describe the influence of weather on the port operations, a list of weather-events is defined. Since container terminals are designed to operate at normal climate, the weather events that deviate from the normal climate negatively influences the container terminal. This list of weather events contains a set of events resulting from wind speed, temperature, precipitation volume, sea level, or a combination of those. Appendix D elaborates further on the full spectrum of the weather as is described by the quote at the beginning of this section. The limitations that the weather-events induce on the system are related to the assets in the ports (i.e. in case of thick mist the visibility is affected for cranes, vehicles etc.).

5.2. Events related to wind

Wind is an important weather variable in container terminals. Terminal operators keep close contact with nearby weather stations and meteo-organizations to receive good predictions on the wind-speed. At low wind speeds the wind doesn't have any impact on the terminal. 7 Different scales of wind speed are used in this report. The weakest that is considered here is a strong breeze, which is from an average wind speed of 10.8 m/s. This is followed by near gale, gale, strong gale, storm, violent storm and eventually hurricane. The last is when average wind speeds top 32,6 m/s. table 5.1 provides a description of every scale considered, as well as the wind-speed along with that scale and the description on which you can recognize the wind speed.

Table 5.1: Wind types used. Adapted from [29]. The first column shows the name of the wind-scale. The second column describes for which wind speeds this scale applies, and the third column provides a description of that scale.

Scale	**Wind speed (m/s)**	**Description**
Gentle breeze	<10.8	A weak wind, if there is wind at all.
Strong breeze	10.8 - 13.8	Large waves begin to form; white foam crests, probably spray
Near gale	13.9-17.7	Sea heaps up and white foam blown in streaks along the direction of the wind
Gale	17.2-20.7	Moderately high waves, crests begin to break into spindrift
Strong gale	20.8-24.4	High waves. Dense foam along the direction of the wind. Crests of waves begin to roll over. Spray may affect visibility
Storm	24.5-28.4	Very high waves with long overhanging crests. The surface of the sea takes a white appearance. The tumbling of the sea becomes heavy and shock like. Visibility affected
Violent storm	28.5-32.6	Exceptionally high waves. The sea is completely covered with long white patches of foam lying in the direction of the wind. Visibility affected
Hurricane	>32.6	The air is filled with foam and spray. Sea completely white with driving spray. Visibility very seriously affected

Vulnerability to wind

The vulnerability to wind in a port is quite straightforward. The higher the windspeed, the higher the potential impact is. This varies basically from no impact at all at a wind speed of 0m/s to structures that are being heavily damaged during hurricanes. To describe the impact of wind on ports, the work of W. van den Bos [29] has been followed. The 8 scales of wind speed mentioned in table 5.1 are in line with the scales used by van den Bos.

Van den Bos argues that wind impacts the container handling in multiple ways. First of all, crane operations are affected by wind, inducing skew and sway movements during operations. This would thus affect the safety of the crane. Also, according to documents from RWG the movement of the cranes is dependent on the wind speed. If the wind is applying more force on the cranes than the engines can, the crane is no longer able to transport over the rail. This would thus affect the operationability of the cranes.

Without malfunctioning engines, the cranes can travel up to wind gust speeds of 28 m/s. With wind gust speeds up to 28m/s, the average wind speed is about 18 m/s. However, if one or more engines fail, the maximum traveling speed is lower. If for instance 4 engines fail, the maximum wind speed at which the crane can move is 12m/s on average [RWG]. Secondly, container movements on the site are influenced, since the stability of the trailers on which containers are transported are subjected to the wind speed. Thirdly, straddle carriers are impacted. Next to that, the berthing of vessels are subjected to the speed of the wind. If wind speed increases, regular lines and wharf bollards are no longer fit for the job. [RWG] Lastly, is the impact on stacked containers. Stacked containers may slide or tilt under the force applied by wind. Although some also consider possible traffic accidents during maneuvering as risks related to wind in ports, they will not be considered in this study. The quantification of the probability that an accident will occur in a port is nearly impossible to relate to climate variables. There are many factors influencing this probability; the geometry of the entrance channel (or even along the coast), the amount of vessels in the channel, the focus of the operators, the visibility, etc.

Wind-events in the model

From the 8 categories of wind that were initially considered, only 5 categories are further considered in this study. These five are:

1. < Strong breeze
   This category contains all wind speeds below 10.8 m/s. According to the interview with RWG (Appendix E, wind speeds below 10.8 m/s are not having any impact on the operations of a container terminal. Therefore, all wind types with lower speed than 10.8 m/s will be considered as 1 category. This category is not having any impact on the terminal.
2. Strong breeze
   Winds between 10.8 m/s and 13.9 m/s are affecting the crane productivity. The interview with RWG indicated that the effect is not directly measurable, as the operators adjust their speed according to their own insights. Therefore, the estimated impact on the crane productivity is a 5% productivity loss.
3. Near gale
   For near gale the same counts as for a strong breeze. There is no data available on the impact, but the operators adjust their speed according to their own insight. For this, we assume that the crane productivity drops with 20% in that case.
4. > Near gale
   For all wind speeds above 17 m/s port operations are terminated. No operations are allowed above this speed. This implies that the productivity of all assets drop to 0% if this event occurs.
5. Hurricane
   In case of a hurricane, the wind speed is still above 17 m/s, and the productivity of all assets are still at 0 percent. However, when a hurricane occurs, damage can also be expected in the terminal. In case of a hurricane, the weather exceeds operational conditions, but rather survival conditions.

Summarized impact of wind

The wind-related events are summarized in table 5.2. The event is mentioned, along with the effects, the impact category and the condition.

Table 5.2: Summarized effects from wind. The first column shows the weather event, the second column provides the effect of that event. The third column then specifies under which conditions the events occur.

Event	Effects	Conditions
< Strong breeze	Crane productivity stays 100%	Wind speed <10.8 m/s
Strong breeze	Crane productivity drops to 95%	Wind speed <13.9 m/s
Near gale	Crane productivity drops to 80%	Wind speed < 17.2 m/s
Near gale >	All assets operate at 0%	Wind speed >17.2 m/s
Hurricane	All assets operate at 0%	Wind speed >32.7 m/s

5.3. Events related to temperature

Dependent on the location on earth, temperature fluctuates around a certain mean. If you come closer to the equator, it is often a bit warmer, and the temperature is more constant throughout the years.

If you deviate from the equator, the average temperature drops, and fluctuations are bigger. In this model, we consider four weather events related to temperature; Heatwave, soft temperatures, frost and extreme cold. This classification is just used in this research, no scientific source is used to support this classification. A description of these events can be found in table 5.3.

Table 5.3: A description of 4 categories of temperature used in this report. The first column shows the event. The second column provides the temperature that corresponds to that event, and the third gives a description.

Event	Temperature	Description
Heatwave	> 38 °C	Very warm temperatures, too hot to exercise.
Soft temperatures	> 0 °C	Temperatures at which humans function best
Frost	< 0 °C	Below 0 °C water starts freezing, and precipitation becomes solid or freezing.
Extreme cold	< -10 °C	In extremes waterways may freeze.

Vulnerability to temperature

In most cases, temperature is not critical for container terminals. There are some cases known, where temperature played a big role (Like Australia [38]). Two events related to temperature are taken into account for further research.

1. Heat wave
   For temperatures above 38 °C employees are no longer allowed to work outside [61][37]. This would result in a productivity loss for all processes where employees work outside. For simplicity, the terminal capacity drops to 0% for every moment the temperature is above 38 °C. Structural damage as a result of a heatwave, as in Australia [37], is not taken into account.

2. Frost
   In case of frost, precipitation turns into frozen precipitation. This directly influences the speed of AGV's according to RWG's document. The speed in this case drops to 3m/s [RWG].

Summarized impact of temperature

The temperature-related events are summarized in table 5.4. The event is mentioned, along with the impact, the impact category and the condition.

Table 5.4: Summarized impact from temperature. The first column shows the weather event The second column shows the effect of that event. The third column shows the conditions under which the events occur.

Event	Effect	Condition
Heat wave	Terminal capacity drops to 0%	Temperature >38°C
Frost	Speed of AGV drops to 3 m/2	Temperature <0°C

5.4. Events related to precipitation

There are many different types of precipitation. Table **??** gives a summary of the most common types.

Table 5.5: Different precipitation types. In the first column, the type of precipitation is mentioned. The second column shows the sub-type. The third column gives a description on that sub-type.

Type	Sub-type	Description
Rain	Drought	Long time without rain
	Drizzle	Light precipitation consisting of drops smaller than rain
	Regular rain	Liquid droplets of water falling down , <7.5mm/h
	Heavy rainfall	7.5-15 mm/12h
	Intense rainfall	15-30 mm/12h [30]
	Extreme rainfall	>30 mm/12h
Freezing precipitation	Freezing drizzle	Super cooled droplets smaller than rain, freeze when hit the ground
	Freezing rain	Super cooled raindrops, freeze when it hits the ground
	Rain and snow	Mixture of snow and freezing rain

Frozen precipitation	Snow	Composition of small ice particles
	Snow grains	Small solid drops <1mm
	Ice pellets	Small solid drops of ice 1-2 mm
	Hail	Solid drops between 5 and 150 mm
	Snow Pellets	2-5mm balls of rime
Fog	Fog	<1000m visibility
	Mist	>1000m visibility

Vulnerability to precipitation

Of all the types of precipitation, only a few are really directly influencing the performance of the container terminal. Initially it was expected that rainfall would influence the visibility in the container terminal. However, the interview with RWG (Appendix E) pointed out that it was not the case at all. They have experienced extreme precipitation in the port of Rotterdam, and they did not at all experience any influence from it. There might be several reasons for that. RWG invested a lot in automation. The vehicles are automatically guided, and are therefore not affected by visibility. The crane operators also operate from the office, instead of from the crane. their visibility is not the visibility from the crane-cabin, but the visibility gained by the different cameras around the cranes and hooks. Visibility is thus not affected by rainfall, nor is it by mist. The impact from precipitation can be described with three events.

1. Extreme rainfall
   As is discussed above, extreme rainfall does not affect the visibility in the port. But, it does affect the conditions of the road. The speed of AGV's is reduced to 6 m/s in case of this event. For all precipitation volumes above this, counts the same.

2. Frozen and freezing precipitation
   In case of frozen precipitation and freezing precipitation the settings of the AGV are also adjusted. At slowdriving settings, the AGV's only proceed at 3m/s. This setting is chosen in any kind of frozen or freezing precipitation.

3. Heavy snowfall
   While the rainfall is not affecting visibility, it is assumed that heavy snowfall does actually affect visibility. Because the particles are much bigger than the raindrops, and the snowflakes can pile up, the operators can adjust the speed of the cranes to their own insights. It is assumed that the speed will reduce to 80% of its maximum speed in case of heavy snowfall.

Summarized impact of precipitation

The precipitation-related events are summarized in table 5.6. The event is mentioned, along with the impact, the impact category and the condition.

Table 5.6: Summarized impact from precipitation. The first column shows the weather event. The second column shows the effect of that event. The third column shows the conditions under which the events occur.

Event	**Effect**	**Condition**
Extreme rainfall	Speed of AGV drops to 6 m/s	Precipitation > 30mm/12h
Frozen precipitation	Speed of AGV drops to 3 m/s	Temperature <0°C and Precipitation >0mm/h
Heavy snowfall	Crane productivity drops to 80%	Precipitation > 3cm/h [17]

5.5. Events related to coastal waters and rivers

The events related to water are less straightforward than the events discussed before. Firstly we consider the height of the water. This is a variable that is a sum of four separate variables. These four might also have separate effects on the performance of the container terminal. Each of them will briefly be elaborated here

1. Wave height
   Wave height is the deviation of the sea as a result of gravitational waves.

2. Tides
   Tides is gravitational influence from the sun and moon, which results in waves with a very low amplitude.

3. Storm surge
   Storm surge is a flood occurred by differences in pressure.

4. Mean sea level
   The mean sea level is the average level of the sea surface. Although this is relatively constant during one year, the general trend seems to point out that sea level is slowly increasing. While effects in 1 year may seem nearly invisible, the average sea level might have risen by 60 cm near the end of this century [48].

Vulnerability to water
By adding up the four variables that are mentioned in previous subsection, we have our first effect; flooding. If the actual height of the water is higher than the height of the quay, the surface of the quay is being flooded. In this case, all operations are halted.

Also, if wave heights are above 1.5 meters, tugboats are no longer able to effectively assist vessels in their maneuver through the canal. In that case, the speed of a tugboat will become 0 m/s.

Summarized impact of water
The water-related events are summarized in table 5.7. The event is mentioned, along with the impact, the impact category and the condition.

Table 5.7: Summarized impact from water. The first column provides the name of the weather event. The second column shows the impact, and the third column describes the conditions under which the event occurs.

Event	Effects	Conditions
Flooding	Terminal capacity drops to 0%	Water level > quay height
High waves	Speed of tugboats drops to 0 m/s	Wave height > 1.5 m/s

5.6. Summary of weather impact

Overall, only a few weather events are having a clear impact on container terminals. The weather events used in this research are either related to wind, temperature, precipitation, water or a combination of those. These are the events that are described in the previous sections. A total list of all events that are taken into account can be find in table 5.8, The event is mentioned, along with the impact, the impact category and the condition under which the event occurs.

Table 5.8: Summarized impact from weather events. The first column shows the name of the weather event. The second column shows the effect of that event on the container terminal. The third column shows the conditions under which these events apply.

Event	Effects	Conditions
< Strong breeze	Crane productivity stays 100%	Wind speed <10.8 m/s
Strong breeze	Crane productivity drops to 95%	Wind speed <13.9 m/s
Near gale	Crane productivity drops to 80%	Wind speed < 17.2 m/s
Near gale >	All assets operate at 0%	Wind speed >17.2 m/s
Hurricane	All assets operate at 0%	Wind speed >32.7 m/s
Heat wave	Terminal capacity drops to 0%	Temperature >38°C
Frost	Speed of AGV drops to 3 m/2	Temperature <0°C
Extreme rainfall	Speed of AGV drops to 6 m/s	Precipitation > 30mm/12h
Frozen precipitation	Speed of AGV drops to 3 m/s	Temperature <0°C and Precipitation >0mm/h
Heavy snowfall	Crane productivity drops to 80%	Precipitation > 3cm/h
Flooding	Terminal capacity drops to 0%	Water level > quay height
High waves	Speed of tugboats drops to 0 m/s	Wave height > 1.5 m/s

6

THE CLIMATE IN MANZANILLO

The next step in this research would be to determine how often the weather events from the previous chapter are occurring. This chapter is dedicated to that goal. Figure 6.1 shows the position of this chapter in this thesis. This chapter fits in the weather distribution topic. This chapter provides a description of how the probability distribution functions of the weather variables from the previous chapter are shaped. With these functions, we can determine how often the weather events from the previous chapter occur. After describing each of the distributions, a section is related to how the distributions are used to determine the occurrence of weather events. The last section offers a summarized overview of the distribution functions.

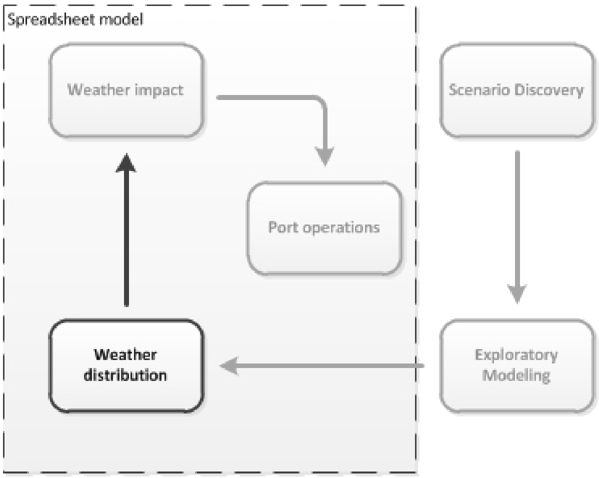

Figure 6.1: The position of chapter 6 in this research. The highlighted box refers to the part of the research that is described in this chapter. The other boxes represent the parts of the research that are already completed in the previous chapters, or need to be done in the coming chapters.

Our interest in determining the probability distributions of weather is to estimate how often the weather-events occurs in a year. For this estimation, the five weather variables mentioned in the previous chapter are used.

1. Wind speed
2. Temperature
3. Precipitation volume
4. Wave height
5. Sea level

These five together describe the occurrence of the weather events. In this chapter, the distribution of each of the variables are discussed. To construct the distribution functions, the dataset from ERA interim is used [8]. This dataset contains a global atmospheric reanalysis from 1979 until this year. The data collected is data related to the port of Manzanillo, Mexico. For more information on the dataset, how the data is downloaded, and how this data then is analyzed, see Appendix G. Each section about a weather variable will first provide the outcomes of the data from the ERA interim dataset, and then provide the distribution function that will be used in this thesis. Note that the probability distribution functions are simplified representations of possible future states. Describing the climate, or making predictions about the weather cannot be accurately done with the functions that are proposed in this research. The goal of this thesis is not to provide accurate predictions about the time at which a container terminal is not longer operating at appropriate levels, but about identifying vulnerabilities. The distribution functions are fit for this purpose.

6.1. Distribution of wind speed

The wind speed data from Manzanillo contains the measured wind speed at 10 meter above surface. The wind variable contains a speed and a direction. The direction of the windspeed is excluded in this model, thus only wind-speeds are presented. Figure 6.2 is the histogram that represents the dataset.The horizontal axis describes the wind speed in meters per second, the vertical axis represents the frequency that the value occurs in the database. As you see here, the average wind-speed is not even 3 meter per second. You might recall that the wind was only impacting the performance of a container terminal from 10.8 m/s. The maximum value occurring in the dataset is 9.1 m/s. This indicates that the terminal so far has never experienced any impact from wind.

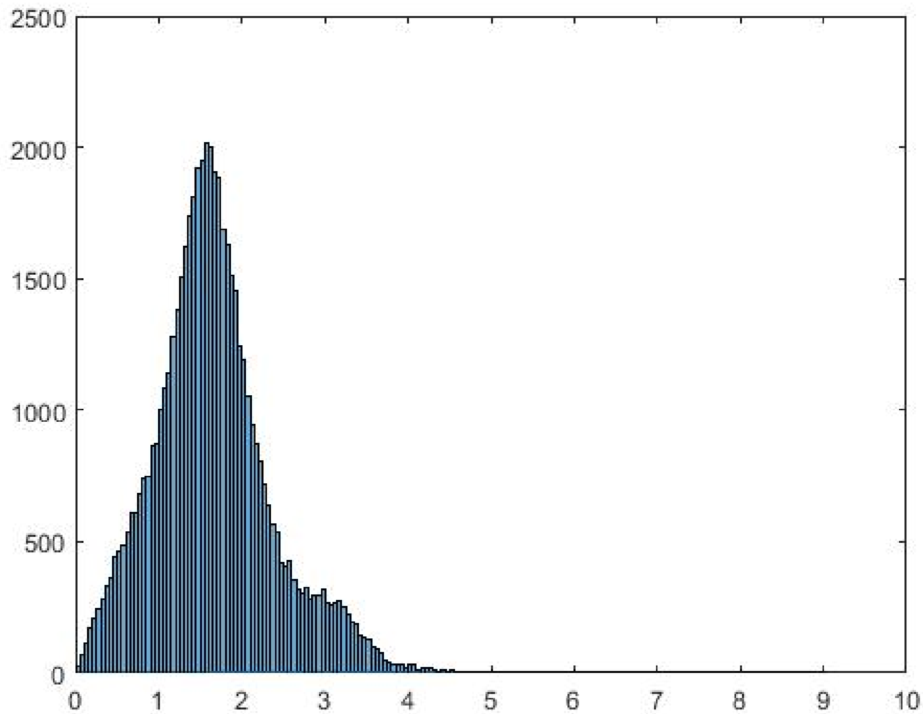

Figure 6.2: A histogram of wind-speed data from Manzanillo in the ERA Interim daily dataset. The Y-axis is the frequency that a value is measured, the x-axis is the wind speed in meter per second.

No distribution function could statistically be derived from the function presented above. Although we cannot validate the use of a function by statistical analysis, some other papers have concluded that weibull distributions would give the best fit for wind-speed probability distributions [58] [55]. When the data is fitted to a weibull distribution, the distribution can be descibed with 2 parameters; a scale parameter, and a shape parameter. The shape parameter would be 2,3544, and the scale parameter 1,8747. The new defined distribution is presented in figure 6.3.

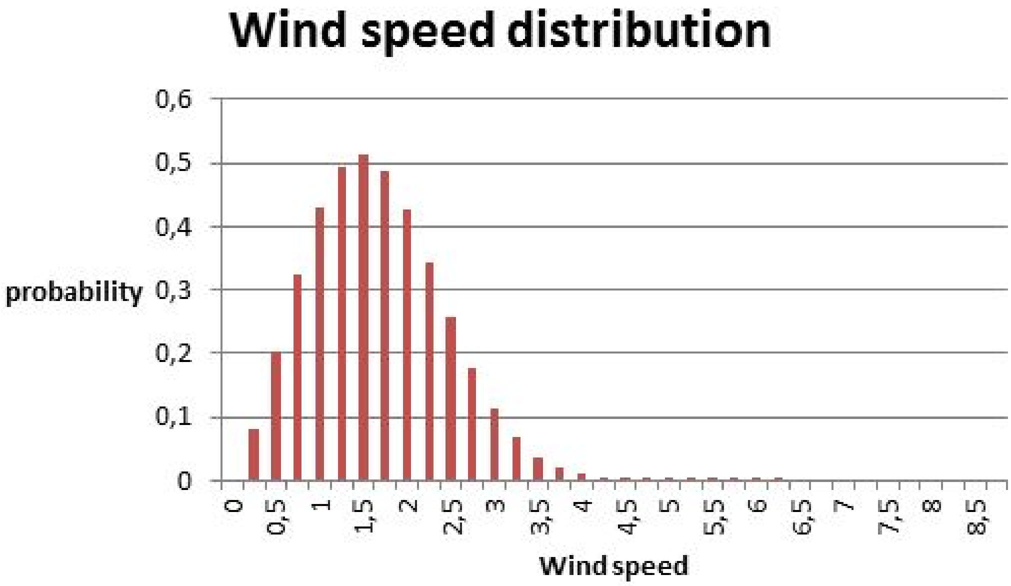

Figure 6.3: The distribution of wind-speed in Manzanillo, represented by a weibull distribution. The y-axis shows the probability, the x-axis shows the wind-speed in meter per second.

6.2. Distribution of temperature

The temperature data used for Manzanillo is measured at 2 meter above the surface (figure 6.4). Note that the data is presented in Kelvin, and not in Celsius or Fahrenheit. The mean is approximately 296 Kelvin, or 23 degrees Celsius. The minimum recorded temperature is 278 degrees Kelvin, which is approximately 5 degrees Celsius. The maximum temperature in the dataset is 308 Kelvin, or 35 degrees Celsius. Just like with the wind-speed, these values are quite beneficial for the terminal operations. None of the defined temperature-related weather event occurs under these conditions.

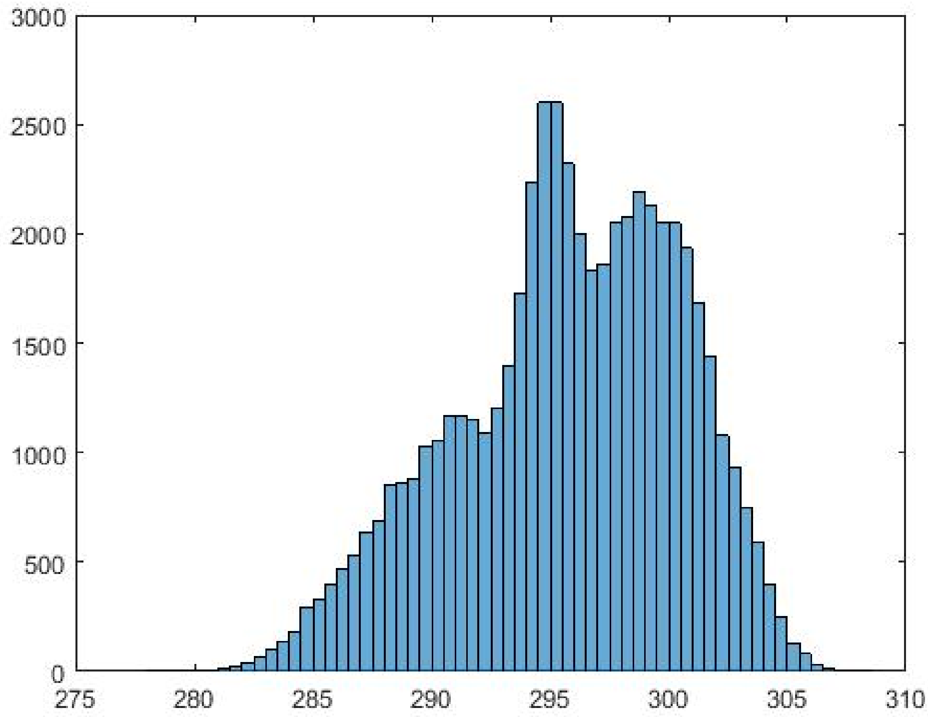

Figure 6.4: A histogram of the temperature data from Manzanillo, ontained from ERA Interim. The Y-axis is the frequency that a value is measured, the x-axis is the Temperature in Kelvin.

Again, no distribution function could be statistically derived from this dataset. Therefore, weibull is again chosen to describe the probability distribution of temperature. The scale parameter would then become 298,0099, and the shape parameter 72,4099. Figure 6.5 shows the weibull function created with these parameters. Note that his graph is showing the values in Celsius, compared to Kelvin in the previous histogram.

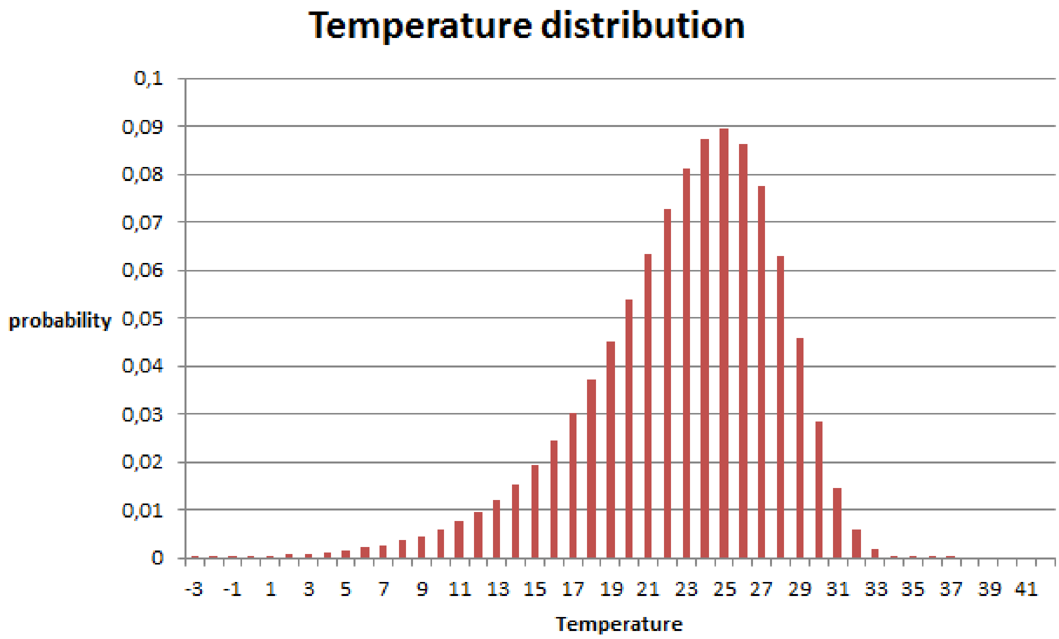

Figure 6.5: The weibull distribution used to represent the Temperature in Manzanillo. On the y-axis the probability is shown, on the x-axis the temperature in degrees Celsius

6.3. Distribution of precipitation volume

The precipitation volumes has been measured as meters of precipitation per 12 hours. The maximum precipitation since 1979 in the database was 0,0532 meter in twelve hours. This is more than the threshold value for extreme rainfall, frozen precipitation and heavy snowfall. This thus implies that the port may have already experienced any negative effects from weather events. The average precipitation volume over all datapoints is 0,00017m/12 hours, which is 1,7 mm in 12 hours. Figure 6.6 shows the precipitation data from Manzanillo in a histogram. As you can see, there is a huge amount of datapoints at approximately 0 meter per 12 hours. Actually, the rest of the data isn't really visible. As it doesn't rain every day, most of the data will indeed be stacked around this value.

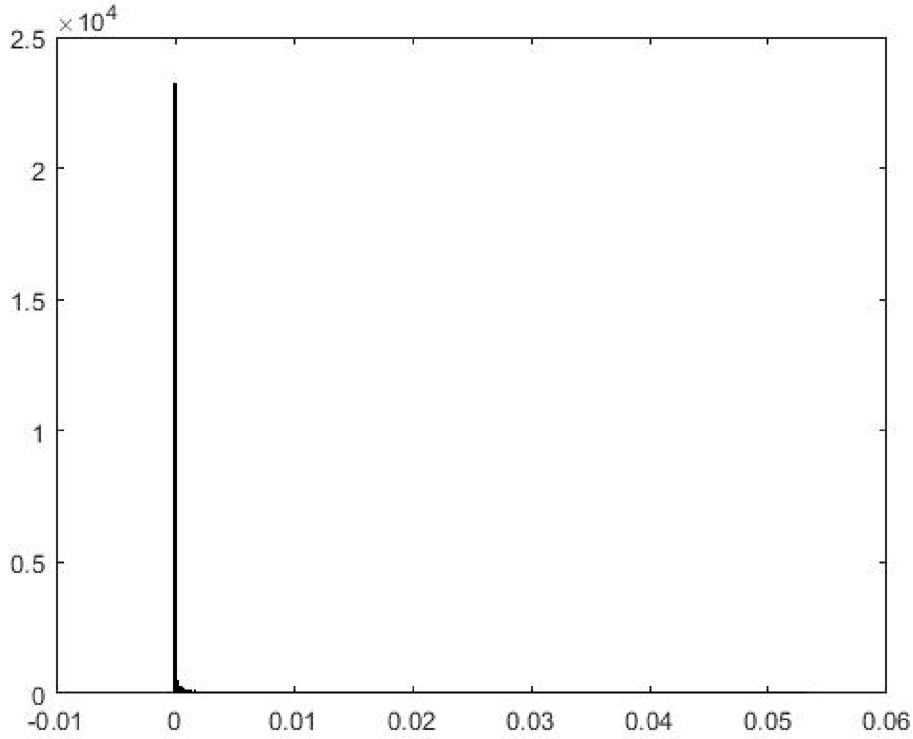

Figure 6.6: The precipitation data from Manzanillo, The y-axis represents the number of measurements, the x-axis shows the precipitation in meters/12 hours

The visual of the data already indicates that a weibull distribution might not be fit for describing precipitation patterns. The gamma distribution as described by Wilks [52] is used by many authors for the distribution of precipitation [67]. When the obtained data is fitted to a gamma-distribution, a shape parameter is set at 0,034 and scale parameter is set at 0,005. This distribution is presented in figure 6.7. Note that the scale used is slightly different from the one in figure 6.6.

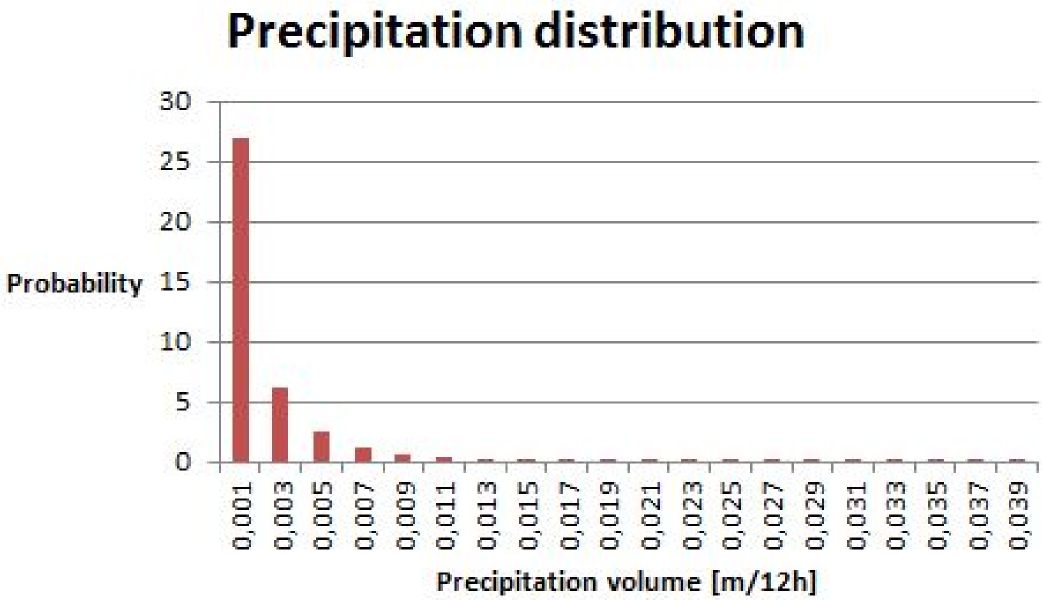

Figure 6.7: Gamma distribution for precipitation in Manzanillo. The y-axis shows the probability, while the x-axis shows the precipitation volume in meter per 12 hours

6.4. Distribution of wave height

Under waves height we consider 'the significant height of combined wind waves and swell'. For Manzanillo, the maximum wave height was 4,6 meter, and the minimum 0,7 meter. the average wave height is slightly above 1,5 meter. This would indicate that tugboats are not able to transfer ships through the canal. However, there are some notes that have to be made about this data. Firstly, the data is somewhat out of the coast. The wave-height changes when you move closer to the coastline. There is no conversion factor used to estimate the wave-height in the terminal. Also, there are breakwaters, which reduce the height of the wave in the terminal. This implies that the data that is used for the wave height is not accurate for the port of Manzanillo. However, this is the best data available. Figure 6.8 provides the histogram of the retrieved data set.

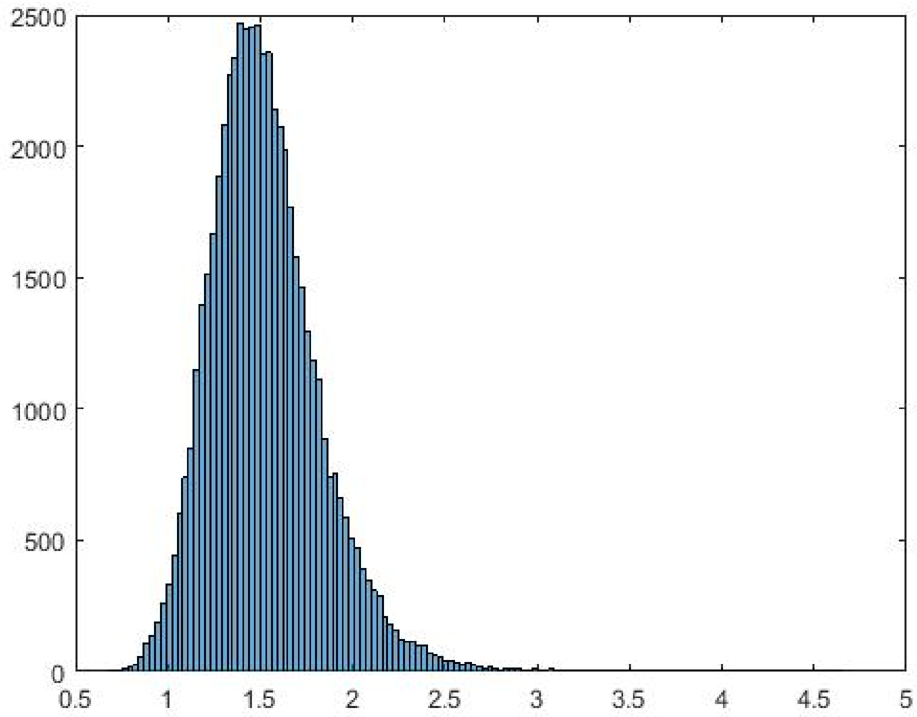

Figure 6.8: Histogram of wave-height just off-shore at Manzanillo. The y-axis represents the number of measurements, the x-axis shows the wave-height in meters.

Two probability distributions have been widely used to describe the probability of significant wave height. These two are the log-normal distribution and again, the Weibull distribution. Battjes, [32], Mathiesen[54] and Ferreira [45] all indicate that weibull fits the distribution of wave height well. Thus, another Weibull distribution is used. This time for describing the significant wave height, just off-shore from Manzanillo. The shape parameter for the distribution is equal to 4,8171, while the scale parameter is equal to 1650,2. These parameters describe the Weibull distribution as presented in figure 6.9. Note again that the scale is a bit different from the one used in the figure 6.8.

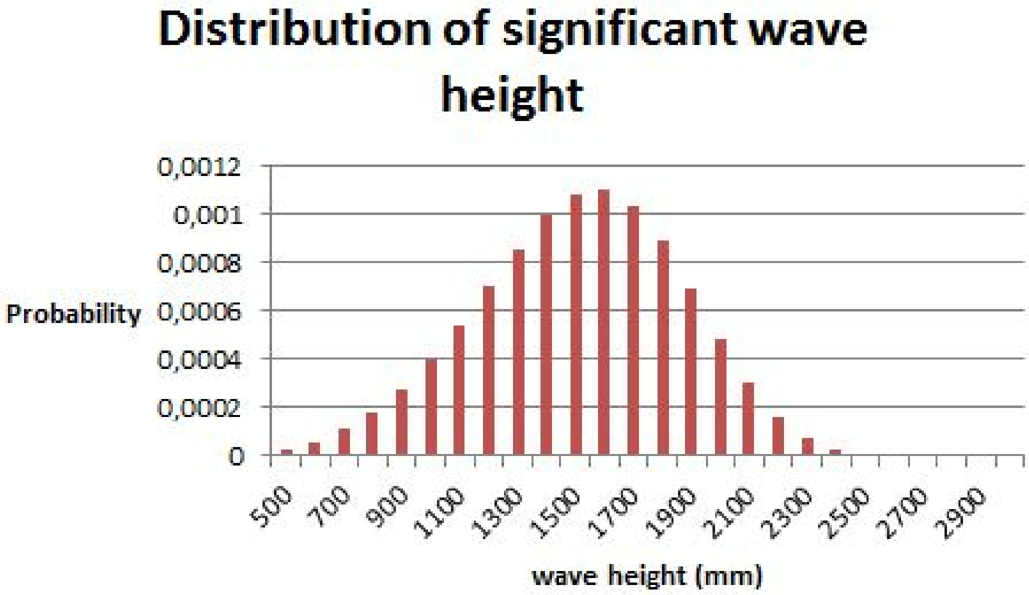

Figure 6.9: Weibull distribution of wave-height just off-shore at Manzanillo. The y-axis represents the probability of measurements, the x-axis shows the wave-height in millimeters.

6.5. Distribution of (mean) sea level

Since ERA Interim has not stored data related to the sea level, the distribution of sea level is constructed with help of another database. This data comes from the Sea Level Center of the University of Hawaii [25]. The water level is defined as the 'sea surface height above reference level'. This data does not include the waves, which are discussed in the previous section. All tides are however included. As you can see in figure 6.10, the sea level in Manzanillo is typically between 3 meters and 5 meters. The maximum sea level in the dataset is 4923 mm, the minimum 3005 and the mean is 3918 mm.

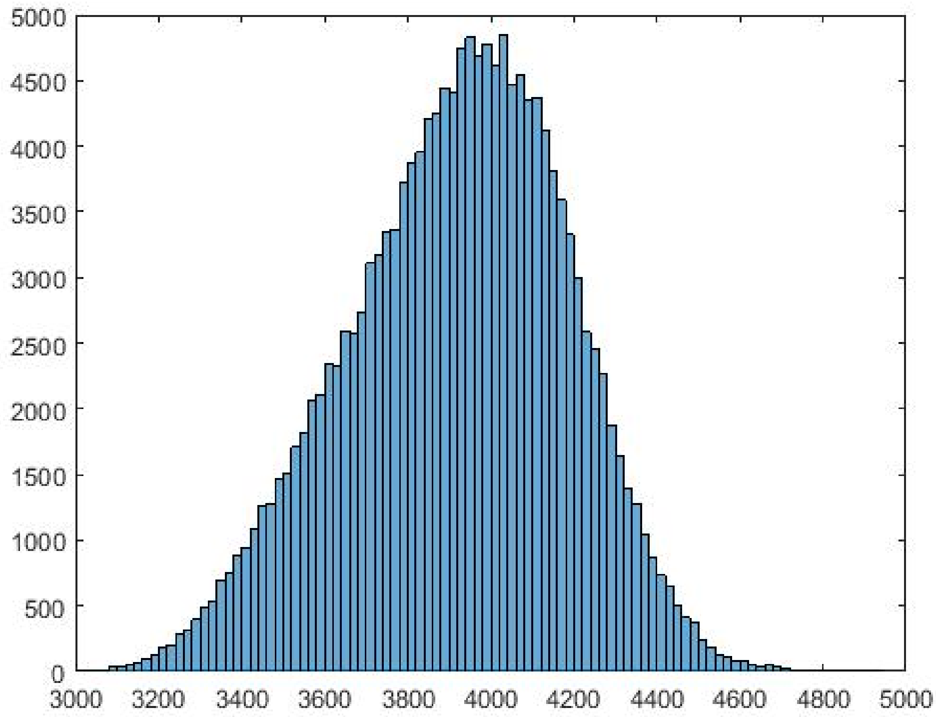

Figure 6.10: Sealevel in the port of Manzanillo. The y-axis represents the number of measurements, the x-axis shows the sealevel in millimeters.

But, on top of this, still come the waves. By adding the data of wave height and sealevel together, it is possible to see which height the waves reach in relation to the reference level. For this combined function -the one which contains wave height as well as sealevel- another Weibull function is used. The shape parameter is 12,8, the scale parameter 5693,9. Figure 6.11 represents the weibull function with these parameters. You see that the sealevel is rarely above 7 meters. The height of the quay is approximately 11 meter [20]. Thus, currently also the sealevel is not such a threat to operations.

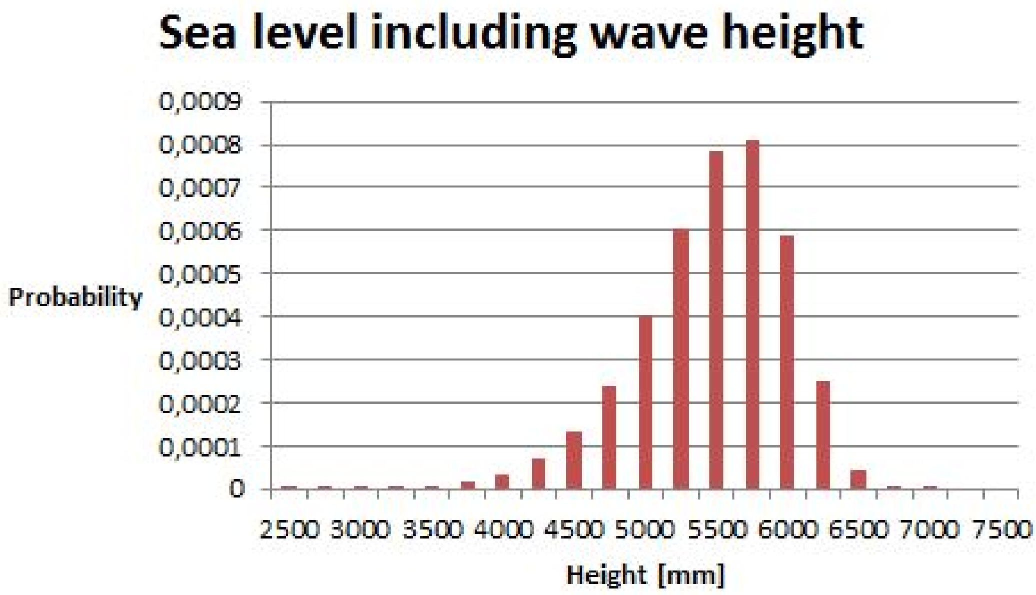

Figure 6.11: The weibull function representing sealevel included with wave height in Manzanillo. The y-axis represents the probability, the x-axis shows the height of the water in millimeters.

6.6. How distribution functions are used to determine weather events

The distribution functions are used to describe how often each of the weather events occur. The distribution functions are not used to determine as stochastic values. Instead, the functions are used to describe the expected value for each of the weather events. Consider the example from figure 6.12.

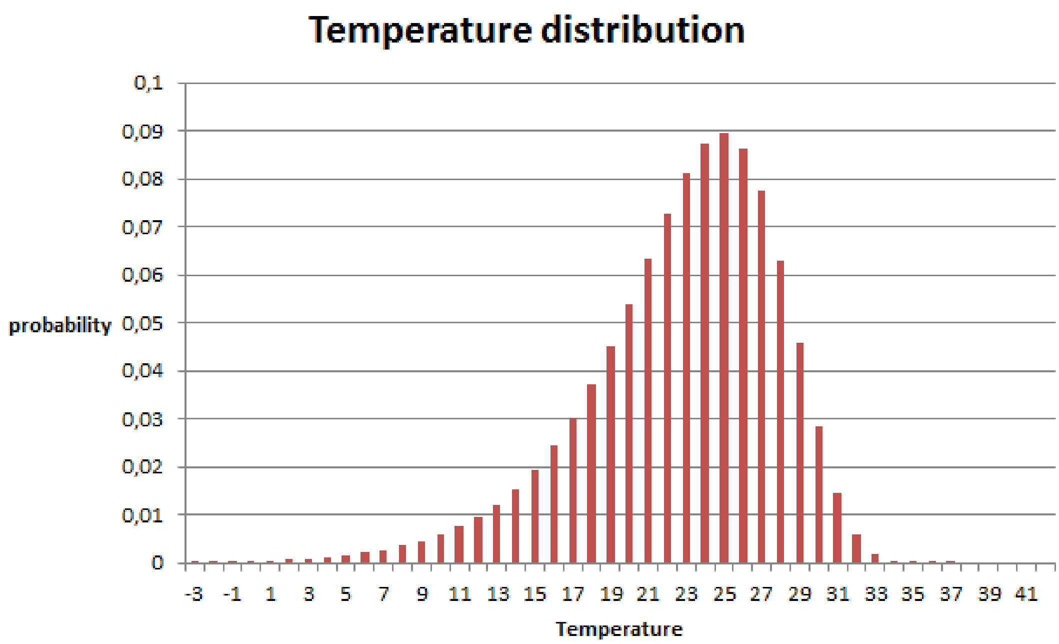

Figure 6.12: The weibull distribution used to represent the Temperature in Manzanillo. On the y-axis the probability is shown, on the x-axis the temperature in degrees Celsius

The figure above shows the distribution function of Temperature. Considering that there are 8760 hours in a year (24*365), we can distribute 8760 hours of time over this function by multiplying the probability to the total amount of hours. If we use the cumulative distribution, and multiply the probability with 8760 hours, figure 6.13 is the outcome.

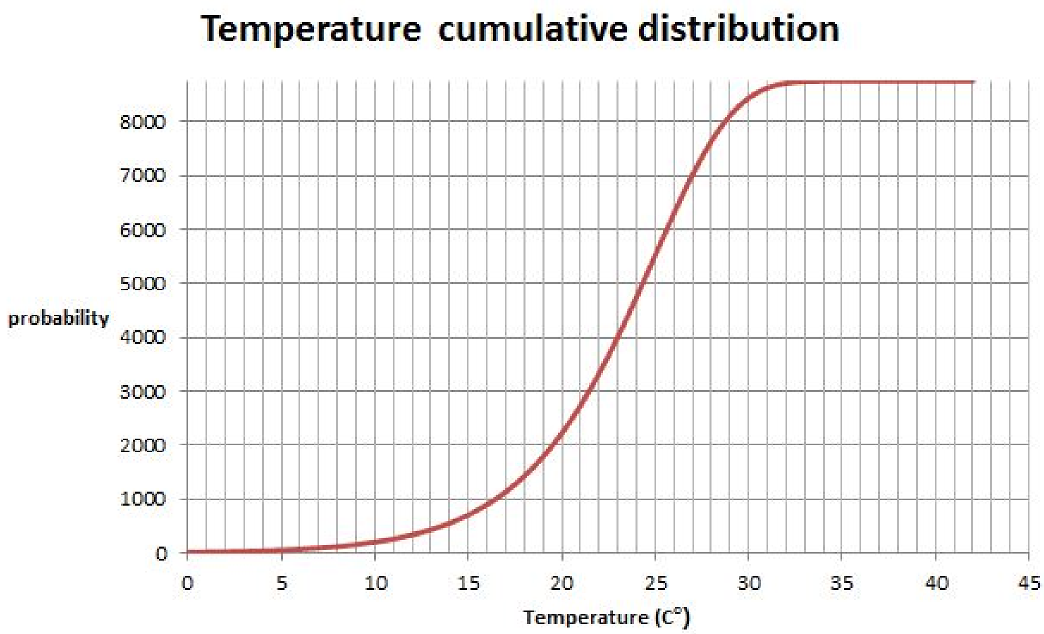

Figure 6.13: The weibull distribution used to represent the Temperature in Manzanillo. On the y-axis the probability is shown, on the x-axis the temperature in degrees Celsius

From this figure, we can conclude that approximately 4000 hours per year the temperature is expected to be lower than 23 degrees Celsius. Although it is nearly invisible on this scale, the number of hours that the temperature is below 0 degrees Celsius, is 15. Thus, in this model, there will be 15 hours of frost in this case. Through this method, the expected hours that every event will occur in a year will be determined.

6.7. Summarized distribution functions for weather variables

So, all of the distributions have been described. The distributions per variable are summarized in table 6.1 along with the used parameters. These parameters , along with a parameter that still needs to be introduced will be used in the next section, which elaborates on how the scenario discovery is performed.

Table 6.1: Weather distribution functions. The first column shows the name of the weather variable. The second column provides the type of probability distribution. The third column shows the value for the shape parameter, and the fourth column provides the value of the scale parameter.

Weather variable	Distribution	Shape parameter	Scale parameter
Wind speed	Weibull	2,3544	1,8747
Temperature	Weibull	72,4099	298,0099
Precipitation volume	Gamma	0,034	0,005
Wave height	Weibull	4,8171	1650,2
Sealevel	Weibull	12,8	5693,9

7

EXPERIMENTAL SETUP

In this chapter, the settings that are used to define the experiments are presented. To run the experiments, Exploratory Modeling Analysis (EMA) is used. This tool is used to compute many different climate scenarios. Three different experiments are executed. First, one to represent the container terminal in Manzanillo under normal climate change. As a proof of concept, two other experiments has been performed too. The second experiment is the container terminal in Manzanillo under extreme climate change. The last one is a fictitious case, under normal climate change conditions.

This chapter provides the values that has been used to represent each of the cases, as well as the uncertainty space that has been used to represent the climate change. Also, a section is dedicated to the threshold values that have been used to define when a container terminal is under performing. Then, a section provides a discussion on the number of runs for each experiment. Lastly, a concluding section is provided.

7.1. Initial settings of the case

As mentioned before, three different experiments are performed in this research. Two of them, are related to the container terminal in Manzanillo, while one is a fictitious case. This section shows the initial values that have been used to represent all three of the cases. Table 7.1 shows the values for the two experiments related to Manzanillo, and the experiment related to the fictitious location.

Table 7.1: Initial settings of the model

Parameter	Manzanillo	Fictitious		Parameter	Manzanillo	Fictitious
Waiting Time	1h	1h		Number of vehicles	40	40
Distance to Berth	1,5km	1,5km		Initial transport time per container	6min	6min
Initial speed of tugboats	3km/h	3km/h		wind speed shape	2,3544	2,3544
Average containers per ship	10000 TEU	10000 TEU		wind speed scale	5,7	8,1
Container supply	400000 TEU/year	400000 TEU/year		Temperature shape	72,4099	72,4099
Length of berthing facility	800m	800m		Temperature scale	280	306
Length of vessel	150m	150m		Waveheight shape	4,8171	4,8171
Berth occupancy ratio	0,8	0,8		Waveheight scale	1650,2	1650,2
Operational hours	8760h	8760h		Sealevel shape	12,8	12,8
Number of ground slots	2000	4000		Sealevel scale	7100	8100
Height of stack	3TEU	3TEU		Mean sea level	0	0
Average dwell times	5days	5days		Precipitation shape	0,034	0,034
Number of cranes	5	2		Precipitation scale	0,009	0,002
Initial crane productivity	30TEU/hour	30TEU/hour				

7.2. Uncertainty space

Ten parameters have been used to describe the uncertainty space. All of the climate scenario lie within this uncertainty space. These parameters have already been introduced. They are the scale and shape parameters related to the weibull and gamma functions that described the temperature, precipitation, sea level and wind speed.

For the description of scenario, we assume that weather is changing, due to a change in the parameters describing the distribution functions. This is not the first research where change in weather is described as a change in distribution functions [67]. ”*Increasing either parameter increases the frequency of absolute extremes (e.g. the probability of x exceeding a given threshold) and the threshold for a given percentile (e.g. the lower bound for the top 5% of events)*”[67]. Thus, both the shape and the scale parameter influence the frequency of extremes. This study makes use of scenario discovery by changing 10 parameters in a period from 2016 to 2100.

Thus: We have 10 parameters, which change from their initial state in 2016 to a bigger or smaller state in 2100. The bandwidths of these parameters are needed to determine the conditions for the scenario discovery. Table 7.2 shows the ten parameters, and the minimum and maximum the parameter can change in the scenario discovery. The minimum and maximum values that are indicated, represent what we call the growth-factor in the model. A change of 0,002 indicates that the parameter might change with a factor between 1,0 and 1,002 in the next year. Thus, if the the parameter is 100 in year 1, and the change is 0,001 (on average), the value for year 2 is 100,1.

Table 7.2: The parameters that are subjected to change in the model. The first column shows the name of the parameter, the second shows the value that was recovered from the ERA-Interim databse. The third column provides the minimum change rate, and the fourth column provides the maximum change rate.

	Normal climate change		Extreme climate change	
Parameter	**Minimum change**	**Maximum change**	**Minimum change**	**Maximum change**
Wind speed shape	-0,002	0,002	-0,002	0,002
Wind speed scale	-0,01	0,03	-0,01	0,03
Temperature shape	-0,002	0,002	-0,002	0,002
Temperature scale	-0,0005	0,0005	-0,001	0,003
Waveheight shape	-0,002	0,002	-0,002	0,002
Waveheight scale	-0,01	0,03	-0,01	0,03
Sealevel shape	-0,002	0,002	-0,002	0,002
Sealevel scale	-0,001	0,003	-0,001	-0,003
Mean sealevel change	-0,001	0,005	-0,001	0,005
Precipitation shape	-0,002	0,002	-0,002	0,002
Precipitation scale	-0,01	0,03	-0,01	0,03

As we mentioned before, we expect the distribution functions to change. With other words, the shape and scale parameters will change in the future. The software picks a value between the minimum and maximum, which is the growth rate of the parameter. For 2016, the original value is still used. The parameter used for 2017 is then the original value, times (1+random*growth rate). The random indicates a random number between 0 and 1, from a uniform scale.

So for instance, the wind speed scale growth rate is set at 0,01. The scale parameter for 2016 would be 1,8747. For 2017 the scale parameter could be 1,8747*(1+0,4*0,01)=1,8821. 2018, could then be 1,8821*(1+0,8*0,01)= 1,8972. This continues until 2100, for all parameters but the mean sealevel.

The mean sealevel is based on data from the National Oceanic and Atmospheric Administration [13]. According to them, the sealevel at Manzanillo is growing with 3.18+/- 2.17 mm per year.

Insert other excel table here

7.3. Vulnerability of container terminals

To indicate when a container terminal is under performing, the three key performance indicators are used. Level of service, terminal capacity and terminal utilization are all monitored. The terminal utilization is bad when it reaches 1, since that means that 100 % of the terminal's capacity is being used. In order words, there would be no margin for delay anymore, nor can the port grow. Note that the berth occupancy rate is included in the utilization. If the occupancy rate is increased, the utilization will decrease.

The threshold value for the terminal capacity is not as straightforward as the utilization. To determine the threshold, we should know when a certain capacity is no longer beneficial or unacceptable to exploit. There does not seems to be a rule of thumb for that. The desired capacity is dependent on the supply, which in turn is dependent on the competitiveness of the region. So,the assumed threshold value is at 80 % of the original capacity. In this case, that would be 350400 TEU/year.

The last performance indicator is the level of service. The level of service determines the competitiveness of the terminal, assuming that prices in competing terminals are about equal. In the UNCTAD AD HOC meeting they indicated that all container terminals with a productivity below 65 TEU per hour receive less than an A-status [53]. Thus, the level of service should be at least 65 TEU per hour to perform well.

Any scenario in which the utilization is 1, the capacity is below 350400 TEU, or the level of service is under 65 TEU per hour, the port is under performing. The combination of weather variables in these scenarios indicate for which weather variables the container terminal is vulnerable.

7.4. Number of runs for experiment

While doing scenario discovery, the software should be able to pick random samples, over 10 different parameters. Since the sample-space is 10-dimensional, there should be sufficient runs to cover all sorts of combinations between the ten parameters.

To make sure that the range of different scenarios is sufficient, a sample size of 10.000 runs has been selected. This selection is made based on two arguments. The first argument is related to run-time, while the second is related to changes in the mean outcome of the experiment.

Mean changes in outcome

To determine the number of runs for an experiment, we look at the mean outcome over the number of runs. When too few runs are selected, the number of runs may not represent the entire field of future states of the climate. In figure 7.1 the mean capacity over the sample size is presented. Up to approximately 2000 runs, the mean is still unstable. After that, adding more runs does not have a big effect on the mean capacity. Thus, according to this, if the number of runs is above 2000, it should be sufficient.

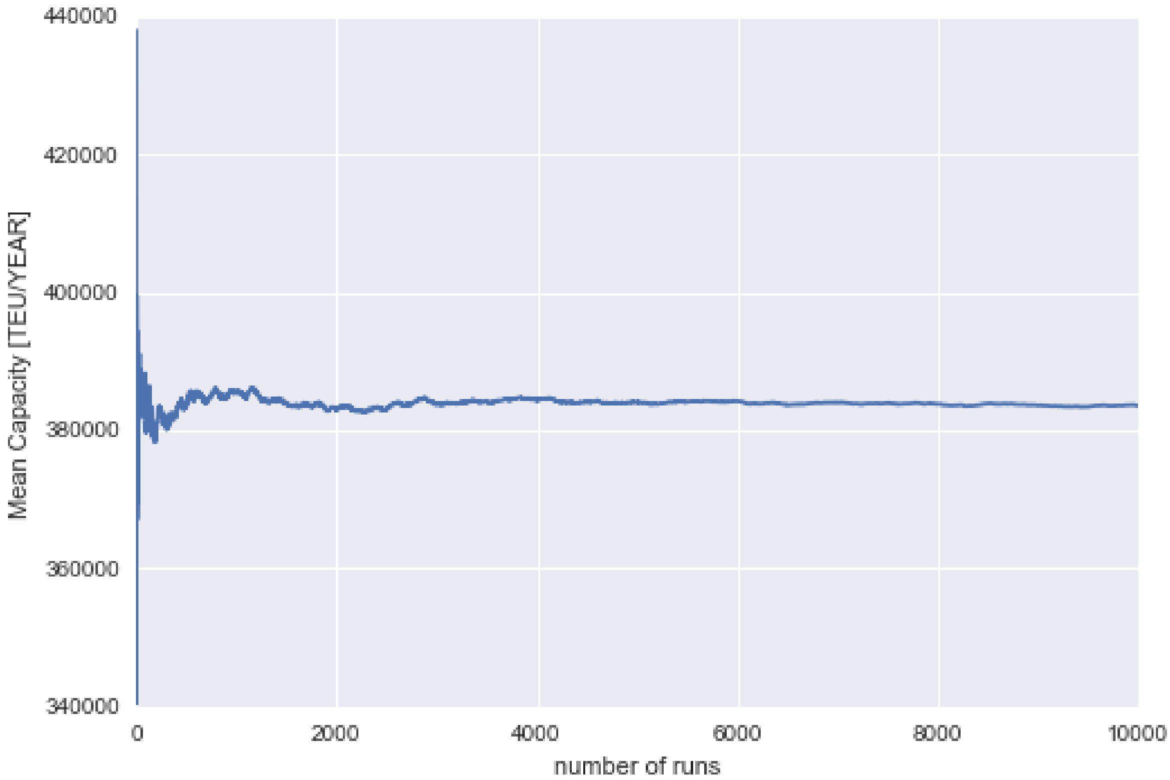

Figure 7.1: Mean capacity over the number of runs. On the Y-axis is the capacity, on the X-axis the number of runs.

However, since the runtime of the experiment with 2000 runs is still very short (3 minutes), 3 minutes of time for running one experiment is not constraining this research. If we use a runtime of 15 minutes, the model is able to make approximately 10.000 runs. Since having a bigger size can only improve the quality of the data, we use 10.000 runs as standard for the experiments.

8

RESULTS

By running the model with the bandwidth of climate change scenarios that were indicated in the previous chapter, a large set of results is generated, which in turn can be analyzed to determine vulnerabilities to climate change. This chapter shows the results from three case studies. Figure 8.1 shows the position of this chapter in this research. With all previous chapters the model can be run. The results from these runs can be analyzed with the Patient Rule Induction Method (PRIM).

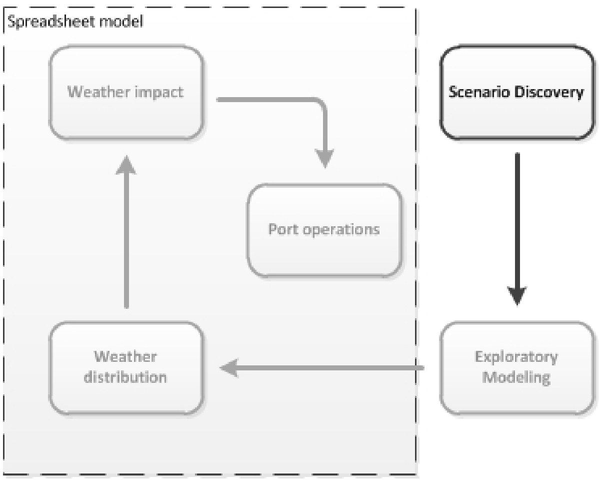

Figure 8.1: The position of chapter 8 in this research. The highlighted box refers to the part of the research that is described in this chapter. The other boxes represent the parts of the research that are already completed in the previous chapters.

The first section covers the performance of the container terminal when the initial state of the model is used. The second section offers an interpretation of results for three different situations: Manzanillo under normal climate change, Manzanillo under extreme climate change, and a fictitious case under normal climate change. In the third section, the PRIM analysis is described, as are the outcomes of this analysis. The last section draws some conclusions from the analyses that are performed.

8.1. Initial state of the port of Manzanillo

The case in Manzanillo is semi-fictitious; the weather-data of the Manzanillo case is used, but not the real characteristics of the container terminals. The values that are presented here do not represent the performance of any of the existing terminals in Manzanillo. At the initial settings of the model, we use the following design variables for the case.

- Waiting time: 1 hour
- Distance to berth: 1,5 km

- Initial speed of tugboats: 3 km/hour
- Average containers per ship: 10.000 TEU
- Container supply: 400.000 TEU/year
- Length of berthing facility: 800 meter
- Average length of vessel: 150 meter
- Gap between vessels: 20 meter
- Berth occupancy ratio: 0,8
- Operational hours: 8760 hours/year
- Number of ground slots: 2000
- Height of the stack: 3
- Average dwell time: 5 days
- Number of cranes: 5
- Initial crane productivity: 30 TEU/ hour
- Number of vehicles: 40
- Initial transport time per container: 6 minutes

The parameters that describe the weather are:

Table 8.1: Ten parameters that describe the distribution of weather

Parameter	**Value**	**Parameter**	**Value**
Wind speed shape	2,3544	Wind speed scale	1,8747
Temperature shape	72,4099	Temperature scale	298,0099
Wave height shape	4,8171	Wave height scale	1650,2
Sealevel shape	12,8	Sealevel scale	5693,9
precipitation shape	0,034	Precipitation scale	0,005

If we then take a look at the weather events, we conclude the following: The wind is under 10.8 meter per second for the entire year. There is thus no negative impact from wind on the container terminal. Furthermore, there is no moment in that year where the sealevel exceeds the height of the quay. There is thus not flooding. For 4658 hours, the wave height exceeds the 1.5 meter threshold. This would imply that the speed of tugboats is reduced. Concerning temperature; the temperature is some seconds above 38 degrees Celsius, and about 15 hours beneath 0 degrees Celsius. The heatwave is not impacting the terminal due to it's low duration. Frost only has a negative effect whenever the frost is combined with precipitation. This event only occurs for about 2 hours. Lastly, the heavy precipitation occurs approximately 82 hours in 2016.

Thus, overall the terminal is not experiencing a lot of weather events in 2016, and those events that do occur, do not have a devastating impact on the terminal. The three key performance indicators are calculated as:

- Level of service: 145,4866
- Terminal capacity: 438000
- Terminal utilization: 0,913242

The key performance indicators are suggesting that the container terminal should be performing well this year.

8.2. Interpretation of results

The outcomes of three different settings is presented here. The first one represents the port of Manzanillo, under normal climate-change predictions. Since the results of that run were not that enlightening, another run is performed on Manzanillo, this time with more extreme, hypothetical parameters, for illustrative purposes. The third run relates to another fictional container terminal, which is located in a less mild climate.

8.2.1. Manzanillo under normal climate change

By running the model that represents Manzanillo, with normal climate change parameters, figures 8.2, 8.3 and 8.4 are produced. They represent the level of service, the terminal capacity and the terminal utilization.

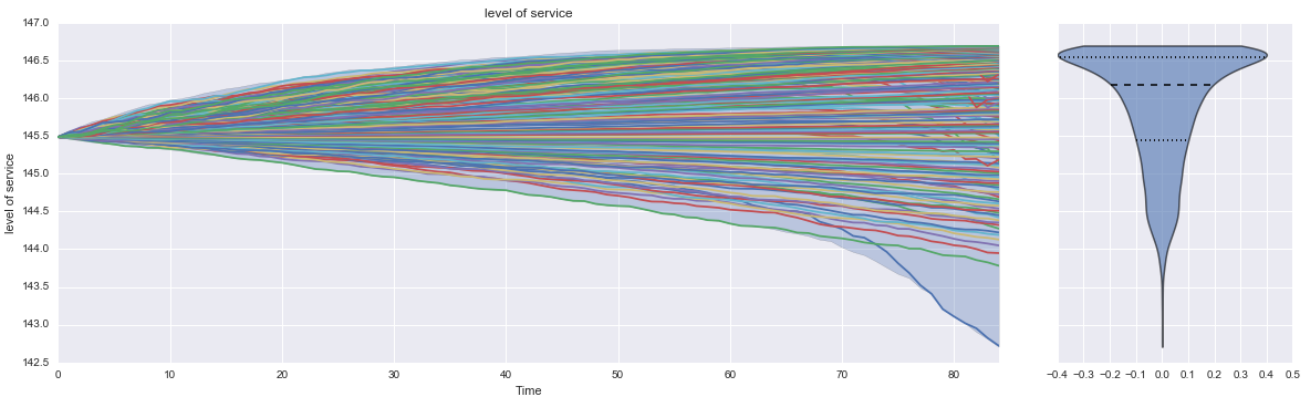

Figure 8.2: The level of service for normal climate change in Manzanillo. On the y-axis: the level of service. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

In figure 8.2 the level of service is always above 142.5. The threshold would be 65 before the terminal's level of service is no longer satisfying. This implies that the level of service will always be satisfying under these conditions. Some interpretations can be made in respect to this figure.

1. **The probability density**
   The rights plot represents the probability that a certain outcome will be reached. Most of the outcomes will reach a level of service which is higher than the initial level of service. Also note the sudden halt in the probability density function above 146.5. This is an indication that this is the absolute maximum of the system. In that setting, the terminal will not be influenced at all by the weather.

2. **The growing level of service**
   The level of service can grow when wave conditions in the port are improving. As the wave-height was the only weather event that was occurring in the terminal, this explains the growth of level of service. Note however that there are some remarks on the quality of the wave-data.

3. **The declining level of service**
   A decline in level of service is possible when wave-conditions are worsening. If waves are becoming higher, or high waves are becoming more frequent, the effect from waves is increasing, and thus the level of service declines.

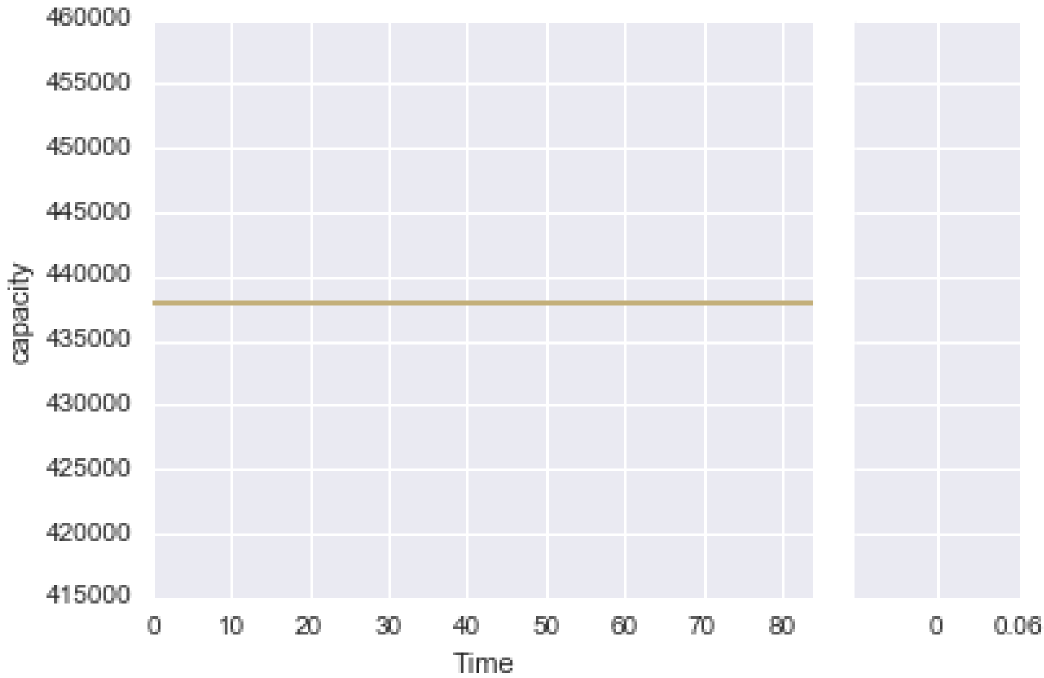

Figure 8.3: The capacity for normal climate change in Manzanillo. On the y-axis: the capacity in TEU per year. On the x-axis: the time in years from 2016.

The capacity that is shown in figure 8.3 is constant over the entire period. None of the runs resulted in a change in capacity.

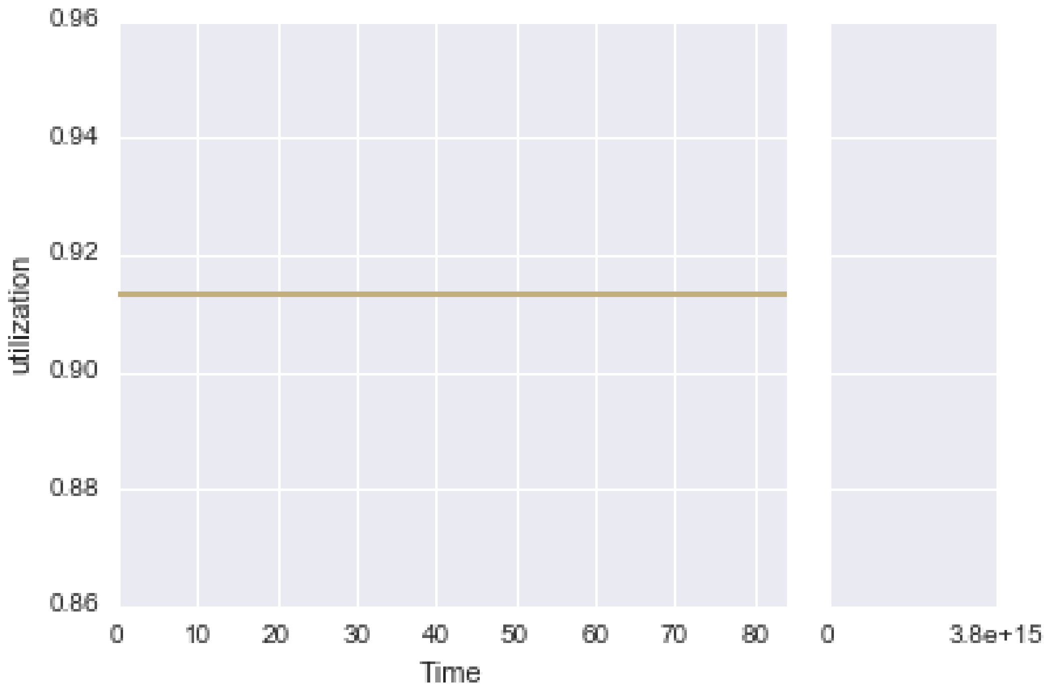

Figure 8.4: The utilization for normal climate change in Manzanillo. On the y-axis: the utilization per year. On the x-axis: the time in years from 2016

The presented utilization in figure 8.4 shows the same behavior as the capacity from figure 8.3. From these three graphs, we can conclude that the performance of the terminal is unaffected by the change in climate. We knew up front that the climate for the container terminal was favorable. As a proof of concept, two other experiments will be performed. The next subsection shows the results for Manzanillo with extreme climate change. The subsection thereafter shows the results from a new case, which has a less favorable initial climate, and some of the characteristics of the terminal are tweaked.

8.2.2. Manzanillo under extreme temperature change

To show the behavior of the system when it is heavily affected by climate change, extreme growth of some of the distribution parameters is used. For this case, the potential growth of the temperature scale parameter is adjusted. Instead of a value between -0,0005 and 0,0005 we now use a value between -0,001 and 0,003.

Figure 8.5 shows the results in level of service, figure Y the results in terminal capacity, and figure Z the results in terminal utilization. The interpretation of the outcomes is provided immediately after the figures.

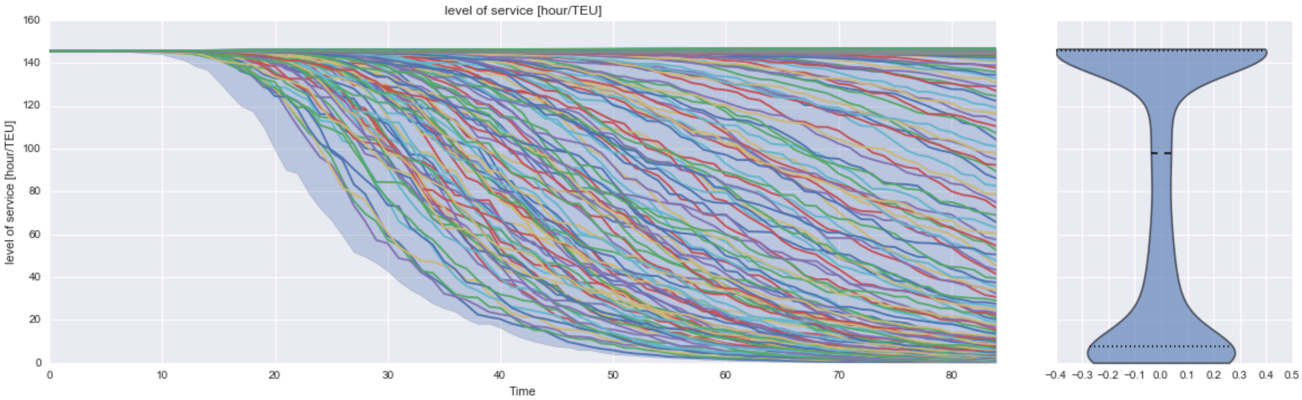

Figure 8.5: The level of service for extreme climate change in Manzanillo. On the y-axis: the level of service per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

The first key performance indicator is the level of service, an indicator that represented the interests of the shipping companies. The left side of the image shows the entire field of results, which is highlighted in blue. In that blue field, some random results are plotted. These are the colored lines in the blue area. The right side of the image, is called a violin plot(although i would rather call it a hourglass plot in this case). The violin plot is a probability distribution, visualizing the probability that the outcome of an experiment will reach a certain result. As you can see here, most of the results are either a high level of service, or a very low one.

From this first graph related to the level of service, already some insights can be distilled.

1. **Probability density**
   The probability density that is shown in the violin plot indicates that most of the outcomes lay close to the original level of service, or close to 0. This would imply that the level of service from the container terminal in most cases is either very much affected by the weather, or nearly not affected.

2. **Slope of the functions**
   The slope of the level of service differs quite a lot. There are situations where the level of service drops very rapidly, and situations where the level of service declines slowly. The level of service is dependent on the unloading capacity. These two different slopes are related to whether the decline is influenced by temperature or wind.

3. **Moment of decline**
   It takes more than 11 year before the influence of the most extreme scenarios start to become visible with this definition of the level of service. Thus, according to this model, and this definition, it would take at least ten years before the climate becomes less suitable.

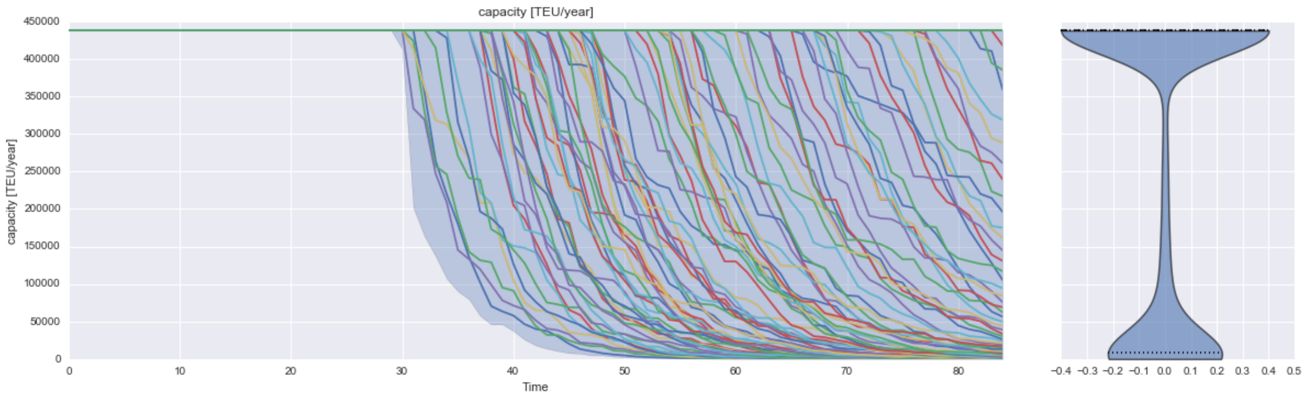

Figure 8.6: The capacity for extreme climate change in Manzanillo. On the y-axis: the capacity in TEU per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

Figure 8.6 shows the solution space of the terminal capacity. There are three characteristics that are notable. Each of them is elaborated upon.

1. **Slope of the functions**
   Just like was the case with the level of service, once the decline starts, the capacity keeps declining until it eventually approaches 0. It is striking to see that the slope is rather steep. This indicates that a year's change made a huge difference. For that reason, it is very unlikely that this decline is resulted by wind speed. If wind speed was increasing, we would first see a slow decline, which becomes steeper if wind was further increasing.

2. **Probability density of the outcomes.**
   Similar to the situation with level of service, the density of the outcomes is mostly biased around a capacity that is either close to the initial value, or close to 0. In between that, the density is much lower. The amount of results that are close to the initial value can be explained by situations that are not cause by the increase in temperature. If the temperature is staying constant, and wind speed is steadily increasing, this would result in values which are closer to the initial value of the capacity.

3. **Decline only occurs after year 25.**
   The last notable item is that any change in the capacity only occurs after approximately 25 years. This indicates that even with very big changes in weather, it still takes quite some time before the terminal is affected by the weather. This indicates that the current climate is rather prosperous for the terminal. There are other locations where the weather is already affecting the operations. However, the terminal capacity was defined as the minimum of the storage capacity and the quay capacity. As the initial quay capacity is approximately ten times higher than the storage capacity, the decline in the capacity might only become visible from the moment the quay capacity drops below the storage capacity.

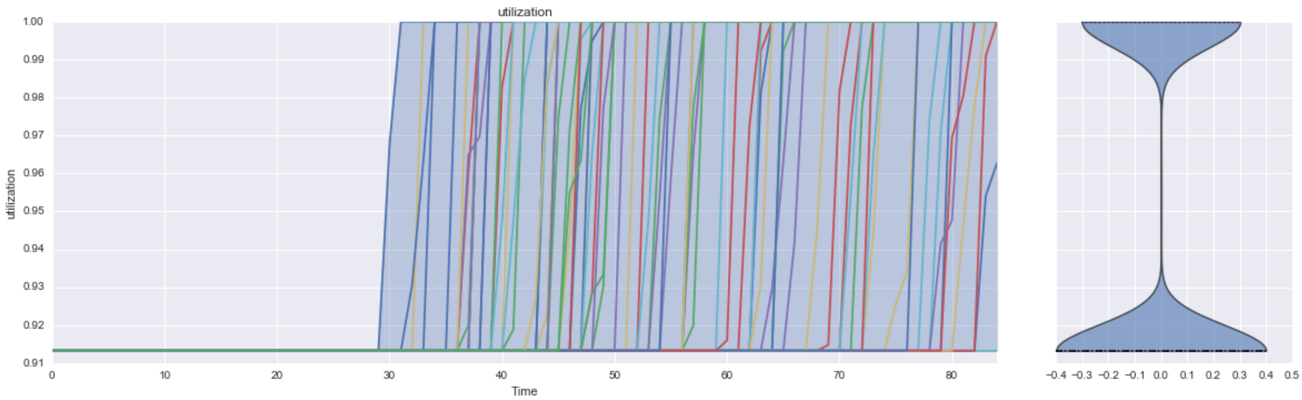

Figure 8.7: The utilization for extreme climate change in Manzanillo. On the y-axis: the utilization per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

The last of the three key performance indicators is the terminal utilization. As the utilization is defined as the used capacity over the maximum capacity, it is very much dependent on demand and supply functions. These are however not included in this model yet. Some of the behavior of this indicator is described in the next bullets.

1. **Steepness of the slope**
   It strikes immediately that the slope of the utilization is extremely steep. In most cases, it seems to be nearly vertical. To understand this behavior, we need to refer to the definition that is used for the utilization, and then especially, to the definitions of maximum capacity and used capacity. The used capacity is the capacity that is currently used. The maximum capacity, is would it could potentially use in relation to these weather variables. If the supply of containers is as big as the maximum capacity, or bigger than the maximum capacity, the utilization becomes 1. The terminal uses its full potential in this situation. As the initial utilization is already very high (over 91 %!!), a relatively small decline in capacity would already result in a big change in utilization. Also, as mentioned in the elaboration on the previous picture, the capacity drops when the crane capacity is lower than the storage capacity. Therefore it takes quite a while before any change in utilization becomes visible.

2. **Distribution of density**
   Just as with the previous two key performance indicators, the violin plot indicates that most of the results are either near the initial utilization, or near 1. Note also that the probability in between these two situations is very small. This is related to the steepness of the slope.

The results from all of the three key performance indicators behave as expected. The steep decline in capacity and utilization might be adjusted if the minimum and maximum values that the parameters may take become smaller.

8.2.3. Another fictional case under normal climate change

The last situation that is simulated is a terminal that looks a bit like the one that is used for Manzanillo. Some small changes are made, to highlight some of the results. The previous two experiments have shown that the effect on capacity is cloaked since the capacity is defined as the minimum of the crane capacity and the storage capacity. The initial crane capacity is a tenfold higher than the storage capacity. Thus, crane capacity can drop by 90 percent before the model notices it. Thus: This model contains 4000 ground slots compared to 2000 in Manzanillo, and 2 cranes compared to 5 in Manzanillo. The initial crane capacity is now just twice as big as the storage capacity. The changes in the model are presented in table 8.2.

Table 8.2: Changes in the settings of the model

Parameter	Old situation	New situation
Number of ground slots	2000	4000
Number of cranes	5	2
Wind speed scale	1,8747	8,1
Temperature scale	298,0099	306
Sealevel scale	5693,9	8100
Precipitation scale	0,005	0,002

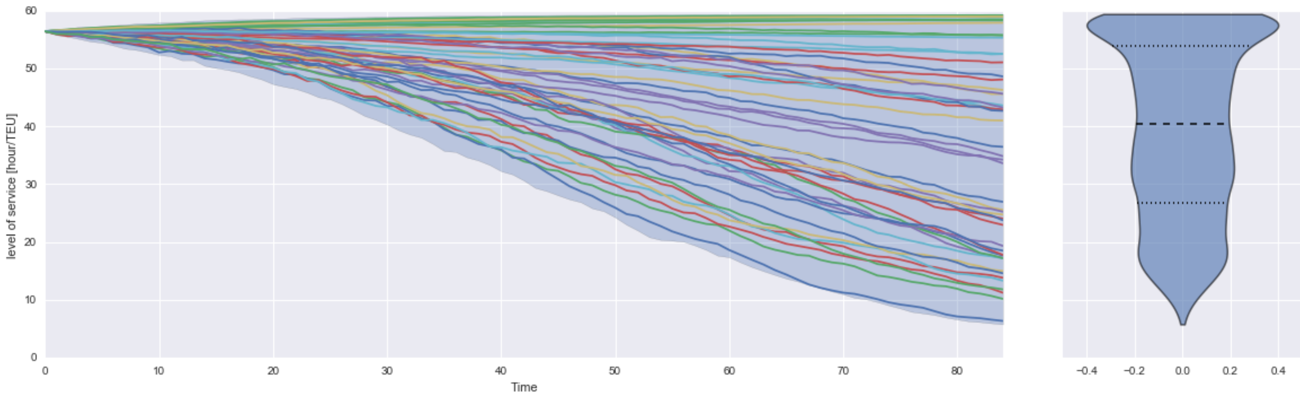

Figure 8.8: The level of service for normal climate change on a fictional location. On the y-axis: the level of service per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

Figure 8.8 shows the outcomes of the model for the fictional port in a less favorable climate. On the right of the graph the violin-plot (more like a nail-plot now) is presented. Note that the initial value of the level of service is already way lower than the level of service that we saw in the previous cases. This is due to the lower amount of cranes used. Due to this, the vessels remain longer in the terminal.Let's further discuss the remarks on this graph with some notes again.

1. **Density of the function**
   The density of the outcomes differ quite a lot from what we saw in the previous cases. As half of the runs resulted in a lower level of service than 41, most of the scenarios result in a lower performance of the container terminal. However, there also seem to be quite a bunch of runs that resulted in a higher level of service than the initial state. As the density function is flat at the top in stead of a sharp point, these values might have reached the absolute maximum level of service that the terminal can reach given these parameters.

2. **Bigger level of service**
   There are still quite some runs that resulted in a level of service that was higher than the original state. This indicates that the climate has become more favorable in these cases. This was expected, for the parameters were chosen such, that they could also result in lower wind-speeds, temperature, precipitation volume or sealevel in the future.

3. **Slope of the function**
   As we see, the level of service does not reach 0 in any of the scenarios. The slope of the plots is not very steep. In other words; it takes quite some time before level of service drops. This gives time to start implementing mitigation actions.

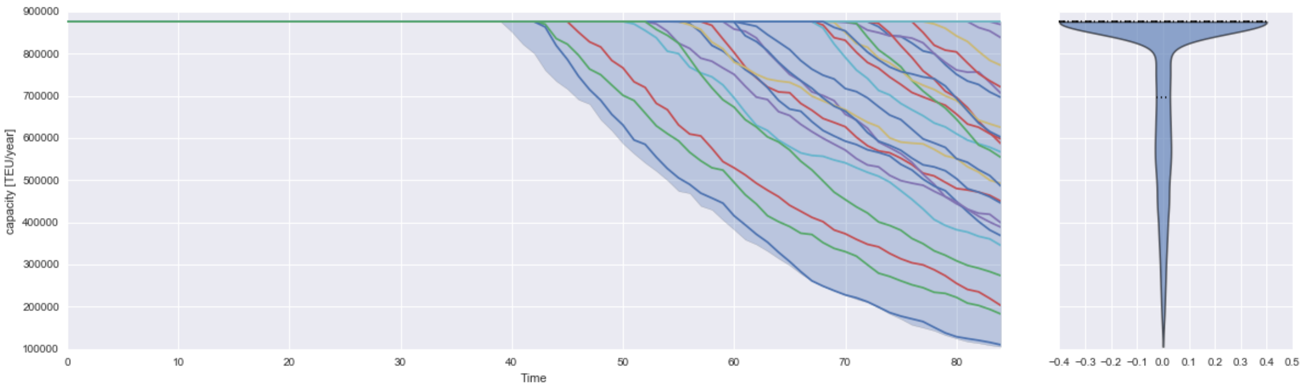

Figure 8.9: The capacity for normal climate change on a fictional location. On the y-axis: the capacity in TEU per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

The capacity of the terminal is shown in figure 8.9. There is a lot of remarkable behavior to be seen in these plots.

1. **Density plot**
   Firstly the density. This plot looks like a nail again. The flat top indicates that an absolute maximum is present. Due to the definition of the terminal capacity, this is indeed the case. The theoretical maximum is dependent on the storage capacity. This capacity is not influenced by the weather. As long as the storage capacity is smaller than the crane capacity, the storage will set the terminal capacity. Remarkably, More than 75% of all the scenarios result in a capacity above 850.000 TEU/year in 2100.

2. **Decline from T = 35**
   As we see, *if* the capacity drops, it will happen from T = 35 on, and not sooner than that. In the worst climate scenarios that were applied, the effects in capacity will thus only be visible from 2051 on.

3. **Slope of the plots**
   In contrary to what we have seen with the level of service, is that in every scenario where the capacity drops, the decline is quite steep. Although the gap between the storage capacity and the crane capacity is reduced in this setting, it is still visible that the crane capacity is already rapidly declining way before it is visible in the terminal capacity.

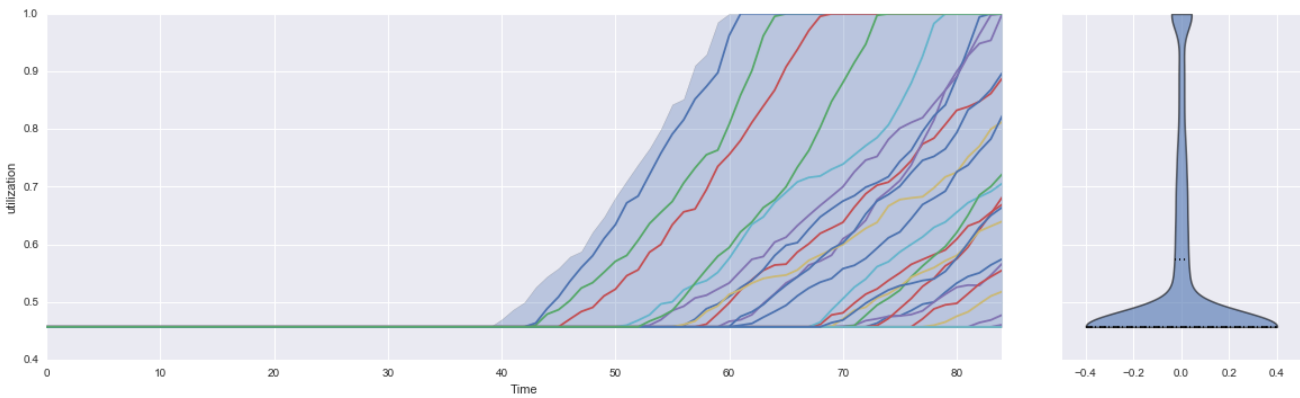

Figure 8.10: The utilization for normal climate change on a fictional location. On the y-axis: the utilization per year. On the x-axis: the time in years from 2016. Every colored line is one random run. The plot on the right is a probability density function of the outcomes, including the upper 75%, 50% and 25%.

The terminal utilization for the fictitious case presented in figure 8.10 is the last overview of plots to present. On first sight the utilization looks very similar to the plot in figure 8.9, only mirrored. Some points are highlighted again.

1. **Similarity to capacity in figure 8.9**
   No only the plots itself, but also the density plot looks strikingly similar to the capacity plots. This makes sense, for the utilization is the used capacity/max capacity. The used capacity is related to the supply, which is constant. The only influence in this function is thus the current capacity.

2. **Lower utilization than previous cases**
   The starting utilization is lower than the utilization that we have seen in the previous cases. Because the settings for this terminal were slightly different, while the supply remained the same, the ratio between capacity and supply changed.

8.3. PRIM Analysis

To identify the vulnerabilities in a container terminal, the Patient Rule Induction Method (PRIM) is used. For those not familiar with the PRIM analysis, consider the following box.

The PRIM analysis selects a box in the parameter's uncertainty space (which is 10 dimensional in this case), and then computes two values; the density and the coverage. Both of these values are related to the threshold value. For this experiment there are two threshold values: Terminal capacity: 700800 TEU/year and Level of service: 50.

- **Density**
  The density is the ratio between the outcomes of the runs that is below the threshold, over the outcomes that are higher than the thresholds. Thus, if the experiments that are conducted within a specific box of parameters all result in a capacity lower than 700800 TEU/year, the density would be 1. If half of the outcomes in that box of parameters would be lower than the threshold, the value would be 0,5.

- **Coverage**
  The coverage only considers the values that are below the threshold value. The coverage is the amount of runs within that box of parameters that is below the threshold value, divided by the total amount of runs that resulted in a value below the threshold. Thus, if all of the outcomes that were lower than the threshold were in the same box of parameters, the coverage would be 1. On the other hand, if only 10 out of 100 outcomes lower than the threshold originates from the same box of parameters, the coverage would be 0,1.

Both the density and the coverage of each box is relevant for this study. The higher the density, the higher the likelihood that the container terminal's performance is affected in these climate scenarios. Thus: A high density implies that if the climate change is following the trends of that specific box, the container terminal has a big chance that it's performance will be too low in 2100. The higher the coverage, the higher the amount of critical scenarios covered by this box. Thus: If the coverage of the box is high, this means that scenarios outside this box will likely *not* result in a bad performing container terminal.

Two PRIM analyses are conducted. One analysis for the terminal capacity, and one for the level of service.

8.3.1. PRIM analysis terminal capacity

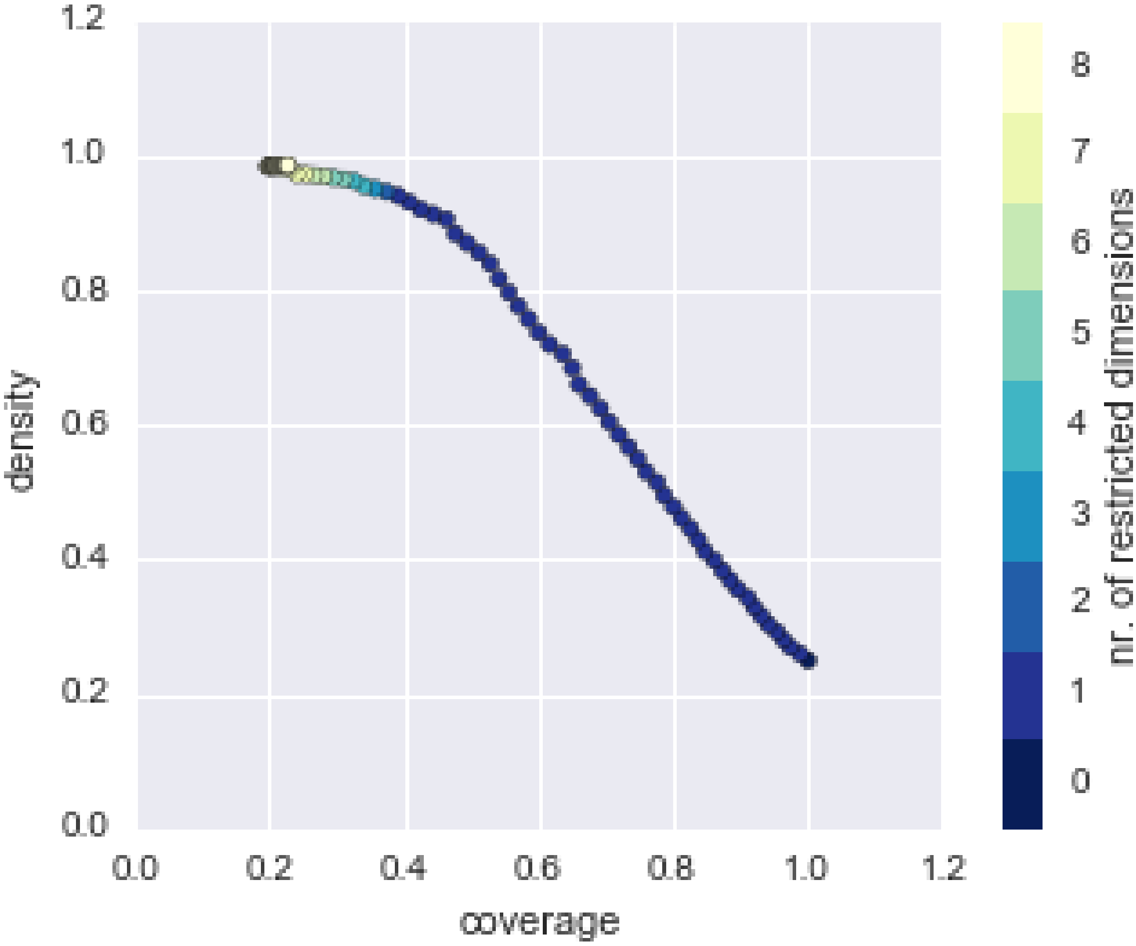

Figure 8.11: Results of PRIM analysis related to the terminal capacity. Each circle in the figure represents one box constructed by the PRIM-analysis. on the right, the legend is shown which indicates the amount of dimensions that are used to describe each box.

Figure 8.11 provides an overview of a set of 96 boxes that can be used to describe the vulnerability of container terminals to some of the weather variables. We see that the boxes vary from a density of nearly 1 and a coverage of 0,2 to a density of 0,25 and a coverage of nearly 1. At the high-density area, we see some boxes which contain 8 variables, like box 96. However, this box has a low coverage, while some boxes with 1 or 2 variables also have a density of over 90. The coverage for these cases lies around 0,4. We zoom in on two specific boxes; 8 (figure 8.13), and 96(figure 8.12).

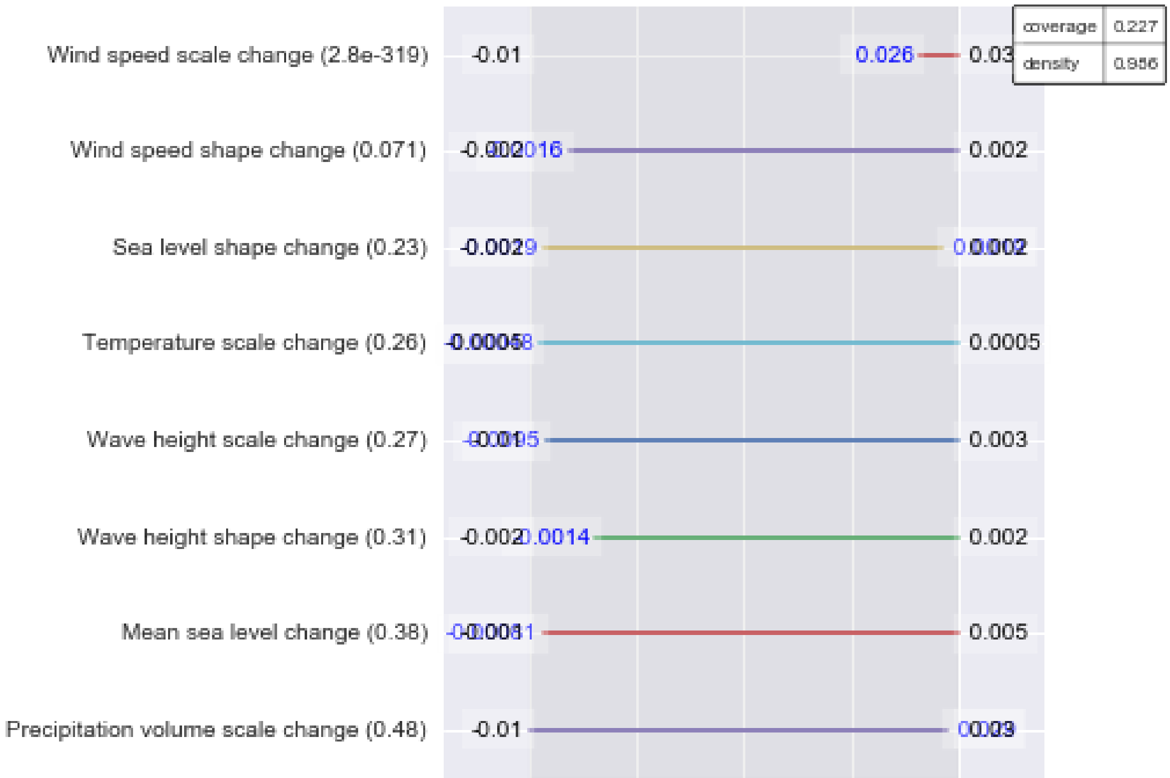

Figure 8.12: The shape of box 96 of the PRIM analysis of capacity. On the left, the different variables that set the shape of the box are mentioned. The lines and numbers in the graph shows what the range of that variable is in the box. on the top right, the density and coverage of this box are shown.

Figure 8.12 shows the shape of box 96. As you can see, the box is 8 dimensional. Most of the variables are however not significant. Only wind speed scale change is significant for this box. Since the box is basically defined by wind speed scale change only, this also explains why a reduction in parameters does not have a big effect on the density. The coverage of this box is 0,227, while the density is 0,955.

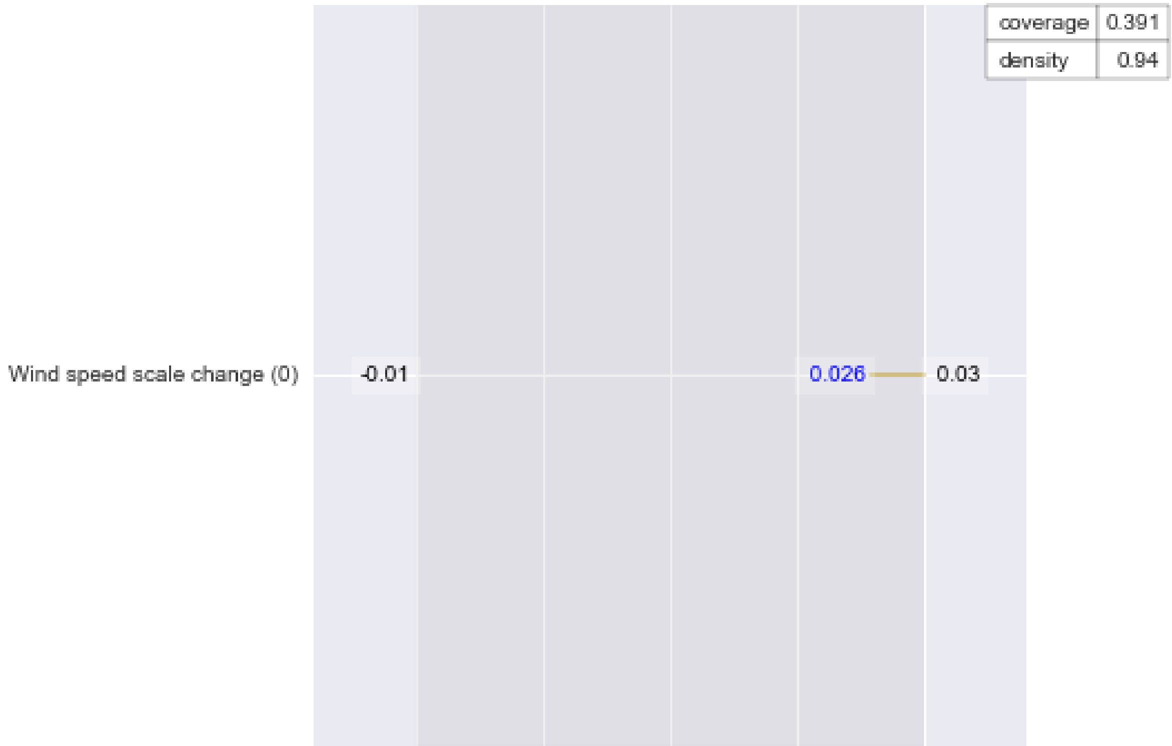

Figure 8.13: The shape of box 8 of the PRIM analysis of capacity. On the left, the variable that set the shape of the box is mentioned. The line and numbers in the graph show what the range of that variable is in the box. on the top right, the density and coverage of this box are shown.

This box of parameters is just 1 dimensional, and is defined by wind speed scale change. For all of the cases with a wind speed scale change between 0,02584 and 0,03, approximately 94% is resulting in a capacity below the threshold. However, only 40 per cent of all the cases that are under this threshold are originating from this box. All the other boxes with 1 variable are still the wind speed scale change. By increasing the bandwidth of this parameter, the coverage is of obviously increasing. We can conclude that for the terminal capacity, the terminal is most vulnerable to a changing windspeed.

8.3.2. PRIM analysis level of service

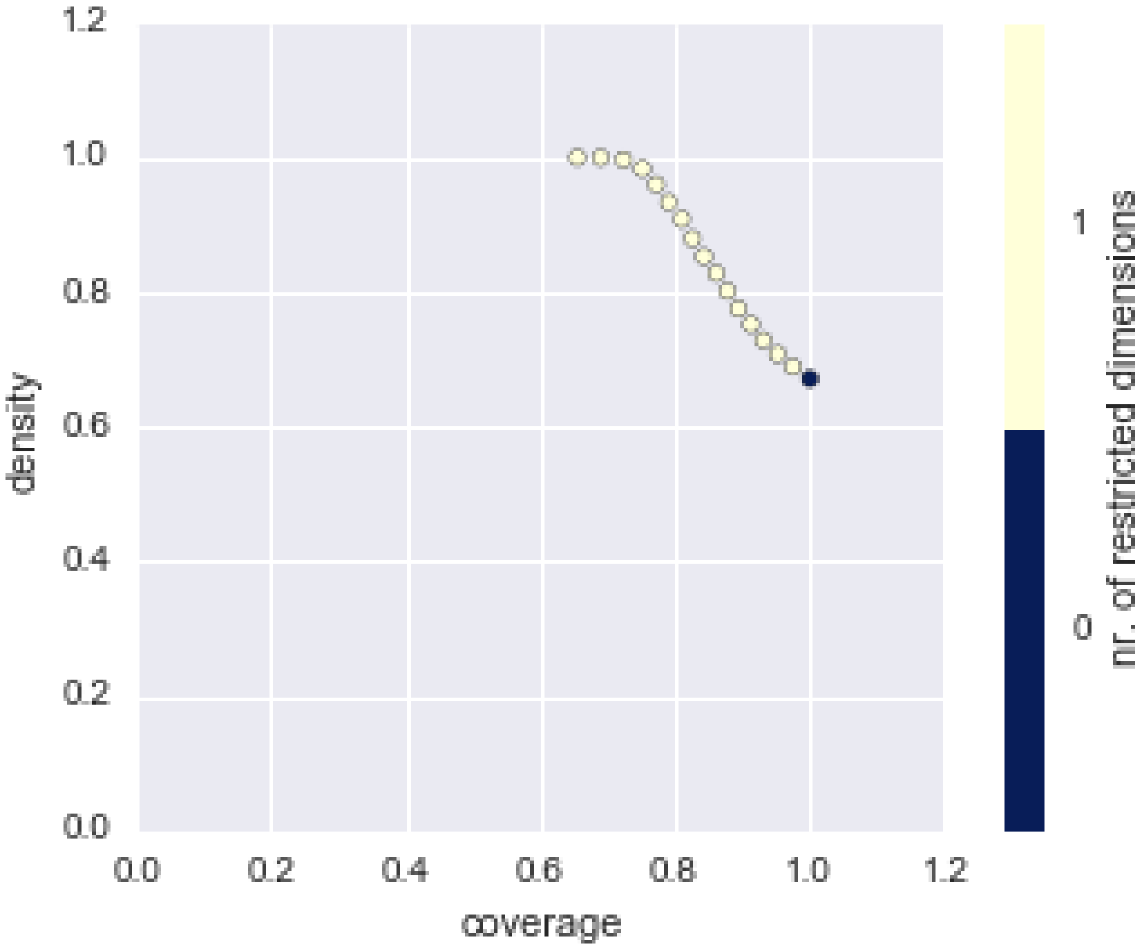

Figure 8.14: Results of the PRIM-analysis related to level of service. Each circle in the figure represents one box constructed by the PRIM-analysis. on the right, the legend is shown which indicates the amount of dimensions that are used to describe each box.

The second performance indicator to be analyzed is the level of service. Figure 8.14 shows the outcomes of the PRIM analysis. Note that all of the "boxes" are just 1 dimensional. If we zoom in on these boxes (as we do with figure 8.15) we note that again the box is defined by wind speed scale change. Box number 16 in this case has a density of 1, which means that for every scenario with a wind speed higher than 0,026, the level of service drops below the threshold. However, the coverage is about 39%. This means that other factors might also have influence on the performance of the system, but just not as much as the wind. So again, the change in weather for which this terminal is vulnerable, is change in wind speed.

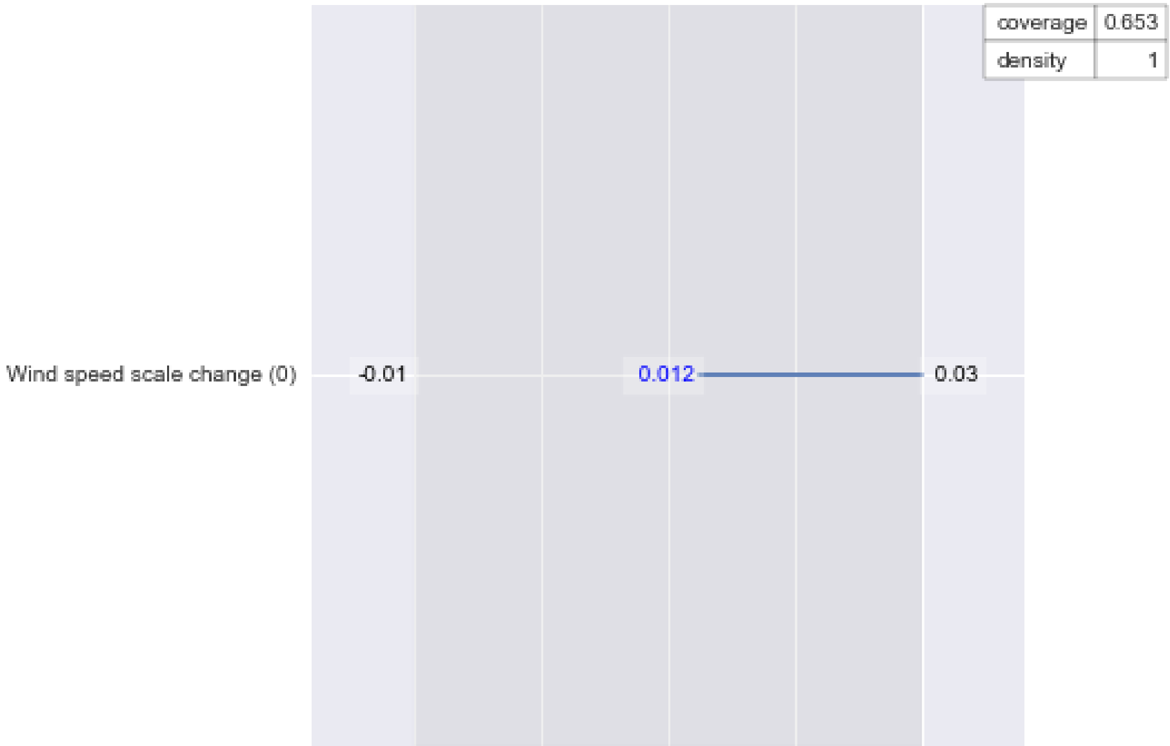

Figure 8.15: The shape of box 16 of the PRIM analysis of level of service. On the left, the variable that sets the shape of the box is mentioned. The line and numbers in the graph show what the range of that variable is in the box. on the top right, the density and coverage of this box are shown.

8.4. Recap

In this chapter several results are discussed. Firstly, the performance of the terminal in Manzanillo, in it's initial state. Then, the terminal in Manzanillo with normal climate change scenarios. No behavior of terminal capacity and utilization was visible here, due to how the terminal capacity and utilization are defined in this research. As proof of concept, two new situations were introduced. One in which the terminal in Manzanillo faced extreme climate change, and one in which a fictitious terminal in a fictitious climate faced normal climate change. In both situations scenarios were present that reduced the performance of the container terminal. Then, a PRIM analysis was performed, to analyze for which weather variables the container terminal was vulnerable. This PRIM analysis was conducted on the fictitious case, for that model showed the best response. For the level of service, as well as the capacity, the wind speed scale change was the biggest threat to the terminal performance.

9 DISCUSSION

This chapter contains a discussion on three important topics. Firstly, a discussion on what the advantages and disadvantages of using EMA/SD for estimating the vulnerability of container terminals to climate change is provided. Then, the scientific relevance is discussed, followed by a discussion on the social relevance.

9.1. Pros and cons of using EMA/SD for this study

Using EMA for this research has several advantages and disadvantages. Due to the deep uncertainty imposed by climate change, it would not be possible to use a consilidative model to analyze this problem. Using EMA, enables us to analyze the behavior of the container terminal as a result of climate change. This does however result in one disadvantage. Due to the exploratory character of the method, it is not possible to deduct any predictive conclusions from this model. Clearly, container terminal operators would like to know at which moment they need to invest in measures against the effects of climate change. This method does not generate these outcomes.

Next to the advantages and disadvantages mentioned above, there has been some experiences with the method on a new topic. I will also note the perceived advantages and disadvantages of using EMA during this thesis.

An advantages of the method is related to the generic character of the workbench created by Kwakkel [10]. A lot of analyses have already been performed in other research. The scripts used for analyzing the data can easily be re-used by other researchers. This same characteristic also imposes a disadvantage. Those who are not familiar with programming languages like python, and lack guidance from one with experience may face difficulties with using the method. The use of python makes it easy to modify, but for many people not user friendly.

Also, the results of the PRIM analysis are hard to interpret without any knowledge of the method. The outcomes of the PRIM analysis are useful, but only with elaboration on how to interpret the results.

Using EMA in large infrastructures was also new. The advantage of using EMA on large infrastructures is that a relatively simple model can be built to be used for many comparable infrastructures. For very specific cases, I would not recommend using EMA. The outcomes of the method are inaccurate, and more in-depth models might be more useful for these cases.

9.2. Scientific relevance

This thesis provides an addition to the literature on EMA. The applicability of EMA to climate related risks in container terminals is new, and hence contributes to the insights of the general possibilities of the method. Furthermore, this thesis provides a method for climate risks management practices in container terminals. This method is a step in the quantification of climate risks in container terminals. This method can be adjusted such that it can be used as a global screening tool for climate risks in container terminals.

With minor adjustments this method can be used for other large infrastructures, if these infrastructures require exploratory insights on the vulnerability to climate change. Some of the steps in this research can be reused for other container terminals, such as the system diagrams, (parts of) the weather influence, the exploratory modeling and the scenario discovery. For other infrastructures, the system diagrams should be revised as well.

9.3. Social relevance

The tool is not sufficiently accurate or reliable to use it as a predictive tool for a specific location, nor can the scenarios be validated. It can however be used as a screening tool, to determine in which regions the container terminals are vulnerable to climate change scenarios.

As the Worldbank currently requires a climate stress-test before any investment, there is social demand for a tool as the one that is developed here. It is not always relevant to make a detailed analysis. A detailed analysis is time-consuming and costly. A screening tool can be used to indicate whether a more detailed analysis is required.

The expected social relevance was to develop a method that container terminals could use to understand how climate change could affect their container terminal. The developed method does show for which types of climate change the container terminals are vulnerable, but there are some drawbacks. The EMA and PRIM-analysis is not widely used. It thus requires some expertise to use these methods to identify critical scenarios for the operator's terminal. Also, the outcomes of the method are very specific: only for container terminals, located at open sea, regarding the operational impact, without downtime, etc. Hence, I would not recommend using this method to directly advise container terminals on investments. Therefore, the social relevance is lower than expected.

10
CONCLUSIONS AND RECOMMENDATIONS

With all steps of this research performed, we can conclude on the research questions. The first section concludes on the main question. The second section concludes on the sub-questions.

10.1. Conclusions on main research question

The main research question was: *"What is the effect of different climate change scenarios on the operational performance of a container terminal?"*. With the exploratory modeling and PRIM analysis we have been able to identify groups of scenarios for which the Manzanillo and fictitious case were vulnerable. The behavior of both the Manzanillo and fictitious case became visible with the exploratory modeling. For the fictitious case, the PRIM analysis pointed out that the terminal is vulnerable to increase in wind speed. The cases show that the method can be used to estimate the vulnerability of a container terminal to climate change. The method is not suitable to use it as predictive tool.

10.2. Conclusions on sub questions

Sub question 1

The first sub question was :*"How do container terminals operate?"*
This question is answered in chapter 3 and 4. Three key Performance Indicators have been defined, which are used to measure the performance of a container terminal. The three KPI's are:

1. Level of service
   The level of service represents the interest of the shippers in a container terminal. They want to deliver as many containers as possible, in as little time as possible.

2. Terminal capacity
   The terminal capacity is important for the terminal operator. In general; the bigger the better. The terminal capacity is defined as the minimum sub-capacity in the logistic chain in the container terminal.

3. Terminal utilization
   The terminal utilization is an indication of how much slack a container terminal has. If the utilization is 100%, it would mean that every delay is critical. IF the utilization is just 30 %, a delay would most likely not cascade to other ships.

Sub question 2

The second sub question was:*"Which weather events influence container terminal operations?"*. The weather events are described in chapter 4. Table 10.1 is a direct copy from table 5.8 in chapter 4. All weather events, their impact, and the conditions under which the event occurs are mentioned.

Table 10.1: Summarized impact from weather events

Event	Effects	Conditions
< Strong breeze	Crane productivity stays 100%	Wind speed <10.8 m/s
Strong breeze	Crane productivity drops to 95%	Wind speed <13.9 m/s
Near gale	Crane productivity drops to 80%	Wind speed < 17.2 m/s
Near gale >	All assets operate at 0%	Wind speed >17.2 m/s
Hurricane	All assets operate at 0%	Wind speed >32.7 m/s
Heat wave	Terminal capacity drops to 0%	Temperature >38°C
Frost	Speed of AGV drops to 3 m/2	Temperature <0°C
Extreme rainfall	Speed of AGV drops to 6 m/s	Precipitation > 30mm/12h
Frozen precipitation	Speed of AGV drops to 3 m/s	Temperature <0°C and Precipitation >0mm/h
Heavy snowfall	Crane productivity drops to 80%	Precipitation > 3cm/h
Flooding	Terminal capacity drops to 0%	Water level > quay height
High waves	Speed of tugboats drops to 0 m/s	Wave height > 1.5 m/s

Sub question 3

The third sub question was: *"Under which climate conditions can weather events be expected?"*. The events occur under the circumstances that were described in the previous table. When these circumstances apply are determined with weather distribution functions. For the occurrence of weather a case study is used. This was Manzanillo, Mexico. Table 10.2 shows the distribution functions used for every weather variable.

Table 10.2: Weather distribution functions. The first column shows the name of the weather variable. The second column provides the type of probability distribution. The third column shows the value for the shape parameter, and the fourth column provides the value of the scale parameter.

Weather variable	Distribution	Shape parameter	Scale parameter
Wind speed	Weibull	2,3544	1,8747
Temperature	Weibull	72,4099	298,0099
Precipitation volume	Gamma	0,034	0,005
Wave height	Weibull	4,8171	1650,2
Sealevel	Weibull	12,8	5693,9

Sub question 4

The last sub question: *"How likely are these events in the future?"* is estimated through varying the distribution functions that we've mentioned in sub question 3. The variability of the weather distribution functions are presented in table 10.3. Note that it is not possible to claim how likely it is that these scenarios are actually happening.

Table 10.3: The parameters that are subjected to change in the model. The first column shows the name of the parameter, the second shows the value that was recovered from the ERA-Interim databse. The third column provides the minimum change rate, and the fourth column provides the maximum change rate.

	Normal climate change		Extreme climate change	
Parameter	**Minimum change**	**Maximum change**	**Minimum change**	**Maximum change**
Wind speed shape	-0,002	0,002	-0,002	0,002
Wind speed scale	-0,01	0,03	-0,01	0,03
Temperature shape	-0,002	0,002	-0,002	0,002
Temperature scale	-0,0005	0,0005	-0,001	0,003
Waveheight shape	-0,002	0,002	-0,002	0,002
Waveheight scale	-0,01	0,03	-0,01	0,03
Sealevel shape	-0,002	0,002	-0,002	0,002
Sealevel scale	-0,001	0,003	-0,001	-0,003
Mean sealevel change	-0,001	0,005	-0,001	0,005
Precipitation shape	-0,002	0,002	-0,002	0,002
Precipitation scale	-0,01	0,03	-0,01	0,03

11 REFLECTION

"Education begins the gentleman, but reading, good company and reflection must finish him"
- John Locke

This chapter contains the reflections on this thesis. To structure it, the reflection is split in four categories; reflections on the assumptions, reflection on the methods that were used, reflection on the social and scientific relevance, and a reflection on the scope. The reflection can help with interpreting the results of this thesis, and may also show that what is learned by the writer, which is me. The reflections are based on choices that i made during the research.

11.1. Reflection on process

The first reflection is on the process. To reflect on the process, I use several questions to confront myself with. By answering these, I should be able to have a structured reflection. Other questions that come up during answering the first questions can be mentioned too. A bit like a self-interview.

1. **Would you classify the process of your thesis as smooth? If not, how come?**
   I would not classify the process as smooth. When the planning was constructed, all steps on high level seemed to be complete, and estimations of how many time it would consume seemed realistic. If that planning could be followed perfectly, or even for the larger part, I would have called the process smooth. However, I soon experienced that especially those parts that were dependent on literature reviews took more time than expected. Firstly since there seemed to be a lack of data related to my topic. Secondly, because I found myself reading a lot of unnecessary literature for this thesis. I would guess that I actually used approximately 5 percent of all the sources that have been read. Although I am not sure whether this is a common thing in research, I felt like losing a lot of time in these situations. I could improve the process by trying to structure the literature study. Especially the snowballing-method led to reading a lot of interesting, but unnecessary reports. By writing down the questions that I was searching for, I could improve the focus during this part of the research. Next to that, I felt like losing a lot of time in creating the research plan. Although it was recommended to spend quite some time on that part, i still felt like losing precious time there. Especially since there was uncertainty about the definitive direction of the research, I was very hesitant in making decisions. By increasing the discussion with stakeholders in that part, the quality might improve, as well as the timely performance.

2. **It seems like you are focusing on efficient use of time in your previous answer. Is this all there is to represent the smoothness of the process?**
   Perhaps not, but the other aspects that i would use to describe smoothness of the process would also result in time-related consequences. For instance; a method that didn't work out as i expected, might need to be changed for another method during the process. This would mean that the initial time-span should be changed. Depending on how much time is spent on the first method, and how much time the new method would consume, we would either be using more or less time.

3. **Are there any relations between your process and the quality of the thesis?**
Obviously this also effects the quality of the thesis. If time is the only driver in the research, decisions may be made to quickly, or mistakes may not be repaired. It seems to be about finding a balance between quality and time, as it usually is in business. In some parts of the process, I invited experts to discuss about certain topics. In these situations, the experts some times suggested to use complex models to represent some minor variables. These models might have provided excellent quality of some data, but would haven taken a lot of time.

11.2. Reflection on methods

1. **Were the methods that you applied suitable for this research?**
There were multiple methods that were used, each of them influencing the outcomes of the method that followed later in the process. First, literature study is used to understand container terminals. Besides that, I did a site visit at a container terminal from RWG in Rotterdam. Although there was need for scientific sources in the main text, I believe the visit to RWG was much more valuable. There are of course many differences between container terminals, so the visit alone would not be suitable. By performing the visit in an earlier stage, the description on container terminals could have been finished faster. Visual learning seems to be very beneficial for describing.

2. **Were the system diagrams fit for purpose?**
Then, system diagrams were used to describe how performance indicators were used in container terminals. The system diagrams gave good insight in how these performance indicators were calculated. Other methods could have been used to calculate how container terminals are performing. These methods could be system dynamics, agent based models or discrete models. Agent based could be used if there was interaction between different stakeholders. The interaction between stakeholders was not our case of interest in this study. One other study has performed an agent based model on this topic (CITE). They ran their model to simulate the effect of weather on the operational performance of one day. Since our interest is in yearly performance, up to 2100, a model that predicts a performance on 1 day was of no use. Of course the model could have been running for a very long time, such that it predicts daily performance up to 2100. However, the model is not fit for this purpose. The same is for discrete models. It would be a waste to use a detailed model for performance on daily basis, if we want to be able to predict yearly performance on long term. Then, a meta-model would make much more sense. Thus, an excel model seemed to be a good method to calculate the impact of climate change on container terminals.

3. **Were the methods used to describe the influence of weather on container terminals good?**
This model should communicate with the climate. To simulate the climate, many different methods could be used. For this research, eventually is chosen to use 5 different weather variables. These five would determine how many hours in a year certain weather conditions apply and via that, how the performance of a container terminal is. This method has several disadvantages. Firstly, we do not know how many downtime there will be as a result of recovery time. We now know only the hours that a storm is occurring, but not how many times. If a storm occurs, the terminal would realistically need some time to recover from that storm. It would make quite a difference if the storm is occurring 30 times with a duration of 20 minutes, or the storm is only occurring twice, with a duration of five hours. The situation where it occurs 30 times for 20 minutes has a bigger impact, since the port might be able to recover for 20 minutes after every storm. The second disadvantage is the exclusion of black-swan events. Since the climate is simulated with distribution functions, it provides the average amount of hours that a certain event would occur in one year. Some black swan events, like a tornado may occur once in 60 years. With the method that is currently used, this could mean that a tornado is occurring for 12 seconds per year. Another option could have been to use weather events as we did now, but don't relate them to weather variables as we did now. If the events have a probability distribution in the duration, as well as in frequency, we might also be able to determine the impact of climate change on container terminals. A big advantage with that method would be that it is then possible to take recovery time of a container terminal into account.

4. **Was changing the distribution functions a good method to compute climate change scenarios?**
For an exploratory study, given that we determine the occurrence of weather events based on the five weather variables, the use of EMA was good. The exploratory character of the study indicates that the precision of the model is not really important; the outcomes should identify for what kind of climate change the terminal is vulnerable, rather than to determine when the terminal is under performing. How realistic the critical climate change is, is a question that should be answered with another study. To generate a set of different climate scenarios, EMA worked well. It generated scenarios within the estimations made by IPCC, but also scenarios outside their bandwidth. Thus, for exploratory purposes I would say the method was indeed fit for purpose.

5. **The simulation of climate change included a random function; does this affect the outcomes of your thesis?**
The change in the distribution functions contained a random variable. The value of the parameter for the next year was calculated as (value for this year) x (growth rate x random uniform [0-1]). So, if the growth rate was 1 per cent, and the value for year 2016 was 100, the value of 2017 could be at maximum 101, at minimum still 100, and on average 100.5. By then, I assumed that this would be a logical choice, for the climate is also following a trend, but not a perfect line. Adding randomness in that function would simulate uncertainty in climate trends. However, this results in unnecessary noise. This noise could have been resolved by either removing the random trend, or by running every climate scenario multiples times. None has actually been done in this research. While removing randomness in the growth-rate of the density functions might make sense, they are currently non-existent in the functions used to determine the impact of a weather event. As operators should adjust the speed of loading and unloading to their own insights, there is a lot of uncertainty in that influence. By not having included uncertainty in that influence, the accuracy of the model is affected. For a new research, this should be included.

6. **Did you follow advice from experts on the methods?**
The advice offered by experts was carefully considered. In some occasions this resulted in directly following the advice. Examples of this were the exclusion of some of the initial research questions, and the use of case studies in this research. There were other occasions where the advice was followed at first instance, but the process, another direction became more straightforward. An example of this was the method used to describe the climate. The advice from an expert was to create a new causal diagram, in which all different kinds of weather-variables were linked, such that all the causal links in climate could be taken into account in the description of climate change. During the process of developing such a diagram, it became clear that this would be extremely time-consuming, while it wouldn't pay off in the outcomes of the model. Later, another direction was chosen, and the description of weather was only related to 5 weather variables, instead of a full causal diagram. Lastly, some advice was considered, but not executed. This could be for several reasons. In some of these occasions it would mean that the scope of the research had to be extended quite significantly. For instance; including the cost of extreme weather events, or including cascading effects in the model. This was then not directly included in the model, but mentioned in the reflection.

11.3. Reflection on outcomes

1. **Were the outcomes what you expected?**
No, not at all. The first experiment resulted in no change in performance at all. After investigating this behavior, I noted 2 important points. Firstly, the climate in Manzanillo was really favorable. Secondly, the definitions of the key performance indicators that I used were not showing all the changes in performance. A more suitable key performance indicator might have been 'Downtime'. Downtime would be the time in a year that a container terminal cannot load or unload a vessel. It is not possible to calculate downtime with the three performance indicators alone. The downtime can however be calculated with some small adjustments in the model. This should be done in a next research. With the understanding gained from investigating the results from the first experiments, the outcomes from the second and third experiment were as I expected.

2. **Could you make the conclusions on your questions without this research?**

I could not have made the conclusions on the sub-questions without this research. Some experts might know part of the answer, but i have not found a single source that contained all the information. Regarding the main research question: the direction of the impact of climate change could have been predicted with common sense: if the environment for which a system is designed changes, the performance of the system is quite likely to decrease. But, the quantification i could not have done without this research. Although I would not rely on the accuracy of this model, nor would I use this model to make decisions without further research, this research has been a first step in developing a method to quantify the impact of climate change on container terminals. Quantification on this level would not have been possible without this research.

3. **You measured the performance of the container terminal at the year 2100. Does this affect your results?**
   Yes for sure. Since most container terminal have a long-term planning for at most 30 years ahead (and also a contract for 30 years ahead), they would be much more interested in how the terminal is affected within that time-span. It could well be that none of the container terminals is really affected in the period for 30 years ahead. As discussed before, the utilization and capacity only changed after approximately 30 years. So, the only change that would be shown within that time-span would be the level of service.

11.4. Would i do things differently?

If I had to start this research, with the knowledge that I obtained during the last months, I would definitely change some things. What i would have done differently were the start-up process; the reading, and writing of the proposal. I would structure the reading more, and initiate more discussions during the proposal. Furthermore, i would add the downtime to the key performance indicators. Also, i would try to perform this research without using the weather variables, but directly with attaching frequency, probability and after-effects of weather events. Lastly, i would try to set the scope within the first week of the proposal. In this research. part of the scope was not yet determined during the second month. It was hard to narrow down without knowing the exact scope. What i would not change are the use of excel. The use of excel gave me a lot of flexibility in the research. I would also still use EMA and PRIM analysis.

A

Selection of case-study

Since scenarios are applied in this thesis, it is logically to perform a case study. For this, an applicable container-terminal should be identified. To come up with a proper selection, the following requirements are taken into account:

- **Not the obvious choice.** The terminal should not be the obvious choice, this means: Not the port of Rotterdam or the port of Antwerp. Picking another has several advantages. It's a new environment to understand, thus provides new insights in how ports operate. Since nothing is yet taught about this port, a fresh look can be thrown on the situation.
- **Must be vulnerable.** The terminal should be relatively vulnerable, such that the effects of climate-change become visible in the thesis. The bigger the impact of climate-change on the port; the easier it is to deliver the message of the thesis. To see whether a port is vulnerable, at least two characteristics are taken into account; 1) The port should be positioned at open coast and 2) the port should not be laying on high terrain.
- **Not too complex.** The case should not be too complex. By adding complexity, to much effort and time is spend on supervacaneous details. The main goal is to identify how climate-change is affecting port operations. All complexities that are included, are at expense of this goal.
- **Data should be available.** For similar reasons as mentioned above, data should be freely available on the case. All time that is harvest or gather data is at expense of the time that can be used to improve the quality of the thesis.
- **Non- Northern American, European, Australian, Russian, Chinese, Japanese or South Korean.** The importance of robust-decision making is especially true for developing countries [15]. Although the true definition of developing countries is not exactly followed here, it is assumed that the countries excluded from the selection have sufficient access to financial means to adapt to climate-change.
- **TU Delft or Deltares related.** The terminal should preferably be connected to TU Delft or Deltares in any way. This increases the chance that data is accessible, and also increases the added value of the thesis to any of both parties.

So, with the penultimate requirement a geographical demarcation is given. This practically means that a port from Asia, Africa or South-America must be chosen. For ease we use a list that is provided by Wikipedia as reference for available container terminals [17]. It is understood that Wikipedia is open-source, and cannot be trusted as a scientific reference. However, since for this thesis multiple container terminals might suffice as case study, the weight on selecting the very best container terminal is low. Since the list on Wikipedia contains quite an amount of terminals, the probability that one of these might be sufficient is high.

That being said; after removing all terminals that are not within our geographical boundary, a list of 70 container terminals is still remaining, which is still too much. In this case, it is assumed that the availability of a Wikipedia-page about each port is also an indication of the probability that data on the terminal is available. So; if Wikipedia has a page about a certain container terminal, it is more probable that data is available compared to when Wikipedia doesn't have a page about it. After deleting all those terminals that lack a wikipedia-page, a list of 40 container terminals is left. These 40 terminals are presented in table A.1.

Table A.1: List of container terminals

Port of buenos Aires	Mundra Port	Toamasina Autonomous Port	Jeddah Seaport
Port of Santos	Visakhapatnam Port	Port of Klang	Port of Dakar
Port of Rio de Janeiro	Port of Pipavav	Port of Tanjung Pelepas	Port of Singapore
Port of Salvador	Port of Kochi	Tanger Med Port	Port of Durban
Port of Valparaiso	Port of Jakarta	Port of Beira	Port of Cape Town
Port of Djibouti	Port of Haife	Port of Salalah	Port of colombo
Multimodal Caucedo Port	Port of Ashdod	Karachi Port	Port Sudan
Alexandria Port	Port of Kingston	Port Qasim	Port of Latakia
Port of Chennai	Port of Aqaba	Pakistan International Container Terminal	Port of Montevideo
Jawaharlal Nehru Port	Port of Mombasasa	Port of Kaohsiung	Port of Manzanillo

For each of these terminals is checked whether the port is open-coast, and located in a low-laying area. Also, the complexity of the location is estimated. Some of the ports in Northern-Africa were also excluded due to perceived terrorism-related risks. Due to these perceived risks, they should otherwise be included in the risk-estimation. These assessments are primarily performed by inspecting the satellite-images of the location. After these selections, a list of 7 ports remain.

1. Port of Valparaiso, Chile
2. Toamasina Autonomous Port, Madagascar
3. Port of Salalah, Oman
4. Port of Cape Town, South-Africa
5. Port of Colombo, Sri Lanka
6. Port of Montevideo, Uruguay
7. Port of Manzanillo, Mexico

The data that we need for modeling these terminals is available for each of the seven cases. Thus, each of these seven cases can be used for this study. Another report has been written related to the impact of climate change on the port of Manzanillo. Although some might argue that the added value of a thesis with the same case study would be smaller than one related to a new case, Manzanillo is the chosen case. The advantages of selecting it, is that there already is some information about the expected impacts in the other report. It is thus easier to verify and validate. Furthermore, the other report did not cover the same method, nor did it produce the same results. The existence of the other report would furthermore insinuate that there is a call for this knowledge from that area. [6]

B

Clarification of terms and definitions used

There are some terms used in this thesis, which have various meanings in other literature in the same field. The four that deserve extra clarification are 1) adaptation, 2) flexibility, 3) resilience and 4) robustness. Especially the latter two are often used as synonyms, while they are in fact not.

B.1. Robustness, resilience, flexibility and adaptivity

There seem to be many different words to describe a system's ability to coop with a changing environment. Some of the words that are often used in other literature to indicate this ability are robustness, resilience, flexibility and adaptivity. There seems to be a lot of overlap between these four terms. They are often used as synonyms, while they not necessarily bear the same meaning [40]. To prevent any confusing on the use of these terms throughout this document, the definitions as presented below will be used throughout the thesis.

Resilience

One definition of resilience is as follows: *"the ability to become strong, healthy, or successful again after something bad happens"*[21]. This definition speaks of resilience as an ability of a system, to recover after an extreme event. This implies that the system must be able to take some hits, but should also be able to return to full capacity after it is hit. Mind that this means that the system does face consequences when an event occurs, but is fully operational quickly after this event. This definition is the one used when referring to resilience in this thesis.

Robustness

For robustness, the following definition is used: *"strong and effective in all or most situations and conditions"* [22]. Notice that this definition of robustness does not define what the thing is that is strong or effective in these situations. This might be a port, which is built with a lot of redundancy. It might also be a method (for instance a pathway) that ensures that a system stays strong and effective.

Adaptivity

"to adjust oneself to different conditions, environment, etc." [3] . The 'oneself' suggests that the thing/system has the ability to make changes on its own settings. "Adaptivity is the ability of a system to change along with the surroundings of a system". In this sense, a system is adaptive if it contains some sort of dynamic property, which can be used to act upon climate risks. The 'stormvloedkering' is a nice example of an adaptive property of a system; if the springtide is emerging, the stormvloedkering can close, to counter the negative effects of the tide. By adding this adaptive system, the robustness of the system is increased too.

Flexibility

"The ability to be easily modified" [12]. This can be used to describe the system as well as the method.

If a dike is built such that it can be raised further if necessary, this is a flexible measure to counter sea-level rise. On the other hand, if the dike is designed such that it is optimized for the expected sea-level in 5 years, the foundation is the dike is most likely not strong enough to support an increase in height. The design is not flexible in this example. Thus, flexibility can be designed at some cost.

Since the goal is to increase climate-robustness of ports, the outcomes of this research rely heavily on the used definition for robustness. Somehow robustness must be measured as output of the port performance. Firstly a review about robustness in larger literature is provided. With this knowledge, robustness in ports can be described.

C

System diagrams and system dynamics

To gain a solid understanding of how ports operate, the information from the analyses from chapter 3 is merged into a system diagram. Such a diagram provides visual insight in how a system works. To create the system diagram, several processes were followed. Firstly, the 6 processes in a port that are used in this thesis (Navigation, Berthing, Unloading, transferring, storing, transporting) were taken as a starting point for the diagram. For each of the processes was consequently brainstormed which factors influence the speed of that process. The original created diagram provided insight in how several factors influenced the separate processes. But, that is not what we would like to measure. What we would like to know is how the performance of a port is being impacted. If each of the separate processes were decent indicators for performance, the old diagram would suffice. However, three key performance indicators are more often used to measure port performance. These three are 1) the level of service, 2) the terminal efficiency and 3) the terminal capacity. Thus, the diagram was reshaped in a way that all the factors related to these three performance indicators. Figure C.1 shows the revised diagram built around the key performance indicators. As you can see, some of the boxes are marked grey. According to the UNCTAD [53], only capacity at the quay and storage capacity are bottlenecks for the terminal capacity. Those boxes that are marked grey are thus less important to investigate than the ones left white. The arrows indicate that the box from which the arrow originate influences the box where the arrow points at. The plus and minus sign that is presented at each arrow indicate whether the influence is positive or negative. If we look for instance at the *amount of berths*, it is being influenced by the *gap between vessels*, the *length of a standard vessel*, and the *length of berthing facility*. If the *gap between vessels* increases, the *amount of berths* decrease. This is the same for an increase in *length of standard vessel*. However, if the *length of berthing facility* increases, the *amount of berths* increase as well. For further specification of the relations in this model, please read chapter 4.

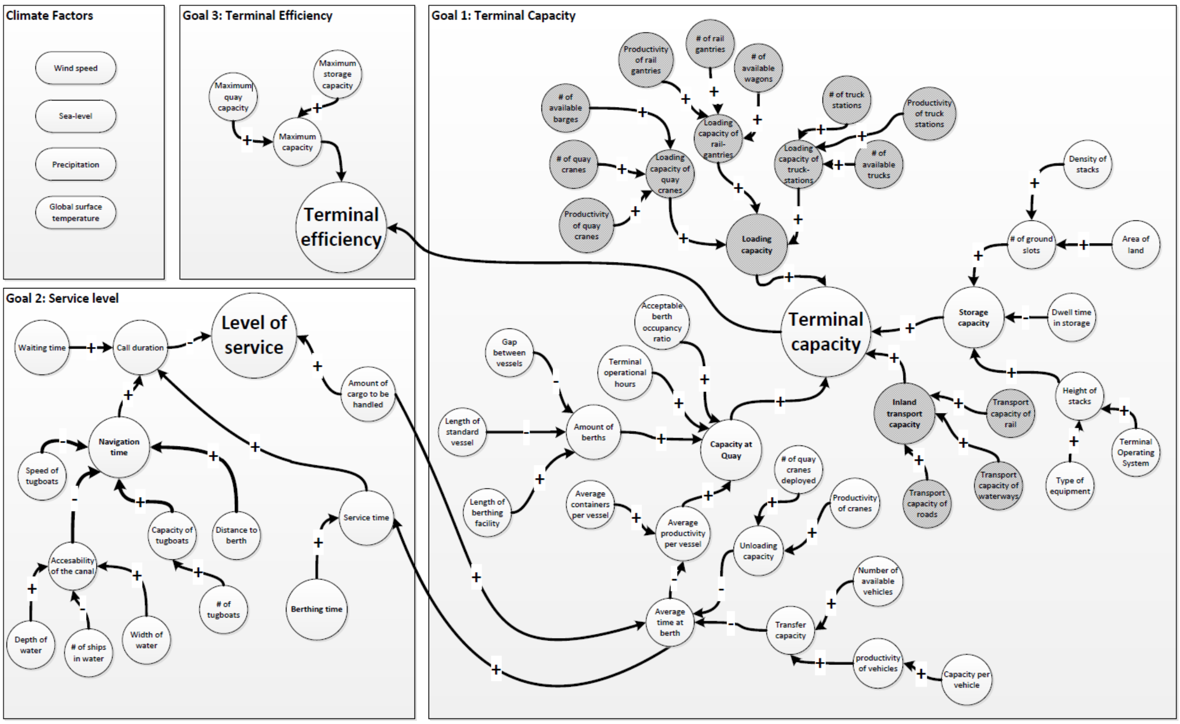

Figure C.1: System diagram of a container terminal

If we use the consolidated system diagram, in which we exclude those parts that are not bottlenecks in the system, we are left with the diagram as presented in figure C.2.

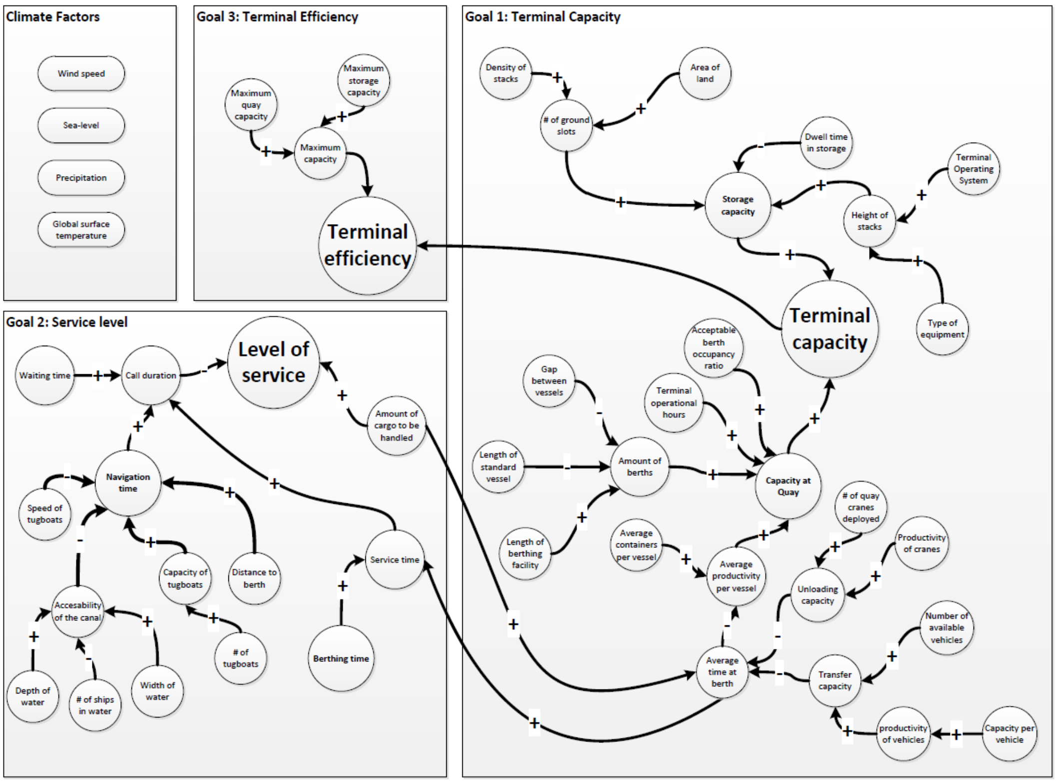

Figure C.2: Consolidated system diagram of a container terminal

As we want to gain insight in how climate is affecting container terminals, climate factors should be inserted in the model as well. In chapter 5 four climate impact categories are presented. These are Wind, Water, Precipitation and Temperature. Including all of them in the model, makes it very messy and chaotic. Therefore 4 replications of the consolidated system diagram are proposed, in which the climate impact of one category is taken into account. Thus, 4 diagrams are presented, in which the vulnerabilities to a climate category are presented. Those boxes of which the lines are thicker are effected by events from that climate category. Figure C.3 shows the operations that are effected by wind, figure C.4 those that are affected by sea-level, figure C.5 the ones affected by precipitation, and figure C.6 those affected by temperature.

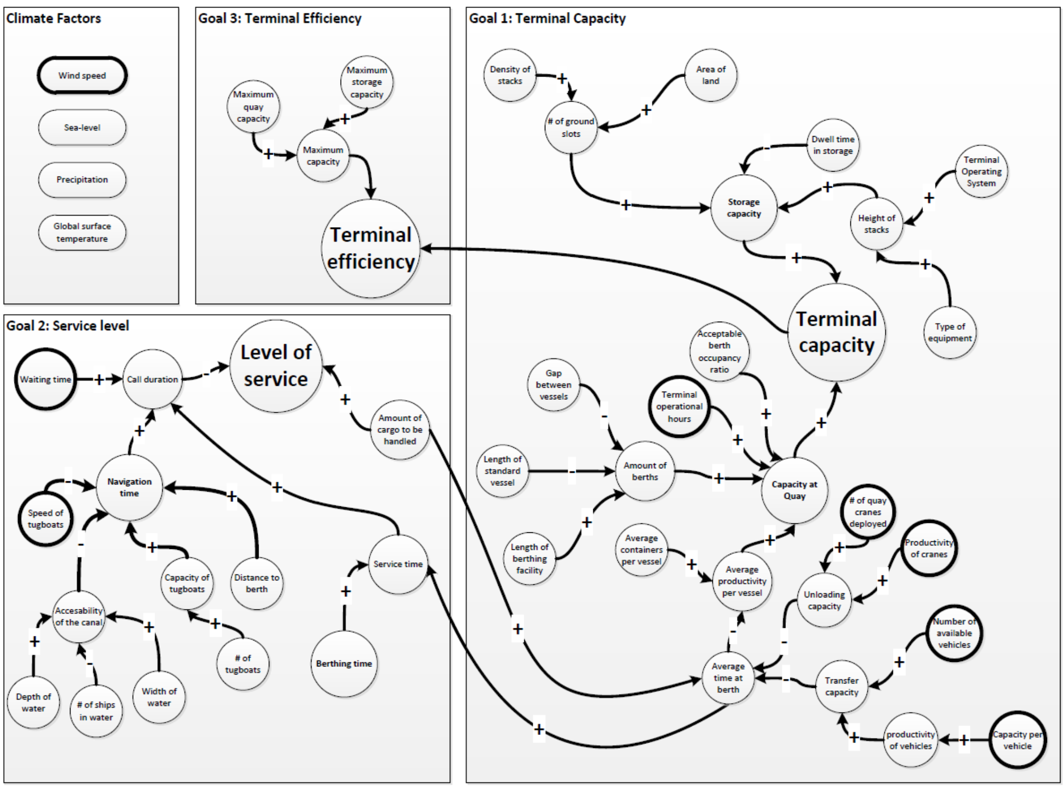

Figure C.3: Wind related impact on container terminals

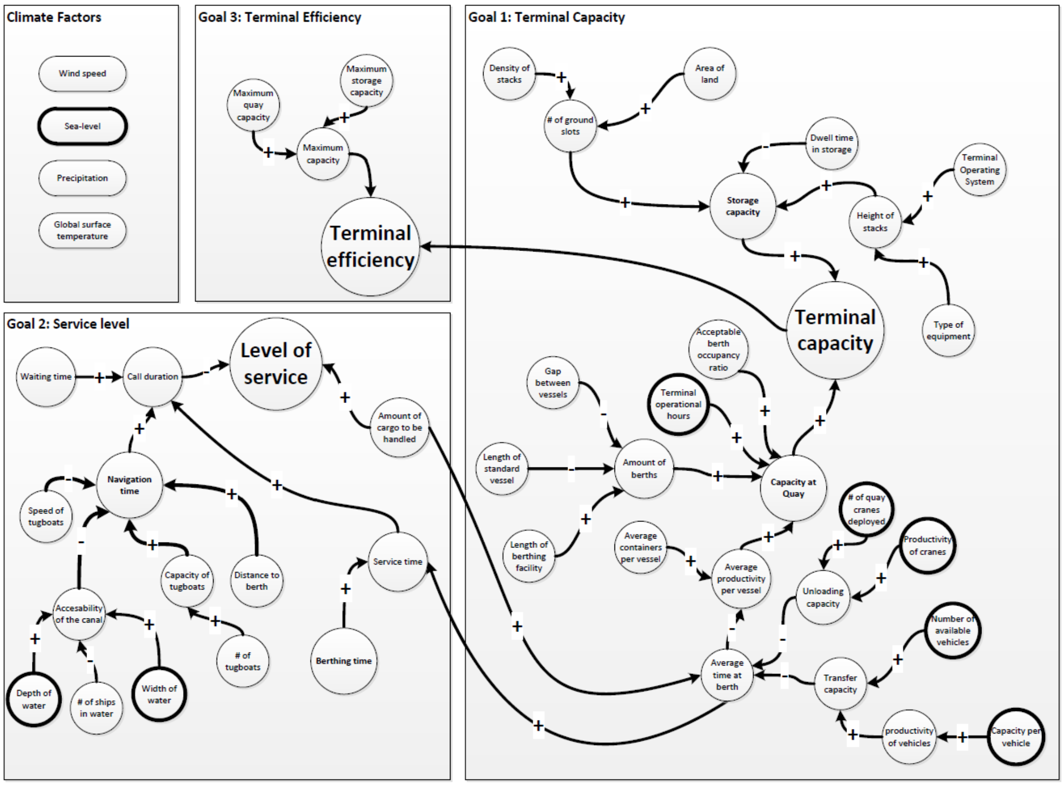

Figure C.4: Sea-level related impact on container terminals

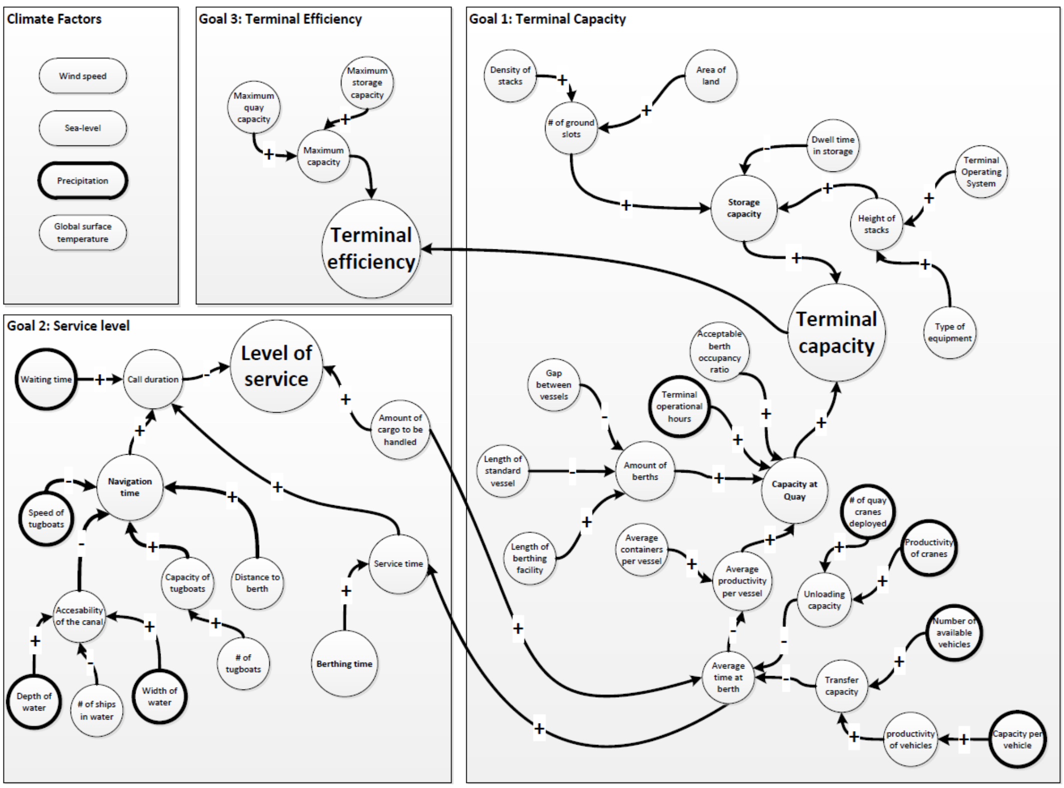

Figure C.5: Precipitation related impact on container terminals

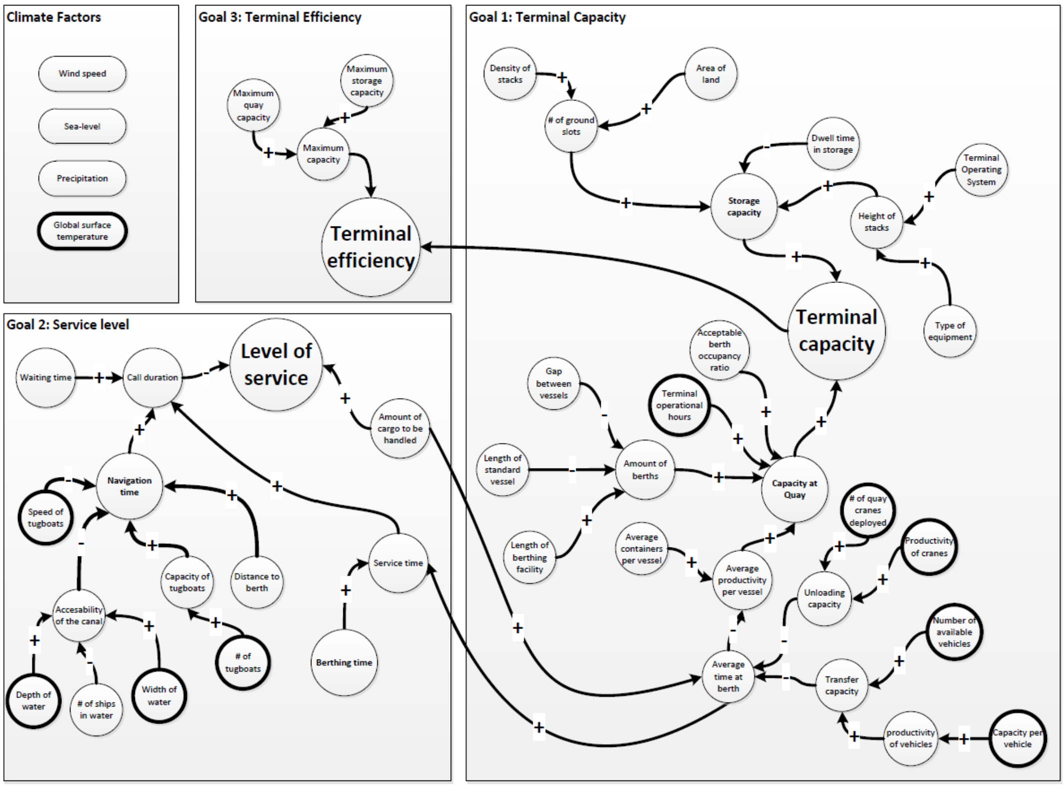

Figure C.6: Temperature related impact on container terminals

D
Weather types

”Weather is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy.” [26]. Weather can vary all over that plain of characteristics. While weather is always present, and very dynamic, weather does not always impact port operations. This appendix provides an overview of the different types of weather, and whether it is expected to influence the performance of a container terminal.

D.1. Hot or cold

Let’s start with a simple one; the temperature. According to scientists, temperature can basically vary from -273.15 degrees Celsius (-459.67 degrees Fahrenheit for Liberia, Myanmar and the U.S.) to 1.416833^{32} degrees Celsius [24]. Gladly, these extremes do not naturally occur on planet earth (yet). Depending on the region and season, earth’s surface temperatures currently vary between -89 degrees Celsius and 58 degrees Celsius [19]. The maximum and minimum values are the extremes, and do not occur occasionally. Also, the extremes are bound to certain regions. Antarctic surfaces have not been warmer than 17,5 degrees in the last centuries ,while Honolulu, Hawaii has not been colder than 11 degrees Celsius [14]. For most temperatures, ports do not experience any troubles. However, above and beneath certain thresholds, port operations are affected by the temperature. Let’s say that in general problems can be expected for all temperatures beneath the freezing point of water (0 degrees Celsius), for the roads might get slippery, and entrance channels might get frozen. Also, when the temperature is too high, human beings are starting to malfunction or work less efficient.

D.2. Wet or dry

Wet or dry refers to whether precipitation takes place or not. In times where precipitation has not occurred for a long time, drought occurs. This results in principle in a shortage on water. On the other hand, if precipitation is happening all the time, and the intensity of the precipitation is high, the amount of new supplied water can be higher than the capacity to transfer the water. In times of a lot of precipitation, we call it wet. Drought can result in lower water-levels, resulting in lower depth of entrance channels, and might have a lot of indirect effects (loss of power due to insufficient cooling capacity for power stations). In times of wetness, water-levels may rise, resulting in flooding. Next to that, high wetness decreases the visibility in the terminal. Furthermore, the current in the canals may increase, resulting in problems with navigation.

D.3. Calm or stormy

Another aspect of weather is the degree to which the wind is blowing, as is described as calm or stormy. If the windspeed is very low or even zero, the weather is calm. If your car is blown of the road, your you fell from your bike, your umbrella broke down and a tree collapsed in your yard, the weather is most likely stormy. The wind speed can vary from 0 m/s to as much as 113 m/s (as is the highest measured windspeed to date [28]). Although this it the highest measured windspeeds, speeds in some cyclones are expected to be higher. However, the measurement instrument usually break down during such a measurement, thus it has not been recorded yet. Anyways- The weather is called calm at low wind speeds, up to about 10 m/s. From 24 m/s the weather is referred to as stormy. If the weather is calm, only sailboats have a disadvantage. As most containers are shipped with an engine-driven vessel, calm weather is not really affecting container terminals. Stormy weather however, can have huge impact on container terminals. Wind affects the operational performance of the terminal, it reduces the speed at which quay cranes operate, but can also inflict damage on infrastructures and assets.

E Interview

Since the literature lacks information about some of the weather-impacts on container terminals, data must be collected in another way. Basically 3 options are available. The first is to guesstimate the relations. This would result in a huge amount of uncertainty in the research however. The second options would be to measure the impacts by yourself. This would however consume a lot of time, especially since some of the events might not even occur in the coming year. The third option is to perform an interview. By doing so, The uncertainty is lower than when the results are guesstimated, and it wouldn't consume too much time, since the interviewee might have seen all of the events in it's lifetime. To cope with the missing data in the climate-risk matrix, an interview with Mike van der Heijden is held. Mike is a experienced practitioner in container terminals. He has a lot of experience at APM Terminals, and has been involved with the development of a new container terminal for RWG.

Wind-related questions

1. from which wind-speeds on do you expect the loading and unloading speed from cranes to decrease?
   The operator adjusts the speed himself when the operator has the idea that it is no longer safe. The cranes automatically halt when the threshold values from the bad weather procedure are realized.
2. At which percentage of the maximum capacity do you expect a quay-crane to operate at average wind-speeds of 16 m/s?
   The loading and unloading speed is not directly affected by the wind-speed.
3. Can you think of any situation where the wind-speed is such high, that containers blow over? If so, at which wind-speeds does this occur?
   When the wind is coming from the wrong direction, empty containers will start to be blown over the quay. There is not much to do about it.
4. Point 3.6.10 in the bad weather procedure describes checks that need to be performed to check for damage of equipment in case of a bad weather event. From which wind-speeds could you expect any damage to equipment? Can you give an example?
   About the same as the previous answer.
5. How long does it take for a terminal to start-up after a stop-phase, and return to full capacity?
   This should not take too much time. Removal of storm-barriers and damage-checks should be finished within half an hour.

Precipitation-related questions

1. Precipitation influences the visibility of operators. From which precipitation volumes could you expect the loading-and unloading capacity of a crane to be affected?
   In the port of Rotterdam, the experiences with heavy rainfall did not show that the visibility for the remote operators was heavily affected. The sight is still quite god during such an event.

2. There are 3 different modes for the automatic guided vehicles. Under which circumstances are these modes activated, and what influence does it have on the speed at which the vehicles transport?
   When there ice is being formed at the quay, the speed at which vehicles move is reduced to 3m/s. When there is slippery weather, but there is no ice, the speed is reduced to 6 m/s.

3. For some types of weather (snow, hail, freezing drizzle) salt is put on the roads to prevent a slippery road. For how much does these weather-types influence the other parts in the terminal? (Cranes, engines, storage facilities) **I can't really see how other parts of the terminal are influenced by these types of weather. At most the wear of the machine will increase**

4. In case of thick mist the visibility of operators and camera's is reduced. Can AGV's still drive at maximum speed in these occasions?
   Yes, AGV's ride full speed under these circumstances In het geval van mist, wordt het zicht van operators en camera's aangetast. Kunnen AGV's nog wel op maximale snelheid rijden in het geval van mist?

Water-related questions

1. In case of a temporary flooding due to for instance high waves, long-term heavy rainfall or high sea level it is imaginable that the terminal goes offline for a certain period. How long does it take for a terminal to restart?
   This is really dependent on whether there is structural damage. If there is no structural damage, the terminal will be fully operational in 1 hour.

2. In case of high waves, it is possible that the stability of the ship is affected. If a ship is subjected to the motion of waves, can the loading/unloading still proceed?
   It depends on the type of ship. A feeder is sooner affected than a deepsea vessel

Other questions

1. Are there any weather-related risks of which you expect them to occur more often in the future?
   Heavy storms i expect to encounter more often in the future.

2. What are in your opinion the 5 most influencing weather-events that can occur in a container terminal? (I.e. mist, high winds, high currents in the canal, heat-wave, etc.)
   Storm, snow, cold, wind and heat.

F

Design philosophy

This appendix provides an overview of how the model is designed. first of all, a discussion is provided on what the model should be able to do. From this discussion follows the type of model that is chosen, as does the general lay-out of the model. The general model is provided in the second section, and presents a high-level description of the model. The third section contains the further considerations of the model.

F.1. What the model must be able to do

The model should be able to measure the impact of climate change on the performance of container terminals. For this, it should be able to give outputs over long-term, say to 2100, preferably yearly outputs, or even monthly. The model must be able to specify when a container terminal is not performing well enough, and under which conditions that is.

Furthermore; we must be able to select which scenarios we apply, insert design parameter like the amount of cranes, and must be able to read out key performance indicators for a given scenario at a given time. Also, it must be possible to trace how a performance indicator is influenced by sub-indicators.

F.2. General model

The model converts climate scenarios and design parameters into yearly values for key performance indicators. The calculations made in the model are in line with those described in chapter 4. In this section the calculating mechanisms will not be described. In this section, the calculations are presented as a black-box. Thus; the inputs for the model are the climate scenarios and the design parameters. The outputs are the key performance indicators.

The climate scenarios consist of yearly values of a few weather variables. These variables are the wind speed, the sea-level, temperature and the precipitation volume. The variables will vary through the years per scenario. Each scenario consists of a different combination of weather-patterns, and will thus have different impact on the outcomes of the model.

The design parameters are those values that are inserted in the model, that describe the characteristics of the port. These parameters are the amount of cranes in the port, the length of the quay, the depth of the canal, the yearly demand for containers, etc. Other parameters that are taken into account are the average length of the vessels, and the average amount of TEU's on a vessel.

G

Data for weather distributions

G.1. How the data is retrieved

Six datasets are retrieved. One is retrieved from the university of hawaii [25]. This is the daily and hourly sealevel dataset for Manzanillo. The other datasets are retrieved via the ERA Interim dataset. These are the wave height, wind speed, temperature and precipitation volume.

Here is how to download it:

- Go to Era Interim daily data: http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/
- Select all dates (from 1979 to now, for complete set)
- Select all times (4 times per day)
- Select step 0 (No forecast, but only real data)
- Select parameter 10 metre U wind component, 10 metre wind v component, total precipitation, waveheight of combined gravitation and swell, and 2 meter temperature.
- Click Retrieve NetCDF
- Change attribute Area to Custom: N255.5, 19.5, S250, W 19.
- Change attribute grid to 0.125x0.125.
- Select retrieve now
- Download file.

G.2. How the data is analyzed

- Open matlab
- ncdisp('total.nc')
- create variables with "Var=ncread('total.nc','varname');
- rescale the variables: "var=var(2,2,:);"
- squeeze variables: "var= squeeze(var);"
- for all but precipitation: wblfit(var);
- for precipitation: gamfit(var);

H

Python script

This appendix contains the script that is used to perform the Scenario Discovery with the EMA work-bench.

In [161]:

```
import sys
sys.path
sys.path.append('D:\dijk_rn\Desktop\Master Thesis\python\EMAworkbench-master\src')
del sys
```

In [162]:

```
%matplotlib inline
```

In [163]:

```
import numpy as np
import matplotlib.pyplot as plt
import scipy as sp
import pandas as pd
import seaborn as sns
import matplotlib as mpl
```

Run the Manzanillo model, with normal weather predictions

Note: The outcomes of the model should be stored in a column instead of a row. When stored in a row, only the first point of data in a timeserie is stored.

In [165]:

```
'''
Created on 27 Jul. 2011

This file illustrated the use the EMA classes for a model in Excel.

It used the excel file provided by
`A. Sharov <http://home.comcast.net/~sharov/PopEcol/lec10/fullmod.html>`_

This excel file implements a simple predator prey model.

.. codeauthor:: jhkwakkel <j.h.kwakkel (at) tudelft (dot) nl>
'''
from __future__ import (division, print_function, absolute_import,
                        unicode_literals)

from ema_workbench.em_framework import (ModelEnsemble, RealParameter,
                                        TimeSeriesOutcome, perform_experiments)
from ema_workbench.util import ema_logging
from ema_workbench.connectors.excel import ExcelModelStructureInterface

from ema_workbench.util import save_results


if __name__ == "__main__":
    ema_logging.log_to_stderr(level=ema_logging.INFO)

    model = ExcelModelStructureInterface("ClimateModel", r"./models/excelModel",
                                         model_file=r'\excel examples2.xlsx')
    model.uncertainties = [RealParameter('Wind speed shape change', -0.002, 0.002, variable_name='C3'),
                           RealParameter('Wind speed scale change', -0.01, 0.03, variable_name='C4'),
                           RealParameter('Temperature shape change', -0.002, 0.002, variable_name='C5'),
                           RealParameter('Temperature scale change', -0.0005, 0.0005, variable_name='C6'),
                           RealParameter('Wave height shape change', -0.002, 0.002, variable_name='C7'),
```

```
                     RealParameter('Wave height scale change', -0.01, 0.03, variable_name='C8'),
                     RealParameter('Sea level shape change', -0.002, 0.002, variable_name='C9'),
                     RealParameter('Sea level scale change', -0.001, 0.003, variable_name='C10'),
                     RealParameter('Mean sea level change', -0.001, 0.005, variable_name='C11'),
                     RealParameter('Precipitation volume shape change', -0.002, 0.002, variable_name='C12'),
                     RealParameter('Precipitation volume scale change', -0.01, 0.03, variable_name='C13'),]
#specification of the outcomes
model.outcomes = [TimeSeriesOutcome('level of service', variable_name="H9:H93"),
                 TimeSeriesOutcome('capacity', variable_name="I9:I93"), # we can also use named range
                 TimeSeriesOutcome('utilization', variable_name="J9:J93")]

#name of the sheet
model.sheet = "INPUT AND OUTPUT"

ensemble = ModelEnsemble()
ensemble.model_structures = model

results = perform_experiments(model, 100, parallel=False)
save_results(results, r'./results/results_Manzanillo_100_v3.tar.gz')
```

```
[MainProcess/INFO] 100 experiment will be executed
[MainProcess/INFO] starting to perform experiments sequentially
[MainProcess/INFO] 10 cases completed
[MainProcess/INFO] 20 cases completed
[MainProcess/INFO] 30 cases completed
[MainProcess/INFO] 40 cases completed
[MainProcess/INFO] 50 cases completed
[MainProcess/INFO] 60 cases completed
[MainProcess/INFO] 70 cases completed
[MainProcess/INFO] 80 cases completed
[MainProcess/INFO] 90 cases completed
[MainProcess/INFO] 100 cases completed
[MainProcess/INFO] experiments finished
[MainProcess/INFO] results saved successfully to ./results/results_Manzanillo_100_v3.tar.gz
```

In [23]:

```
experiments, outcomes = results
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In [24]:

```
experiments
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Out[24]:

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     dtype=[('Wind speed shape change', '<f8'), ('Wind speed scale change', '<f8'), ('Temperature shape change', '<f8'), ('Temperature scale change', '<f8'), ('Wave height shape change', '<f8'), ('Wave height scale change', '<f8'), ('Sea level shape change', '<f8'), ('Sea level scale change', '<f8'), ('Mean sea level change', '<f8'), ('Precipitation volume shape change', '<f8'), ('Precipitation volume scale change', '<f8'), ('model', 'O'), ('policy', 'O')])
```


In [26]:

```
import numpy as np

from ema_workbench.analysis.plotting import lines
from ema_workbench.analysis.plotting_util import BOXPLOT, KDE, VIOLIN

experiments, outcomes = results
oois = outcomes.keys()

for ooi in oois:
```

```
    data_to_sort_by = outcomes[ooi][:,-1]
    indices = np.argsort(data_to_sort_by)
    indices = indices[1:indices.shape[0]:50]

    fig, axes = lines(results, outcomes_to_show=ooi, density=VIOLIN, show_envelope=True,
                experiments_to_show=indices)

    fig.set_figwidth(20)

plt.show()
```

```
---------------------------------------------------------------------------
LinAlgError                               Traceback (most recent call last)
<ipython-input-26-0c1b78d592b2> in <module>()
     13
     14     fig, axes = lines(results, outcomes_to_show=ooi, density=VIOLIN, show_envelope=True,
---> 15                 experiments_to_show=indices)
     16
     17     fig.set_figwidth(20)

D:\dijk_rn\Desktop\Master Thesis\python\EMAworkbench-master\src\ema_workbench\analysis\plotting.pyc in lines(results, outcomes_to_show, group_by, grouping_specifiers, density, legend, titles, ylabels, experiments_to_show, show_envelope, log)
    342                                 grouping_specifiers=grouping_specifiers,
    343                                 experiments_to_show=experiments_to_show,
--> 344                                 titles=titles, ylabels=ylabels, log=log)
    345
    346     if experiments_to_show is not None:

D:\dijk_rn\Desktop\Master Thesis\python\EMAworkbench-master\src\ema_workbench\analysis\plotting.pyc in plot_lines_with_envelopes(results, outcomes_to_show, group_by, grouping_specifiers, density, legend, titles, ylabels, experiments_to_show, log)
    514             plot_envelope(ax, 0, time, value, fill=True)
    515             if density:
--> 516                 simple_density(density, value, ax_d, ax, log)
    517
    518             value = outcomes[outcome_to_plot]

D:\dijk_rn\Desktop\Master Thesis\python\EMAworkbench-master\src\ema_workbench\analysis\plotting_util.pyc in simple_density(density, value, ax_d, ax, log)
    300         plot_boxplots(ax_d, value[:,-1], log)
    301     elif density==VIOLIN:
--> 302         plot_violinplot(ax_d, [value[:,-1]], log)
    303     else:
    304         raise EMAError("unknown density plot type")

D:\dijk_rn\Desktop\Master Thesis\python\EMAworkbench-master\src\ema_workbench\analysis\plotting_util.pyc in plot_violinplot(ax, value, log, group_labels)
    209     for data, p in zip(value,pos):
    210         if len(data)>0:
--> 211             kde = gaussian_kde(data) #calculates the kernel density
    212             x = np.linspace(np.min(data),np.max(data),250.) # support for violin
    213             v = kde.evaluate(x) #violin profile (density curve)

C:\Anaconda\lib\site-packages\scipy\stats\kde.pyc in __init__(self, dataset, bw_method)
    169
    170         self.d, self.n = self.dataset.shape
--> 171         self.set_bandwidth(bw_method=bw_method)
    172
    173     def evaluate(self, points):

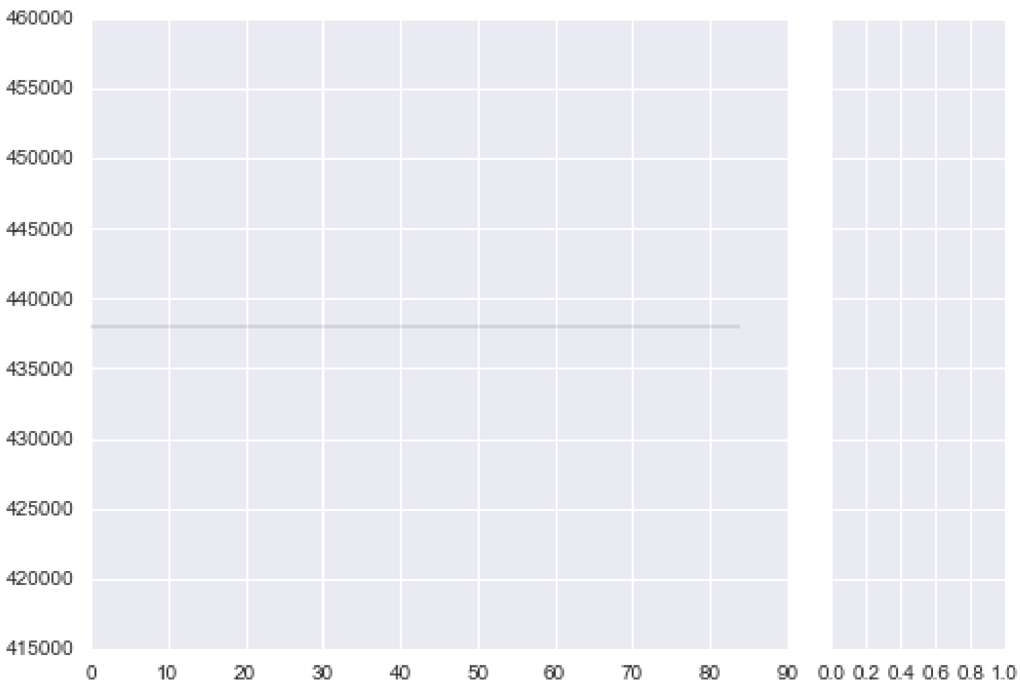
C:\Anaconda\lib\site-packages\scipy\stats\kde.pyc in set_bandwidth(self, bw_method)
    496             raise ValueError(msg)
```

```
    497
--> 498         self._compute_covariance()
    499
    500     def _compute_covariance(self):

C:\Anaconda\lib\site-packages\scipy\stats\kde.pyc in _compute_covariance(self)
    507             self._data_covariance = atleast_2d(np.cov(self.dataset, rowvar=1,
    508                                                bias=False))
--> 509             self._data_inv_cov = linalg.inv(self._data_covariance)
    510
    511         self.covariance = self._data_covariance * self.factor**2

C:\Anaconda\lib\site-packages\scipy\linalg\basic.pyc in inv(a, overwrite_a, check_finite)
    685         inv_a, info = getri(lu, piv, lwork=lwork, overwrite_lu=1)
    686     if info > 0:
--> 687         raise LinAlgError("singular matrix")
    688     if info < 0:
    689         raise ValueError('illegal value in %d-th argument of internal '

LinAlgError: singular matrix
```



In [27]:

```
import pandas as pd

df_experiments = pd.DataFrame.from_records(experiments)
```

In [28]:

```
df_experiments.iloc[1]
```

Out[28]:

```
Wind speed shape change          -0.00177666
Wind speed scale change           0.0216645
Temperature shape change          -0.00100154
Temperature scale change         -5.8771e-05
Wave height shape change         -0.00136442
Wave height scale change         0.00483914
Sea level shape change           0.0006276
Sea level scale change          -0.000786989
Mean sea level change             0.00352068
Precipitation volume shape change  -0.000622156
Precipitation volume scale change   -0.00435174
model                         ClimateModel
policy                            None
Name: 1, dtype: object
```

Running of the Manzanillo model with extreme temperature change

In [150]:

```
'''
Created on 27 Jul. 2011

This file illustrated the use the EMA classes for a model in Excel.

It used the excel file provided by
`A. Sharov <http://home.comcast.net/~sharov/PopEcol/lec10/fullmod.html>`_

This excel file implements a simple predator prey model.

.. codeauthor:: jhkwakkel <j.h.kwakkel (at) tudelft (dot) nl>
'''
from __future__ import (division, print_function, absolute_import,
                        unicode_literals)

from ema_workbench.em_framework import (ModelEnsemble, RealParameter,
                                        TimeSeriesOutcome, perform_experiments)
from ema_workbench.util import ema_logging
from ema_workbench.connectors.excel import ExcelModelStructureInterface

from ema_workbench.util import save_results

if __name__ == "__main__":
    ema_logging.log_to_stderr(level=ema_logging.INFO)

    model = ExcelModelStructureInterface("ClimateModel", r"./models/excelModel",
                                         model_file=r'\excel examples2.xlsx')
    model.uncertainties = [RealParameter('Wind speed shape change', -0.002, 0.002, variable_name='C3'),
                           RealParameter('Wind speed scale change', -0.01, 0.03, variable_name='C4'),
                           RealParameter('Temperature shape change', -0.002, 0.002, variable_name='C5'),
                           RealParameter('Temperature scale change', -0.001, 0.003, variable_name='C6'),
                           RealParameter('Wave height shape change', -0.002, 0.002, variable_name='C7'),
                           RealParameter('Wave height scale change', -0.01, 0.03, variable_name='C8'),
                           RealParameter('Sea level shape change', -0.002, 0.002, variable_name='C9'),
                           RealParameter('Sea level scale change', -0.001, 0.003, variable_name='C10'),
                           RealParameter('Mean sea level change', -0.001, 0.005, variable_name='C11'),
                           RealParameter('Precipitation volume shape change', -0.002, 0.002, variable_name='C12'),
                           RealParameter('Precipitation volume scale change', -0.01, 0.03, variable_name='C13'),]
    #specification of the outcomes
    model.outcomes = [TimeSeriesOutcome('level of service [hour/TEU]', variable_name="H9:H93"),
                      TimeSeriesOutcome('capacity [TEU/year]', variable_name="I9:I93"), # we can also use nam
```

```
ed range
                    TimeSeriesOutcome('utilization', variable_name="J9:J93")]

    #name of the sheet
    model.sheet = "INPUT AND OUTPUT"

    ensemble = ModelEnsemble()
    ensemble.model_structures = model

    results = perform_experiments(model, 10000, parallel=False)
    save_results(results, r'./results/results_Manzanillo_Extreme_10000_v2.tar.gz')
    experiments, outcomes = results
```

```
[MainProcess/INFO] 10000 experiment will be executed
[MainProcess/INFO] starting to perform experiments sequentially
[MainProcess/INFO] 1000 cases completed
[MainProcess/INFO] 2000 cases completed
[MainProcess/INFO] 3000 cases completed
[MainProcess/INFO] 4000 cases completed
[MainProcess/INFO] 5000 cases completed
[MainProcess/INFO] 6000 cases completed
[MainProcess/INFO] 7000 cases completed
[MainProcess/INFO] 8000 cases completed
[MainProcess/INFO] 9000 cases completed
[MainProcess/INFO] 10000 cases completed
[MainProcess/INFO] experiments finished
[MainProcess/INFO] results saved successfully to ./results/results_Manzanillo_Extreme_10000_v2.tar.gz
```

In [151]:

```
import numpy as np

from ema_workbench.analysis.plotting import lines
from ema_workbench.analysis.plotting_util import BOXPLOT, KDE, VIOLIN

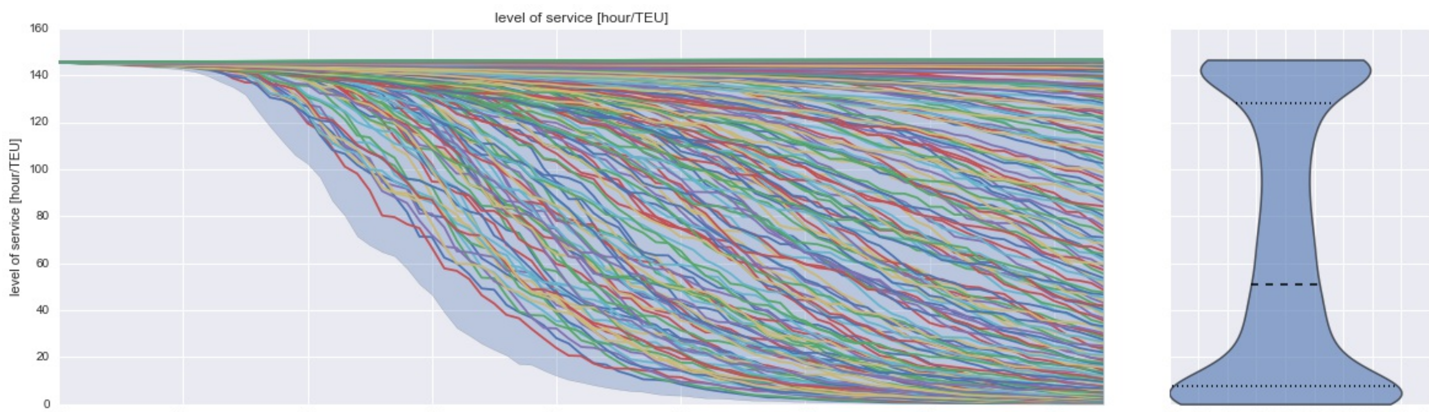
experiments, outcomes = results
oois = outcomes.keys()

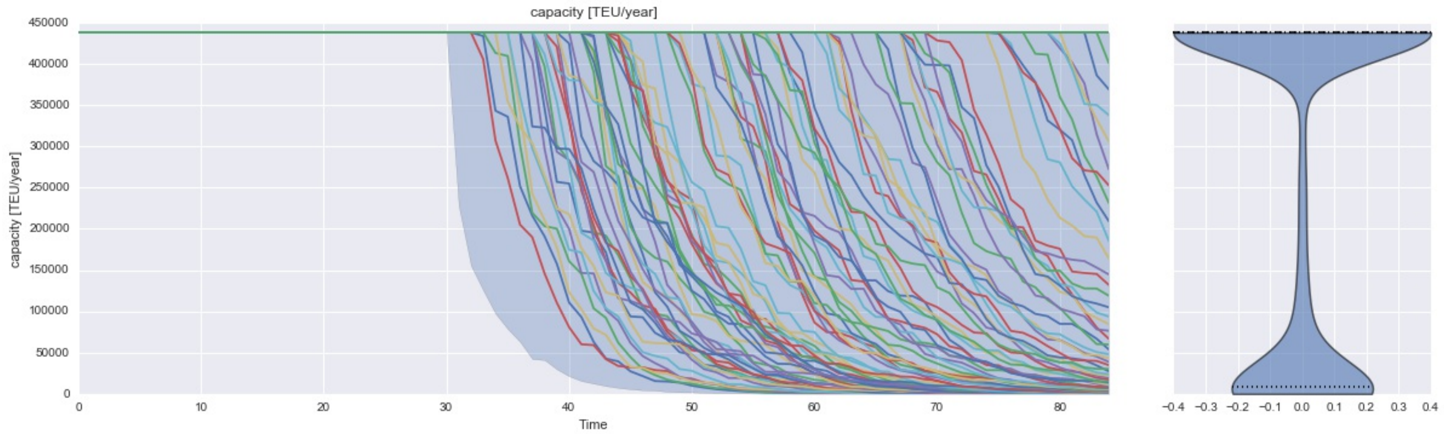
for ooi in oois:
    data_to_sort_by = outcomes[ooi][:,-1]
    indices = np.argsort(data_to_sort_by)
    indices = indices[1:indices.shape[0]:50]

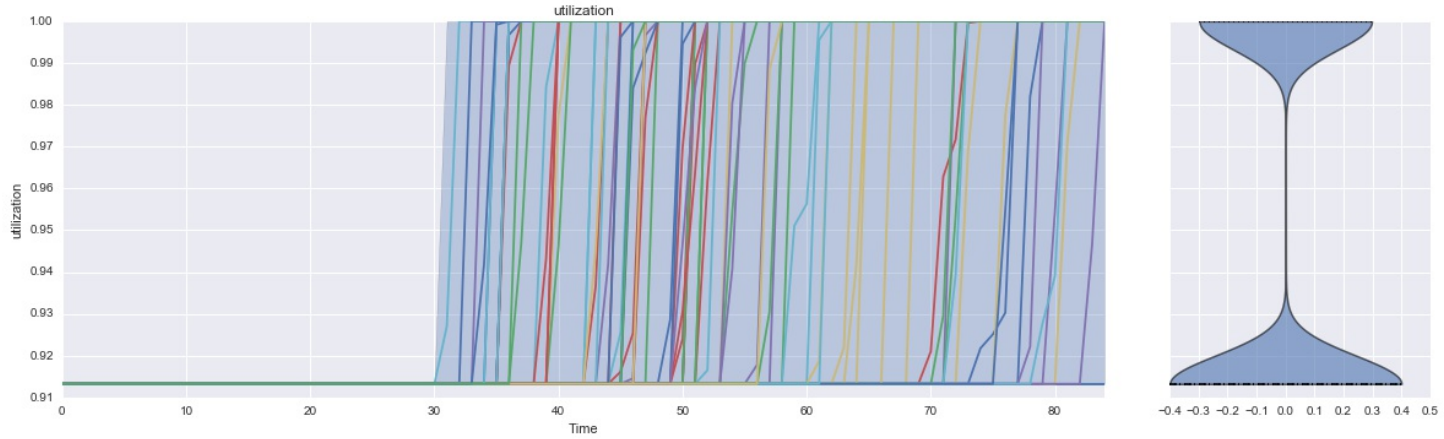
    fig, axes = lines(results, outcomes_to_show=ooi, density=VIOLIN, show_envelope=True,
                      experiments_to_show=indices)

    fig.set_figwidth(20)


plt.show()
```







In [160]:

```
x=outcomes['utilization']
y=outcomes['level of service [hour/TEU]']
z=outcomes['capacity [TEU/year]']

UTIL=[]

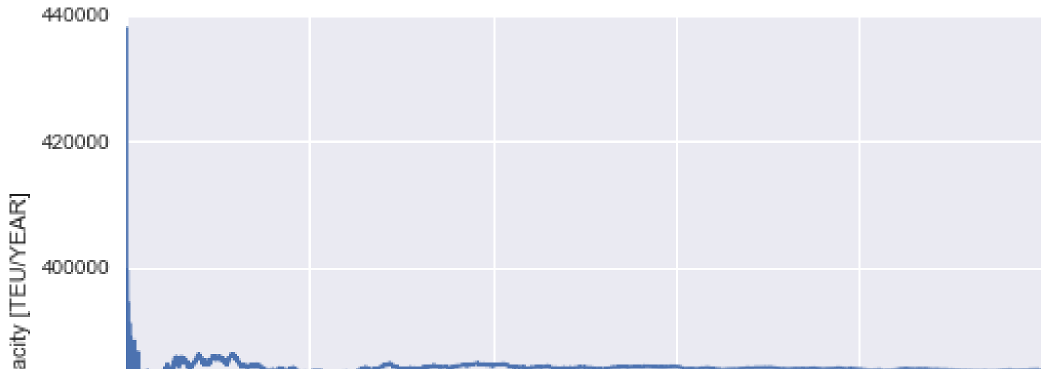
for i in range(1,9999):
    mean=np.mean(x[0:i])
    UTIL.append(mean)

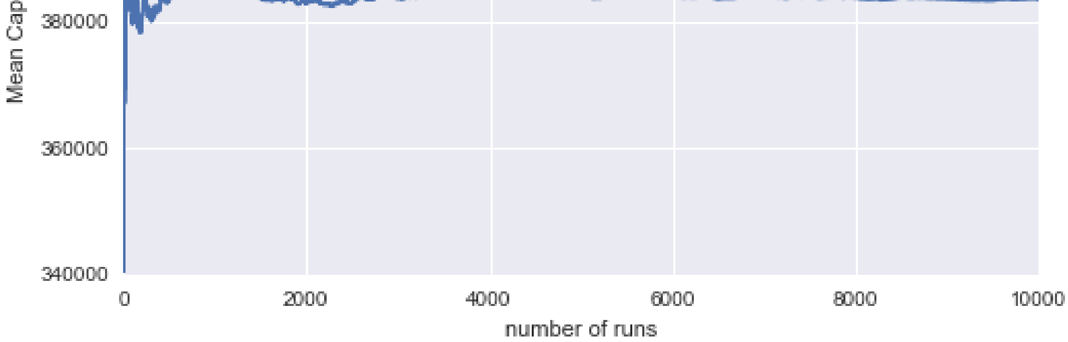
CAP=[]
for i in range(1,9999):
    mean=np.mean(z[0:i])
    CAP.append(mean)

plt.plot(CAP)
plt.xlabel('number of runs')
plt.ylabel('Mean Capacity [TEU/YEAR]')
plt.show
```

Out[160]:

<function matplotlib.pyplot.show>





In [39]:

```
KPI=[]

for i in range(1,x.shape):
    mean=np.mean(x,i)
    KPI.append
for i in range(1,100):
    mean=np.mean(x(1,i)
    KPI.append(x);

for ooi in oois:
    data_to_sort_by = outcomes[ooi][:,-1]
    indices = np.argsort(data_to_sort_by)
    indices = indices[1:indices.shape[0]:50]
```

In [51]:

```
KPI=[]
for i in range(1,data.shape):
    mean=np.mean(experiments(1,i))
    KPI.append
```

```
---------------------------------------------------------------------------
NameError                                 Traceback (most recent call last)
<ipython-input-51-d531bdcfec81> in <module>()
      1 KPI=[]
----> 2 for i in range(1,data.shape):
      3     mean=np.mean(experiments(1,i))
      4     KPI.append

NameError: name 'data' is not defined
```

In [18]:

```
import numpy as np
from ema_workbench.analysis.plotting import lines

experiments, outcomes = results
oois = outcomes.keys()

for ooi in oois:
    data_to_sort_by = outcomes[ooi][:,-1]
    indices = np.argsort(data_to_sort_by)
    indices = indices[1:indices.shape[0]:50]



data=
for i in range(1,data.shape):
    Mean=np.mean(data(1,i))
    KPI.append
```

```
---------------------------------------------------------------------------
NameError                                 Traceback (most recent call last)
<ipython-input-18-79ed53117553> in <module>()
      1 import numpy as np
      2 
----> 3 experiments, outcomes = results
      4 oois = outcomes.keys()
      5 

NameError: name 'results' is not defined
```

In [20]:

```
from ema_workbench.analysis import prim
from ema_workbench.util import ema_logging

ema_logging.log_to_stderr(level=ema_logging.INFO)

x = experiments
y = outcomes['capacity [TEU/year]'][:,-1] < 30000

prim_alg = prim.Prim(x,y, threshold=0.8)
box1 = prim_alg.find_box()
```

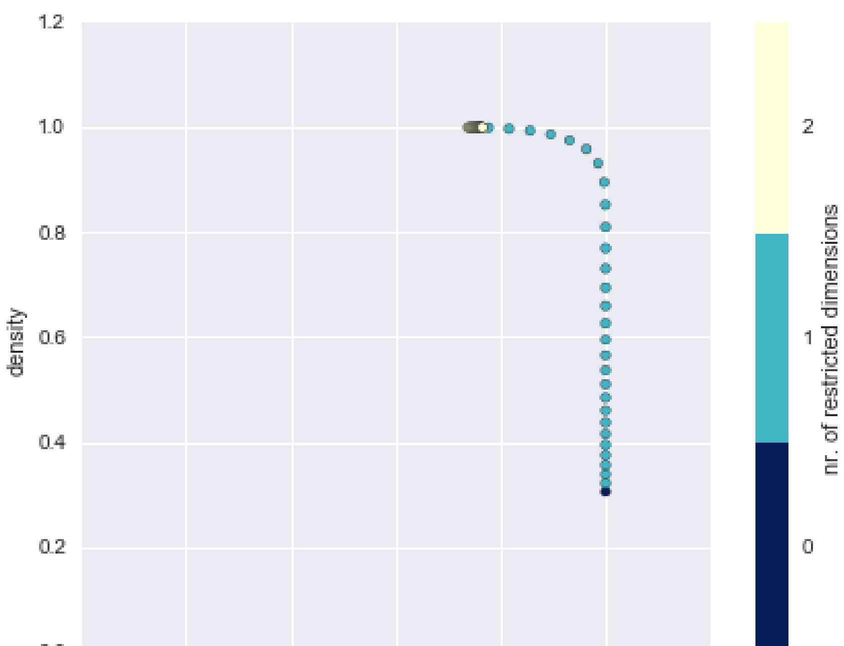
```
[MainProcess/INFO] 10000 points remaining, containing 3051 cases of interest
[MainProcess/INFO] mean: 0.999572100984, mass: 0.2337, coverage: 0.765650606359, density: 0.999572
100984 restricted_dimensions: 2.0
```

In [21]:

```
import mpld3 # enables interaction with trade off curve
fig = box1.show_tradeoff()
change_fontsize(fig)
mpld3.display()
```

```
---------------------------------------------------------------------------
NameError                                 Traceback (most recent call last)
<ipython-input-21-a0aab40646a9> in <module>()
      1 import mpld3 # enables interaction with trade off curve
      2 fig = box1.show_tradeoff()
----> 3 change_fontsize(fig)
      4 mpld3.display()

NameError: name 'change_fontsize' is not defined
```



In [22]:

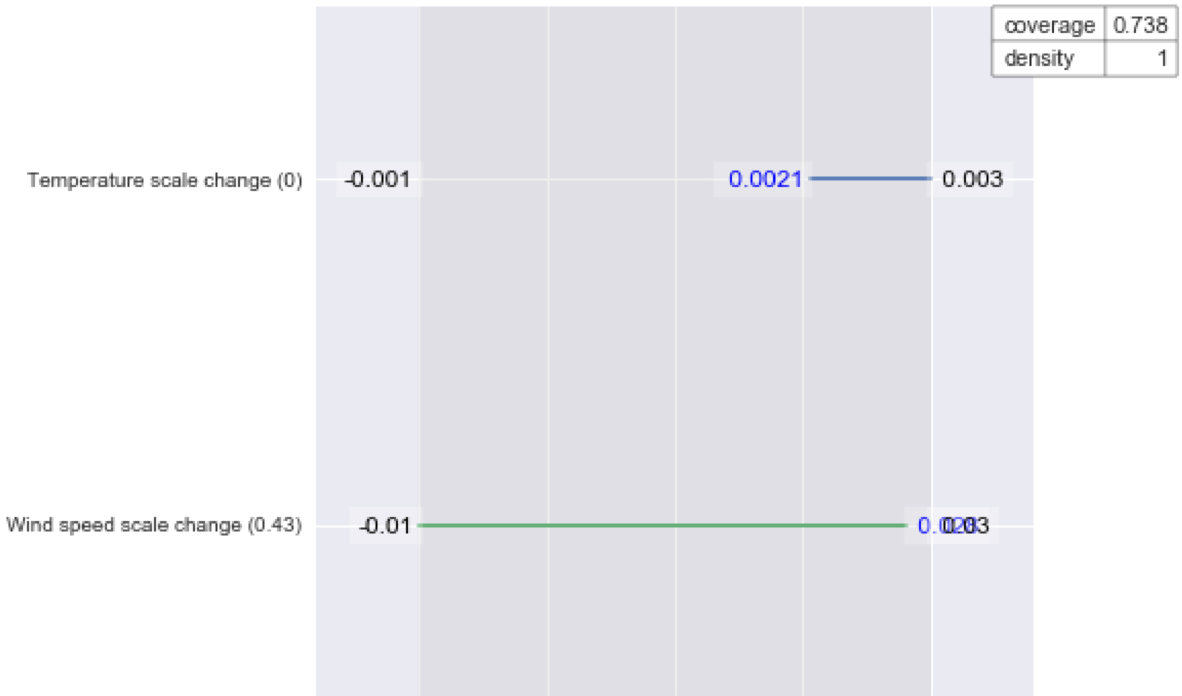
```
box1.inspect(i=29)
```

```
coverage    0.738119
density     0.999556
mass        0.225300
mean        0.999556
res dim     2.000000
Name: 29, dtype: float64

                           box 29
                              min       max qp values
Temperature scale change  0.002051  0.003000  0.000000
Wind speed scale change  -0.009998  0.028084  0.433737
```

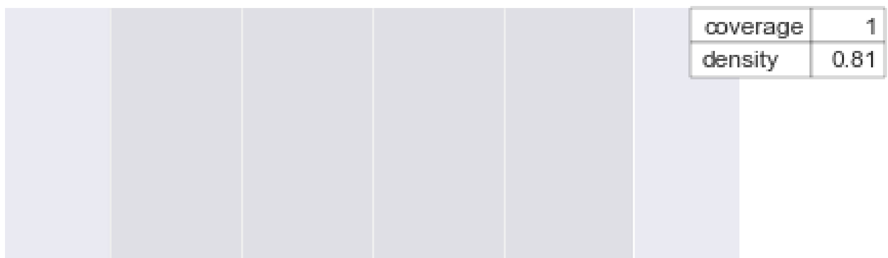
In [23]:

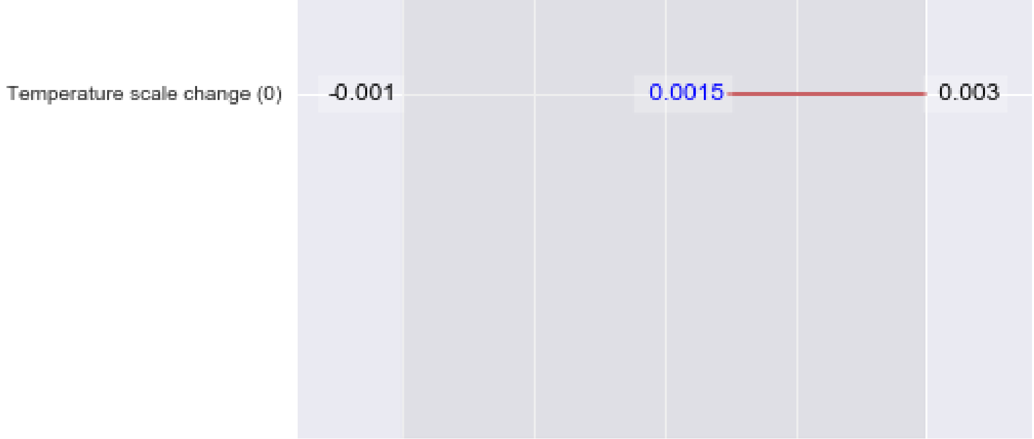
```
fig = box1.inspect(i=29, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```



In [24]:

```
fig = box1.inspect(i=19, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```





A similar container terminal in less favorable climate

In [56]:

```
'''
Created on 27 Jul. 2011

This file illustrated the use the EMA classes for a model in Excel.

It used the excel file provided by
`A. Sharov <http://home.comcast.net/~sharov/PopEcol/lec10/fullmod.html>`_

This excel file implements a simple predator prey model.

.. codeauthor:: jhkwakkel <j.h.kwakkel (at) tudelft (dot) nl>
'''
from __future__ import (division, print_function, absolute_import,
                        unicode_literals)

from ema_workbench.em_framework import (ModelEnsemble, RealParameter,
                                        TimeSeriesOutcome, perform_experiments)
from ema_workbench.util import ema_logging
from ema_workbench.connectors.excel import ExcelModelStructureInterface

from ema_workbench.util import save_results

if __name__ == "__main__":
    ema_logging.log_to_stderr(level=ema_logging.INFO)

    model = ExcelModelStructureInterface("ClimateModel", r"./models/Excelmodel",
                                         model_file=r'\OtherCase2.xlsx')
    model.uncertainties = [RealParameter('Wind speed shape change', -0.002, 0.002, variable_name='C3'),
                           RealParameter('Wind speed scale change', -0.01, 0.03, variable_name='C4'),
                           RealParameter('Temperature shape change', -0.002, 0.002, variable_name='C5'),
                           RealParameter('Temperature scale change', -0.0005, 0.0005, variable_name='C6'),
                           RealParameter('Wave height shape change', -0.002, 0.002, variable_name='C7'),
                           RealParameter('Wave height scale change', -0.01, 0.003, variable_name='C8'),
                           RealParameter('Sea level shape change', -0.002, 0.002, variable_name='C9'),
                           RealParameter('Sea level scale change', -0.001, 0.003, variable_name='C10'),
                           RealParameter('Mean sea level change', -0.001, 0.005, variable_name='C11'),
                           RealParameter('Precipitation volume shape change', -0.002, 0.002, variable_name='C12'),
                           RealParameter('Precipitation volume scale change', -0.01, 0.03, variable_name='C13'),]
        #specification of the outcomes
    model.outcomes = [TimeSeriesOutcome('level of service [hour/TEU]', variable_name="H9:H93"),
                      TimeSeriesOutcome('capacity [TEU/year]', variable_name="I9:I93"), # we can also use nam
ed range
                      TimeSeriesOutcome('utilization', variable_name="J9:J93")]

    #name of the sheet
```

```
    #name of the sheet
    model.sheet = "INPUT AND OUTPUT"

    ensemble = ModelEnsemble()
    ensemble.model_structures = model

    results = perform_experiments(model, 100, parallel=False)
    save_results(results, r'./results/results_Other_Normal_100_v3.tar.gz')
    experiments, outcomes = results
```

```
[MainProcess/INFO] 10000 experiment will be executed
[MainProcess/INFO] starting to perform experiments sequentially
[MainProcess/INFO] 1000 cases completed
[MainProcess/INFO] 2000 cases completed
[MainProcess/INFO] 3000 cases completed
[MainProcess/INFO] 4000 cases completed
[MainProcess/INFO] 5000 cases completed
[MainProcess/INFO] 6000 cases completed
[MainProcess/INFO] 7000 cases completed
[MainProcess/INFO] 8000 cases completed
[MainProcess/INFO] 9000 cases completed
[MainProcess/INFO] 10000 cases completed
[MainProcess/INFO] experiments finished
[MainProcess/INFO] results saved successfully to ./results/results_Other_Normal_10000_v3.tar.gz
```

In [57]:

```
import numpy as np

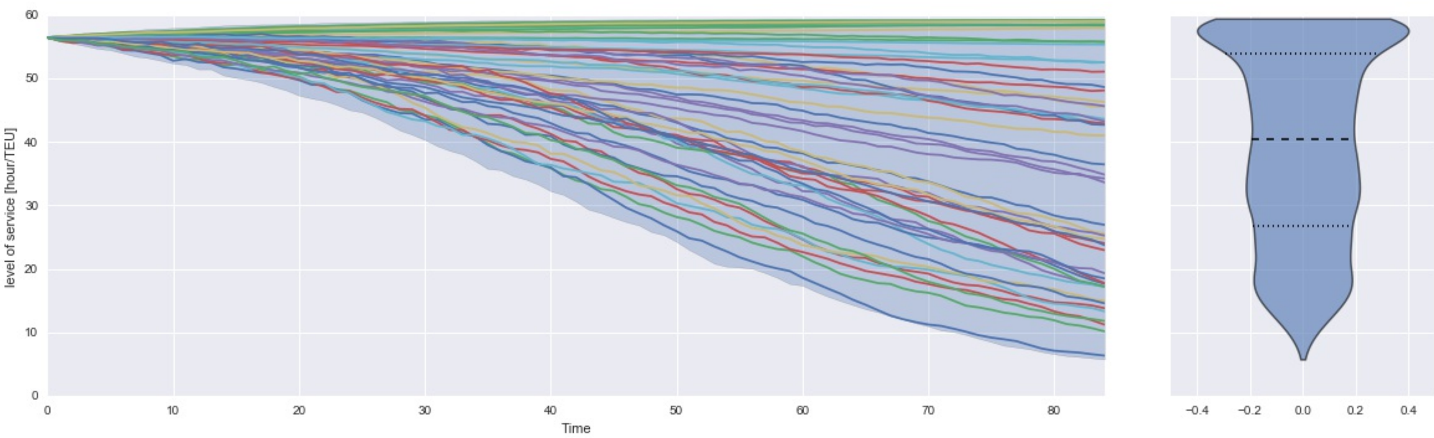
from ema_workbench.analysis.plotting import lines
from ema_workbench.analysis.plotting_util import BOXPLOT, KDE, VIOLIN

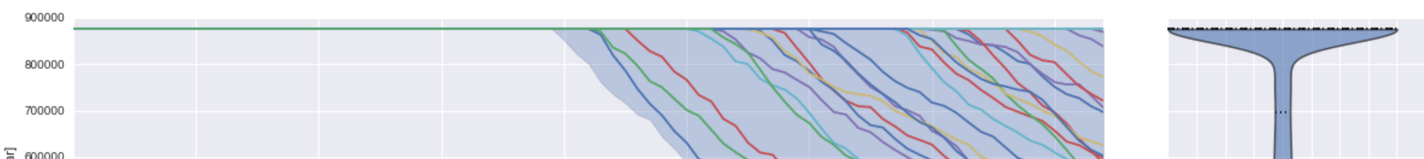
experiments, outcomes = results

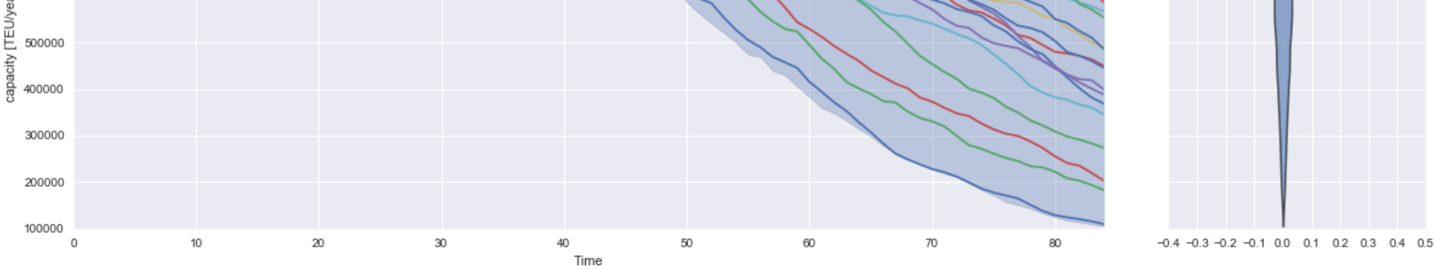

for outcome in outcomes.keys():
    experiments_to_show = np.arange(0, experiments.shape[0], 200)
    fig, axes = lines(results, show_envelope=True, density=VIOLIN,
                      outcomes_to_show=outcome,
                      experiments_to_show=experiments_to_show, titles=None,
                     )

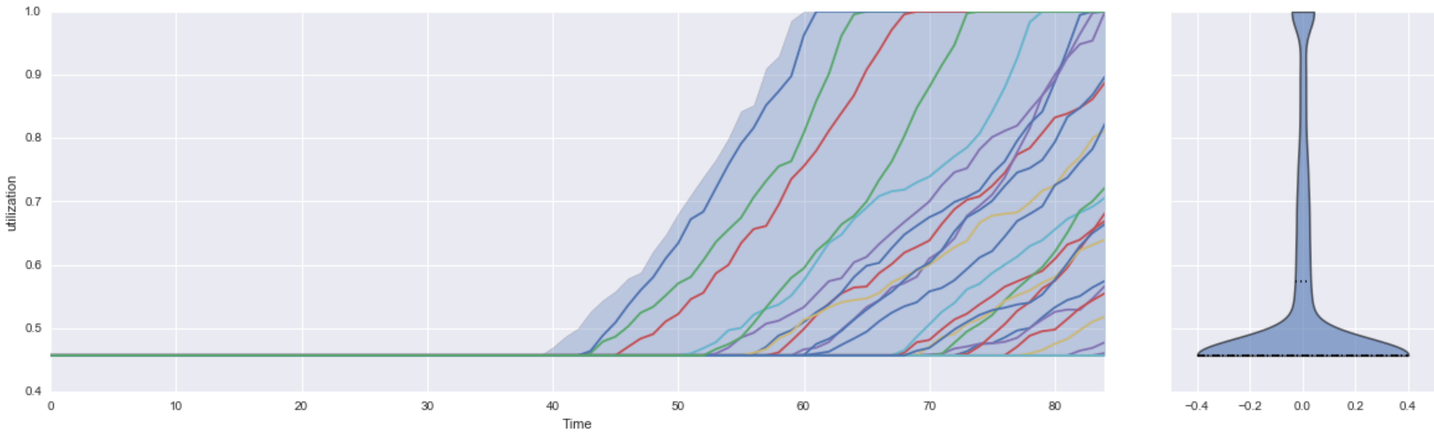
    fig.set_figwidth(20)

plt.show()
```









In [58]:

```
# import numpy as np

# from ema_workbench.analysis.plotting import lines
# from ema_workbench.analysis.plotting_util import BOXPLOT, KDE, VIOLIN

# fn = r'./results/results_1000_v3.tar.gz'
# results = load_results(fn)
# experiments, results = results

# experiments_to_show = np.arange(0, experiments.shape[0], 200)
# fig, axes = lines(results, show_envelope=True, density=KDE, titles=None,)

# plt.show()
```

In [59]:

```
outcomes.keys()
```

Out[59]:

```
[u'level of service [hour/TEU]', u'capacity [TEU/year]', u'utilization']
```

In [60]:

```
from ema_workbench.analysis import prim
from ema_workbench.util import ema_logging

ema_logging.log_to_stderr(level=ema_logging.INFO)

x = experiments
y = outcomes['capacity [TEU/year]'][:,-1] < 700800

prim_alg = prim.Prim(x,y, threshold=0.8)
box1 = prim_alg.find_box()
```

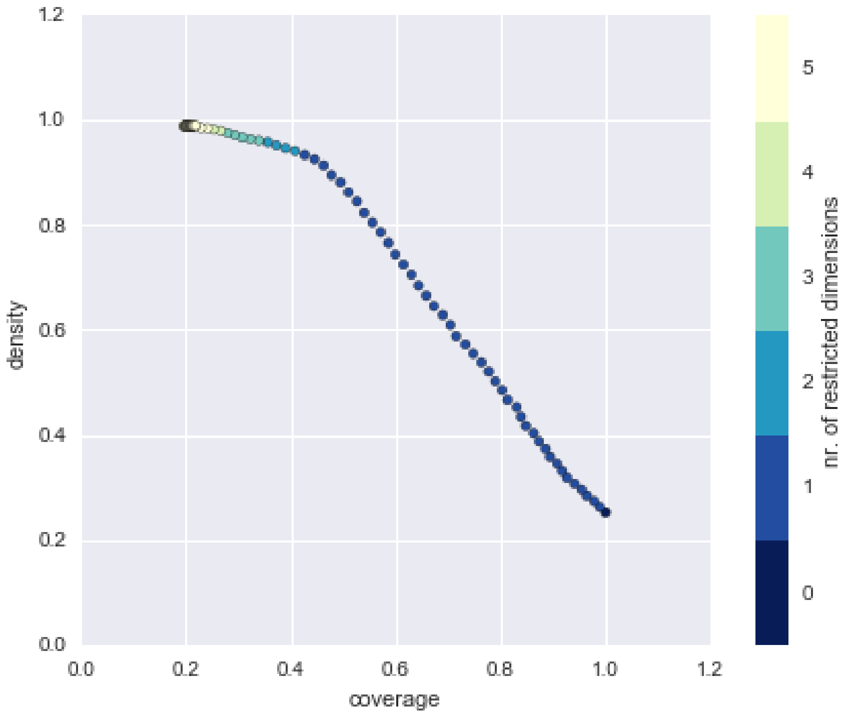
```
[MainProcess/INFO] 10000 points remaining, containing 2521 cases of interest
[MainProcess/INFO] mean: 0.989247311828, mass: 0.0558, coverage: 0.218960729869, density: 0.989247311828 restricted_dimensions: 5.0
```

In [61]:

```
import mpld3 # enables interaction with trade off curve
fig = box1.show_tradeoff()
change_fontsize(fig)
mpld3.display()
```

```
---------------------------------------------------------------------------
NameError                                 Traceback (most recent call last)
<ipython-input-61-a0aab40646a9> in <module>()
      1 import mpld3 # enables interaction with trade off curve
      2 fig = box1.show_tradeoff()
----> 3 change_fontsize(fig)
      4 mpld3.display()

NameError: name 'change_fontsize' is not defined
```



In [62]:

```
box1.inspect(i=44)
```

```
coverage    0.390321
density     0.946154
mass        0.104000
mean        0.946154
res dim     2.000000
Name: 44, dtype: float64

                            box 44
                              min       max qp values
Wind speed scale change   0.025625  0.029999  0.000000
Temperature scale change -0.000443  0.000500  0.250629
```

In [63]:

```
box1.inspect(i=10)
```

```
coverage    0.885760
density     0.373162
mass        0.598400
mean        0.373162
res dim     1.000000
Name: 10, dtype: float64

                            box 10
```

```
                      min       max     qp values
Wind speed scale change  0.006065  0.029999  5.159043e-95
```

In [71]:

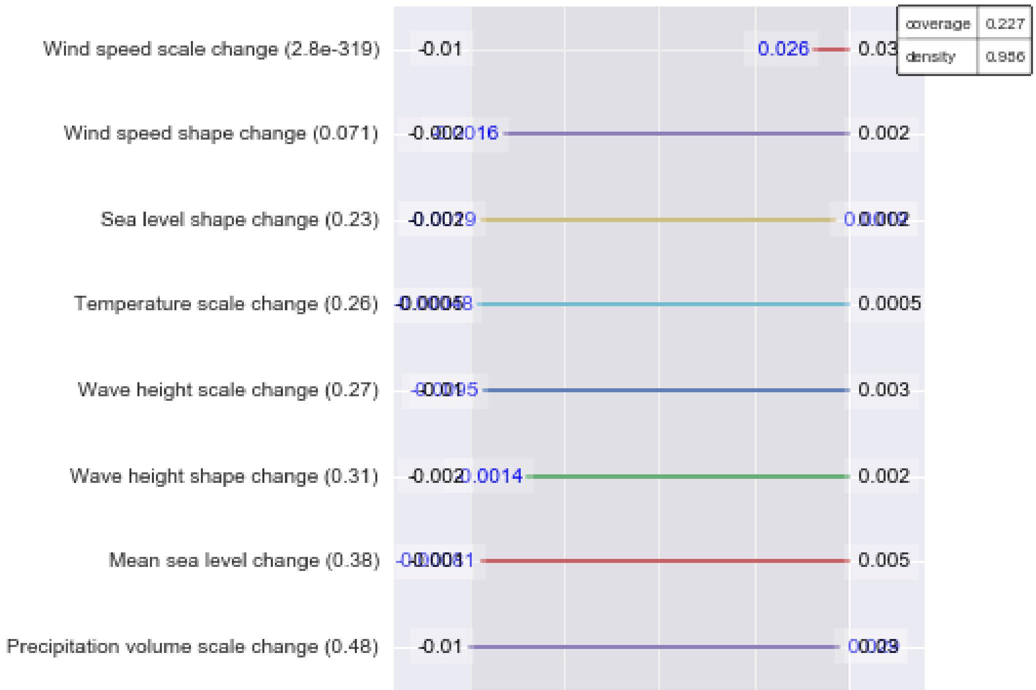
```
box1.inspect(i=94)
```

```
coverage    0.218961
density     0.989247
mass        0.055800
mean        0.989247
res dim     5.000000
Name: 94, dtype: float64

                            box 94
                             min       max      qp values
Wind speed scale change   0.026623  0.029999  2.111455e-310
Wind speed shape change  -0.001250  0.001683   9.418160e-04
Temperature shape change -0.001800  0.001955   1.696737e-01
Temperature scale change -0.000482  0.000500   2.164301e-01
Wave height shape change -0.002000  0.001806   2.482555e-01
```

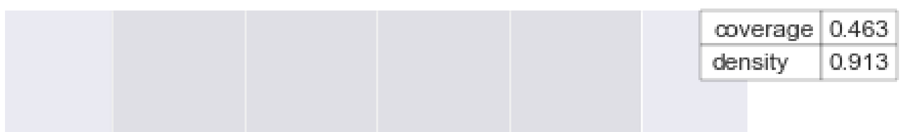
In [129]:

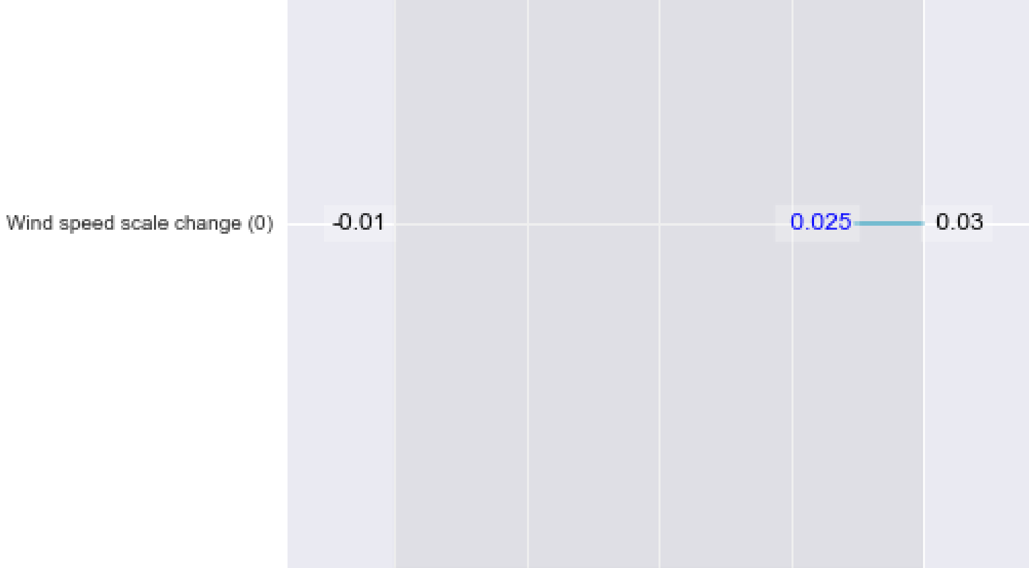
```
fig = box1.inspect(i=96, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```



In [73]:

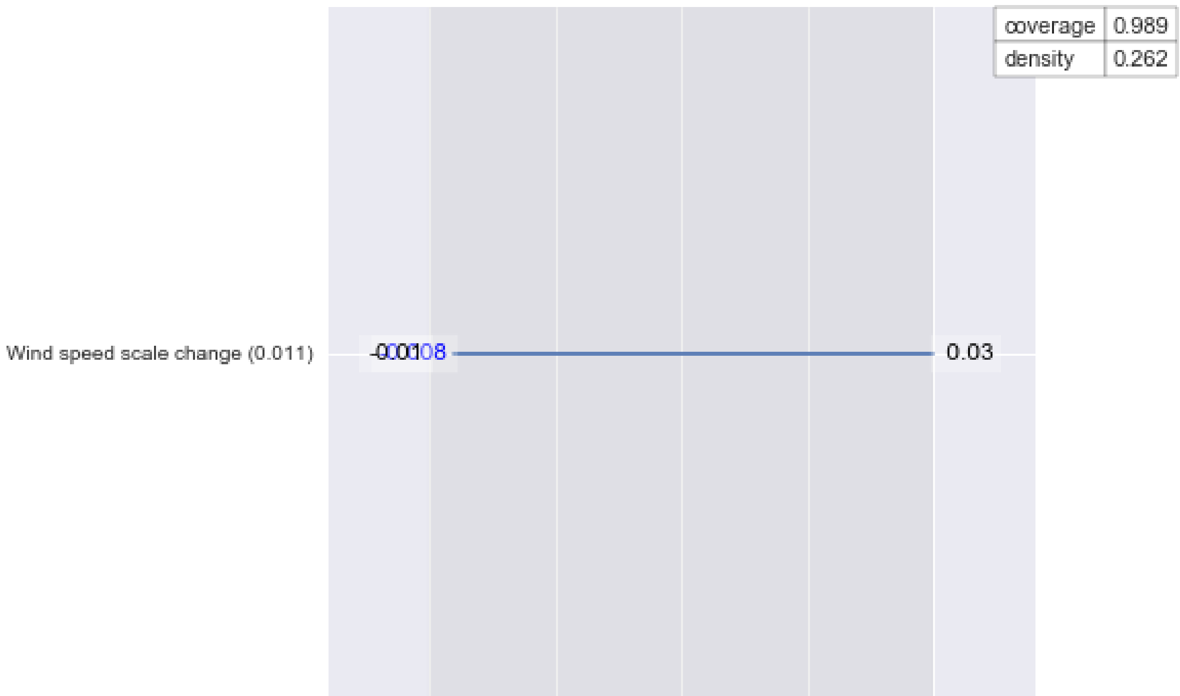
```
fig = box1.inspect(i=40, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```





In [74]:

```python
fig = box1.inspect(i=1, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```



In [75]:

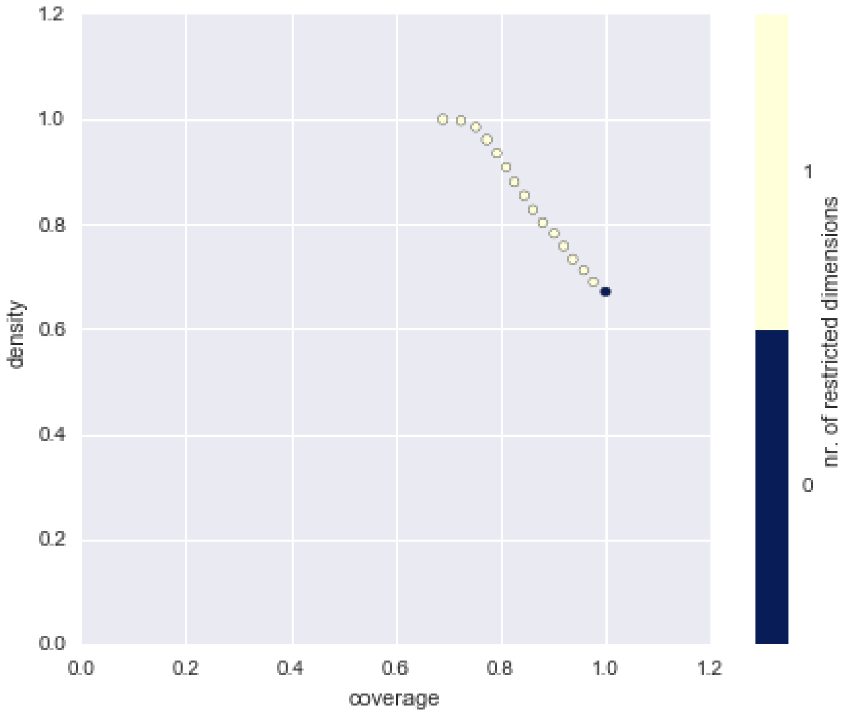
```python
from ema_workbench.analysis import prim
from ema_workbench.util import ema_logging

ema_logging.log_to_stderr(level=ema_logging.INFO)

x = experiments
y = outcomes['level of service [hour/TEU]'][:,-1] < 50

prim_alg = prim.Prim(x,y, threshold=0.8)
box1 = prim_alg.find_box()
```

```
[MainProcess/INFO] 10000 points remaining, containing 6707 cases of interest
[MainProcess/INFO] mean: 1.0, mass: 0.4628, coverage: 0.690025346653, density: 1.0 restricted_dimensio
ns: 1.0
```

In [77]:

```python
import mpld3 # enables interaction with trade off curve
fig = box1.show_tradeoff()
change_fontsize(fig)
mpld3.display()
```

```
---------------------------------------------------------------------------
NameError                                 Traceback (most recent call last)
<ipython-input-77-a0aab40646a9> in <module>()
      1 import mpld3 # enables interaction with trade off curve
      2 fig = box1.show_tradeoff()
----> 3 change_fontsize(fig)
      4 mpld3.display()

NameError: name 'change_fontsize' is not defined
```



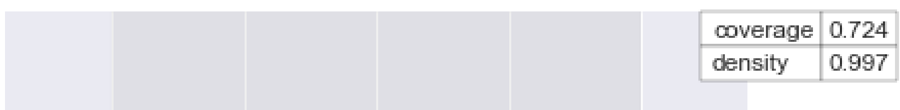
In [79]:

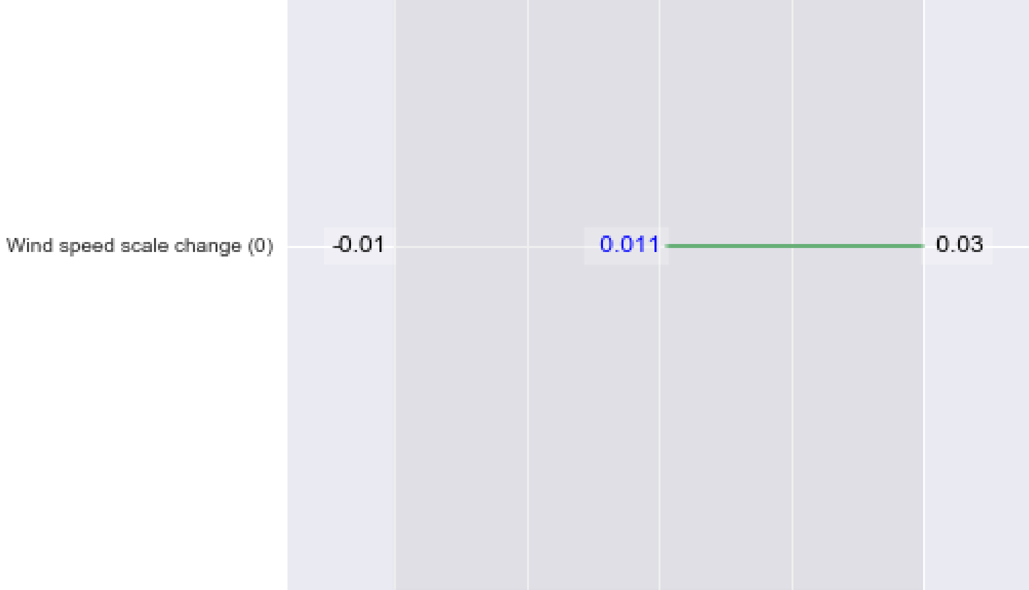
```python
box1.inspect(i=14)
```

```
coverage    0.724318
density     0.997126
mass        0.487200
mean        0.997126
res dim     1.000000
Name: 14, dtype: float64

                            box 14
                               min       max qp values
Wind speed scale change  0.010513  0.029999       0.0
```

In [80]:

```python
fig = box1.inspect(i=14, style='graph')
fig = mpl.pyplot.gcf()
fig.set_size_inches(7, 5)
# save_fig(fig, './figs/', 5)
plt.show()
```





In [167]:

```
>>> a = 5. # shape
>>> s = np.random.weibull(a, 1000)
```

In [ ]:

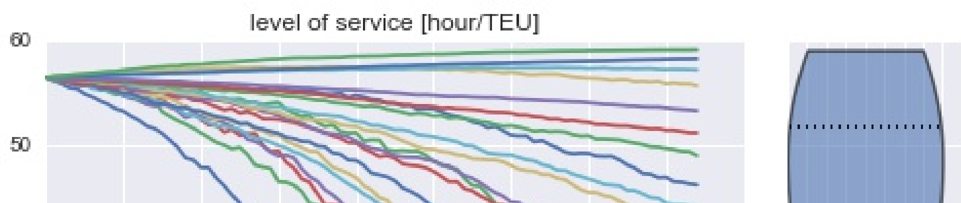
```
>>> import matplotlib.pyplot as plt
>>> x = np.arange(1,100.)/50.
>>> def weib(x,n,a):
...     return (a / n) * (x / n)**(a - 1) * np.exp(-(x / n)**a)
```

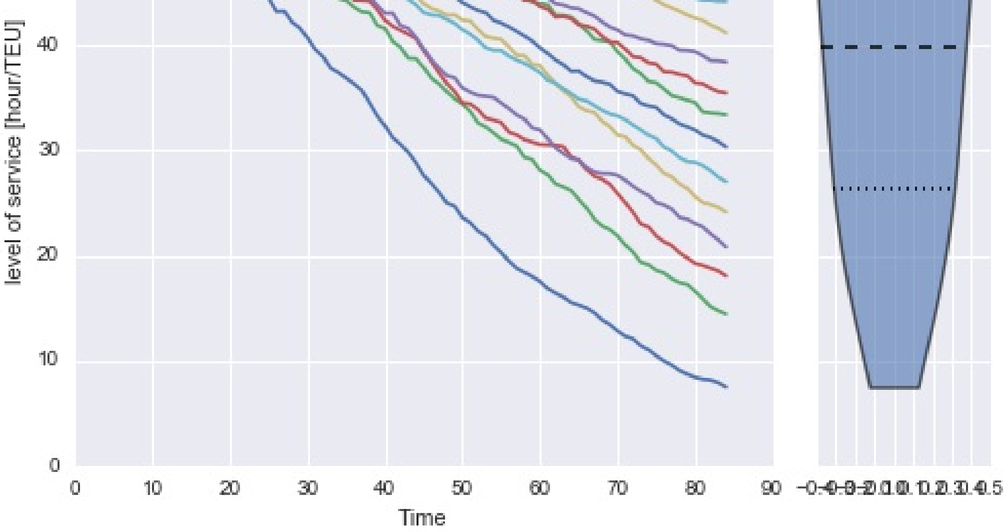
In [ ]:

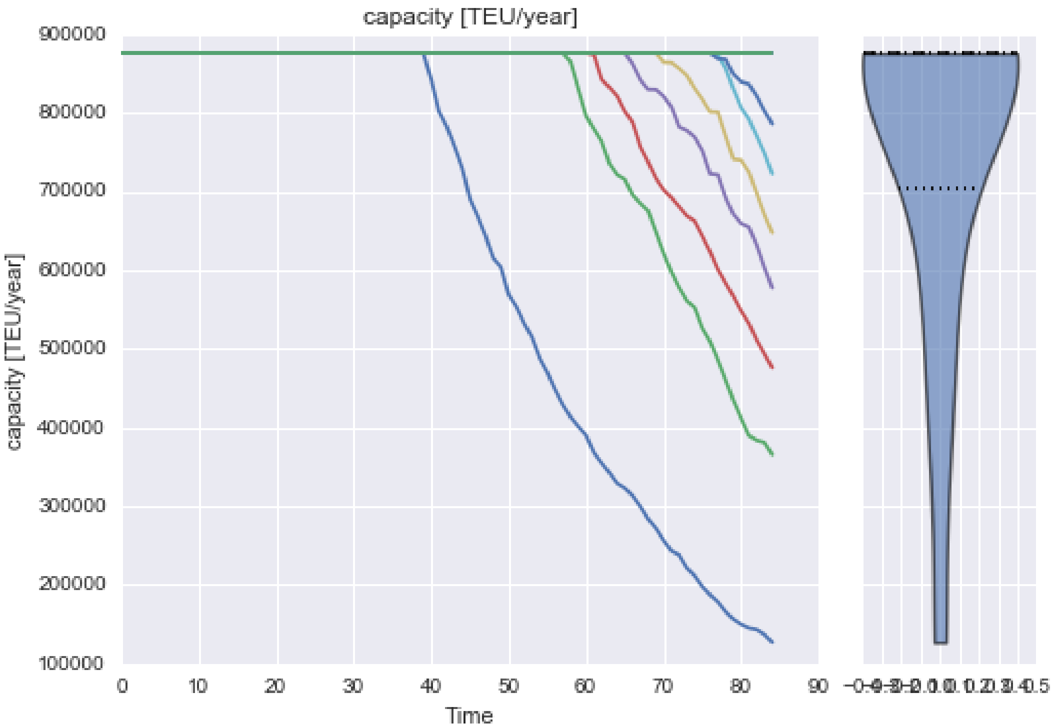
```
>>> count, bins, ignored = plt.hist(np.random.weibull(5.,1000))
>>> x = np.arange(1,100.)/50.
>>> scale = count.max()/weib(x, 1., 5.).max()
>>> plt.plot(x, weib(x, 1., 5.)*scale)
>>> plt.show()
```

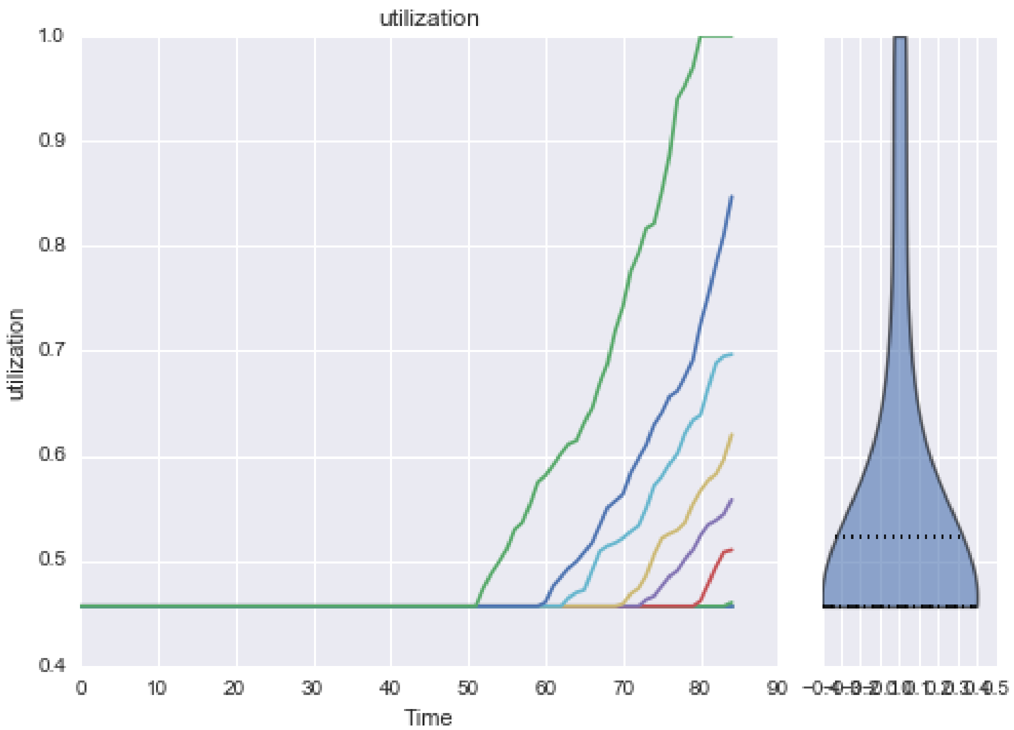
In [50]:

```
import numpy as np

from ema_workbench.analysis.plotting import lines
from ema_workbench.analysis.plotting_util import BOXPLOT, KDE, VIOLIN

experiments, outcomes = results
oois = outcomes.keys()

for ooi in oois:
    data_to_sort_by = outcomes[ooi][:,-1]
    indices = np.argsort(data_to_sort_by)
    indices = indices[1:indices.shape[0]:50]

    lines(results, outcomes_to_show=ooi, density=VIOLIN, show_envelope=False, experiments_to_show=indi
ces)

plt.show()
```




level of service [hour/TEU]
Time


capacity [TEU/year]
capacity [TEU/year]
Time


utilization
utilization
Time

Scientific Article

This appendix contains scientific article that was part of this thesis.

Climate Resilient Ports: A method to screen container terminal vulnerability to climate change

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Climate is changing, and container terminals are vulnerable to a changing climate. For new investments in ports, climate stress tests need to be performed. Research to determine the vulnerability of a container terminal to climate change is time consuming and expensive. Also, current research has been focusing on qualitative reports, effects of single weather events, or effectiveness of resilience measures, rather than making quantitative estimations on the vulnerability of the terminal. To analyze the vulnerability of container terminals to climate change, a method consisting of 5 blocks is proposed. With use of these five blocks, the vulnerability of container terminals to climate change can be quantified. Most of these five blocks are reusable with no or little adjustments for other cases. Due to the reuseability, the method can be used as screening tool for container terminals.

Keywords: Climate Change; Container Terminals; Scenario Discovery; Operations; Climate Resilience; Climate Adaptation; Deep Uncertainty

1. INTRODUCTION

Extreme precipitation occurred in the north-west of Europe on the first of June, 2016. Over 20.000 citizens had to be evacuated in France, streets were submerged, schools closed, dikes were at the point to break and over 15 people lost their lives. [1] [2] [3]. Gerrit Hiemstra, a Dutch weatherman from the NOS responded on these events by making the following statement on the national television: "Welkom in het nieuwe klimaat", which means "Welcome to the new climate" [4]. According to Hiemstra, these situations will most likely occur more often in the future. The consequences of this new climate are among others melting glaciers, more precipitation, more extreme weather events and shifting seasons [5]. Next to that, There might be an increase in regional human health risk [6], flooding risks all over the world is increasing [7] and 15- 37% of all species may be subjected to extinction in 2050 [8].

Large infrastructures such as ports are also vulnerable to climate change. Ports are vital to trade, and serve an important role in the global economy. Recent events have shown the risks that weather can impose on container terminals. Examples are heat waves in Australia [9] and hurricanes in the United States [10]. A changing climate may increase the frequency of extreme weather events, but might also shift the average climate. Container terminals are often found in an area that is exposed to weather-events. Their location make them vulnerable to climate change. Long term plans in container terminals should incorporate climate change. However, only 31% of all container terminals feel sufficiently informed about how climate change may affect their terminal [11]. The EU is currently weighing stress tests for banks' climate risk exposure. This implies that future investments must undergo climate stress tests. [12]

Recent research related to climate change impacts on container terminals included studies on the impact of single weather events to the operations in a container terminal[13], estimating the effectiveness of resilience measures [14] and making qualitative statements on the vulnerability of climate change [15],[16].

The types of studies that has been performed so far are time consuming and costly. Although they might be used as stress tests, other types of studies may be more convenient to perform. Standard methods for estimating the vulnerability of container terminals to climate change can help with selecting the terminals that need more in depth analysis.

This article gives an example of one such method. A method is proposed to estimate the impact of climate change on container terminals. The first section will provide a high-level description of the method.

The subsections following will give a more detailed description on each step of the method. The last section is a discussion on the generic applicability of this method.

2. METHODOLOGY

The method to determine climate change vulnerability of container terminal consists of 5 blocks.

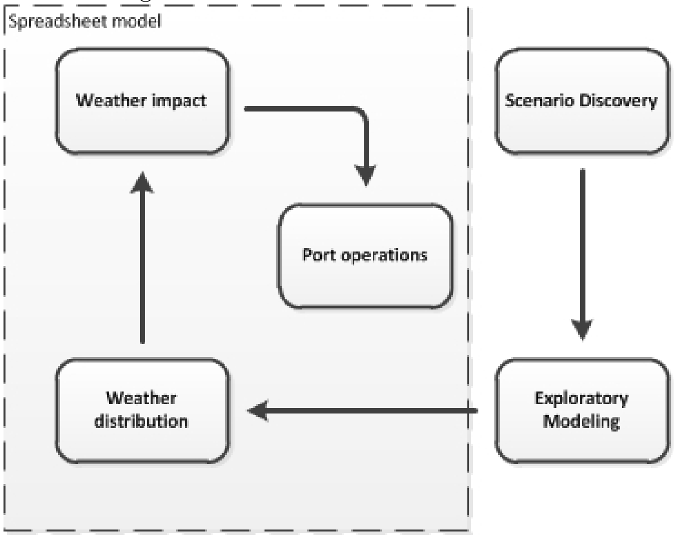
1. port operations
2. weather impact
3. weather distribution
4. exploratory modeling
5. scenario discovery

The method is visually represented by figure 1. Each block in this figure shows one of the building blocks for the method. In the first block, port operations, different assets and processes in a container terminal are identified. In this block, a measurement system for port performance is created. The second block, weather impact consequently describes how different types of weather influence the port operations, and hence the operational performance of a container terminal. Then, the third block, weather distribution is used to determine how often these different types of weather are occurring at a certain location. The first three blocks together are captured in a model, which can be used to calculate the performance of a container terminal given a set of conditions. In our case, an excel model is used. Exploratory modeling is consequently applied to generate a large set of different climate change scenarios. Each climate change scenario describes the distribution of weather at a certain point in the future. Lastly, scenario discovery is applied to analyze the outcomes of all these different climate change scenarios and to describe for which scenarios the terminal is vulnerable.

2.1. Port operations

To measure the impact of climate change on container terminals, the the operational performance of a container terminal must be quantified. Terminal operators and external organizations have already been able to quantify operational performance for a long time. However, diverse performance measurements have been proposed before. As Soner Esmer stated in his report: *"In the world, all ports are unique, and the task of measuring and analyzing performance is not simple"* [17]. The uniqueness of ports implies that a specific performance measure is more relevant to one port than to another. When we consider the key performance indicators presented by the port of Los Angeles [18], a very diverse set of indicators is provided. Examples of these are total ship calls, value of import, annual TEU's and annual gross revenue. Esmer concludes his research by noting the lack of agreement

FIGURE 1. A visual representation of the methodology used to estimate the vulnerability of container terminals to climate change.



on which indicators should be used to measure the performance of a container terminal. Nevertheless, most of the indicators that he mentioned could be divided in four categories: production, productivity , utilization and service[17].

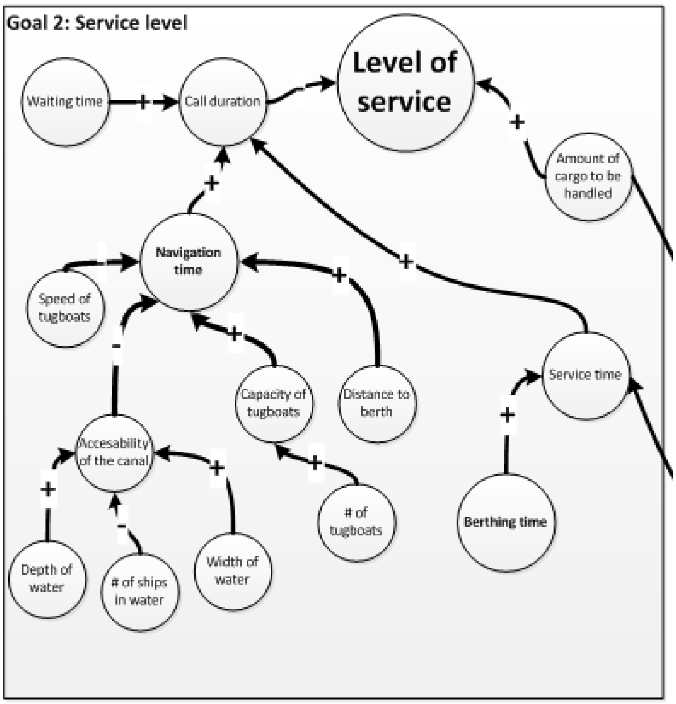
In this paper, we follow the indicators that were opted by an ad hoc expert meeting initiated by UNCTAD[19] as key performance indicators for the container terminal. Three key performance indicators can then be used to define the operational performance of container terminals.

1. **Terminal utilization**
   The utilization is a representation of how much of the terminal's capacity is actually used. It shows a terminal's ability to grow.
2. **Terminal capacity**
   The terminal capacity reflects the maximum amount of TEU a container terminal can handle in a year. This capacity can be restricted by crane capacity, storage capacity or transferring capacity. In this way, it represents all capacities in the terminal.
3. **Level of service**
   The level of service incorporates the interests of the client in the system. It is a measure of how long a vessel is in the terminal for delivering an x amount of TEU in a terminal.

Hence, some performance indicators are selected to reflect the performance of an arbitrary container terminal. The performance indicators used are not the only indicators that are suitable for this type of research. Nevertheless, they are a representation of container terminal performance that were easy to express in this research. How these indicators are calculated is further defined by the UNCTAD [19].

To understand how these key performance indicators are depending on the assets and processes in the container terminal, system diagrams are used. An example of such a diagram is presented in figure 2. The key performance indicator "Level of service" is presented here. Level of service is in this case dependent on the call duration and the amount of cargo to be handled. As the call duration influences the level of service, it is also dependent on other variables.

FIGURE 2. An example of a system diagram, showing the relations of different variables to the the level of service. The plus-signs indicate that the if the variable increases, the variable it is related to increases too.



This can be done for each of the key performance indicators. With these diagrams the inter-connectivity between the performance indicators become visible. The diagrams can consequently be used to construct a calculative body to calculate the performance of a container terminal given a set of conditions. In this case, a spreadsheet model is constructed.

2.2. Weather impact

Weather is influencing the operational performance of container terminals. Their influence should thus be related to the calculative body mentioned in the previous section. The impact of weather on the operational performance of container terminals is already described by several authors. Examples are the reports from the IFC [20], Kong [21], Graigner [22] and Nugroho [23]. The impacts described in these sources are related to performance indicators that were selected by them. The impact on the port performance should thus be adjusted to the performance indicators defined in the "port operations" block.

TABLE 1. Summarized impact from weather events. The first column shows the name of the weather event. The second column shows the effect of that event on the container terminal. The third column shows the conditions under which these events apply.

Event	Effects	Conditions
Less than strong breeze	Crane productivity stays 100%	Wind speed <10.8 m/s
Strong breeze	Crane productivity drops to 95%	Wind speed <13.9 m/s
Near gale	Crane productivity drops to 80%	Wind speed <17.2 m/s
More than near gale	All assets operate at 0%	Wind speed >17.2 m/s
Heat wave	Terminal capacity drops to 0%	Temperature >38°C
Frost	Speed of AGV drops to 3 m/2	Temperature <0°C
Extreme rainfall	Speed of AGV drops to 6 m/s	Precipitation >30mm/12h
Frozen precipitation	Speed of AGV drops to 3 m/s	Temperature <0°C and Precipitation >0mm/h
Heavy snowfall	Crane productivity drops to 80%	Precipitation >3cm/h
Flooding	Terminal capacity drops to 0%	Water level >quay height
High waves	Speed of tugboats drops to 0 m/s	Wave height >1.5 m/s

Nugroho [23] created a matrix to describe the impact of weather on a container terminal. A matrix such as created by Nugroho is not exhaustive, but can be used as a starting point for the weather impact for this article. Table 1 is an example of such a list of weather events, related to the performance indicators from the port operations.

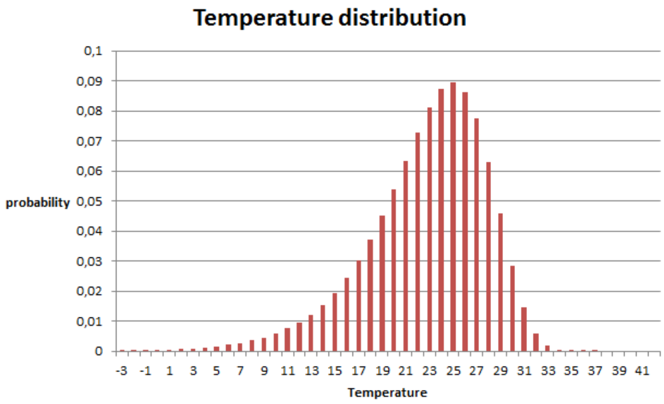
Hence, a list of weather events is constructed, relating to the system diagrams constructed in the port operations. The influence of the weather is taken into account in the spreadsheet model. With this information, the effect of a single weather event can be quantified for a container terminal. However, the operational performance of the terminal must be quantified over a year, rather than over a single point in time. To do so, the amount of time that the described weather events occur should be determined.

2.3. Weather distribution

For determining how often the weather events occur, statistical distribution functions are used. Note that the functions are dependent on the location of the terminal. The specification of weather distribution for one terminal can thus not be used for all terminals around the globe. For the weather events presented in table 1, four distribution functions describe the probability of the events; the function of wind speed, wave height, temperature and precipitation volume.

The weather distribution functions are constructed with historical data from ERA Interim [24]. For the geographic location of the container terminal histograms are constructed for each of the four weather variables. With these histograms the expected number of hours that a weather event occurs in a year is calculated. Consider figure 3. This histogram represents the probability distribution of temperature in Manzanillo, Mexico. When the probability is multiplied with the number of hours in a year, the expected number of hours with a temperature lower than 0 degrees, would be approximately 5. Thus, for 5 hours a year, frost would apply to Manzanillo; resulting in reduced speed of AGV's for 5 hours in a year.

FIGURE 3. Example of the probability distribution of temperature in Manzanillo. The Y-axis represents the probability, the x-axis represents the temperature in degrees Celsius.



Through the weather distribution functions, expected values for the number of hours that every weather event occurs can be determined. Hence, the operational performance of a container terminal can be estimated under a certain climate.

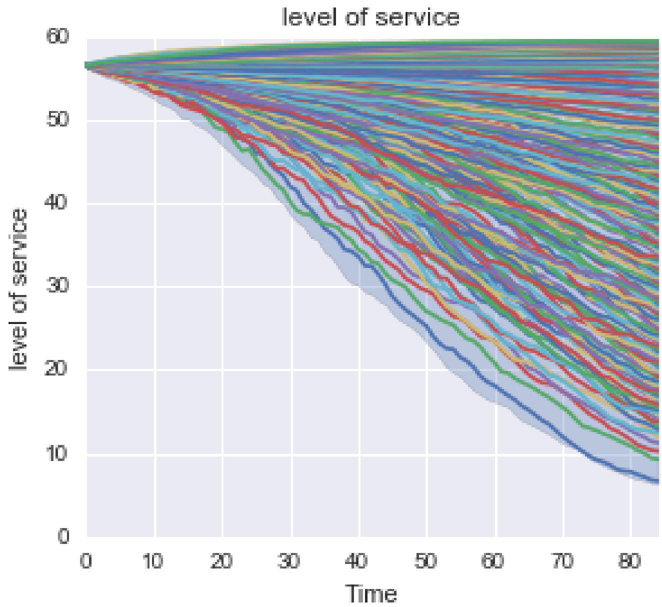
2.4. Exploratory modeling

In traditional approaches, a researcher would create a model with "adequate knowledge about both the system characteristics and initial conditions" [25]. The reliability of the outcomes of such a model relies heavily on the validation of the model. If there is deep uncertainty in the model, validation is not possible. For situations where deep uncertainty exists, such as the uncertainty faced with climate change, exploratory modeling can be used. [26]

The weather distribution functions are the source of uncertainty for the model used. The uncertainty space is defined as the change in distribution functions. Exploratory modeling uses computational experiments to explore uncertainties in the context, the system model and different perspectives. In this case, the uncertainty in the change in weather distribution functions is explored. By changing the distribution functions, weather events are occurring more or less often.

Figure 4 is an example of the outcomes of an experiment with exploratory modeling for a container terminal in Manzanillo, with 10.000 runs. On the y-axis the level of service is presented, on the x-axis is the time. The colored lines each represent 1 random run in the experiment, while the blue area shows the entire bandwidth of outcomes.

FIGURE 4. An example of the outputs of 10.000 runs for exploratory modeling for a container terminal in Manzanillo under climate change. The Y-axis shows the level of service, the X-axis shows the time.



Exploratory modeling thus generates outcomes for many plausible climate change scenario, without claiming that one scenario is more or less likely than another.

2.5. Scenario discovery

The last block in this method is related to analyzing the data from the exploratory modeling. In the example from the outcomes of exploratory modeling in figure 4, we see that in some situations the level of service is declining, while other situations indicate that the level of service is improving. With scenario discovery we analyze the outcomes of the exploratory modeling. Some scenarios with similar characteristics may be showing similar behavior in the outcomes of the level of service. The method used for analyzing the outcomes is the *Patient Rule Induction Method* (PRIM)-Analysis.

Figure 5 provides an example of how PRIM analysis works. With the PRIM analysis, a set of boxes is generated. Each box covers a fraction of the outcomes, and is shaped in the uncertainty space. The figure shows the shape of the boxes in a 2 dimensional space, plus the outcomes of the runs. The grey dots are the runs of which the outcome did not result in a state of interest, while the black ones resulted in an outcome of interest. The boxes that are generated contain 2 characteristics; Density and Coverage. The density is the ratio between the number of outcomes of interest in the box, over the number of outcomes which are not of interest in that same box. The coverage is the number of outcomes of interest in the box, over the total number of outcomes of interest in the entire experiment.

Consider Peel 3, Box 1. All of the outcomes within this box are outcomes of interest; all of them are black. The density of this box, is thus 100%. The coverage is high; a lot of outcomes of interest lie within the box, whereas only a few outcomes of interest are not situated in the box. The coverage for this box is approximately 80%.

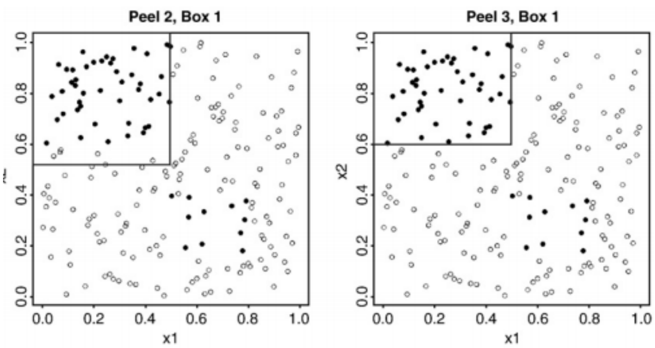


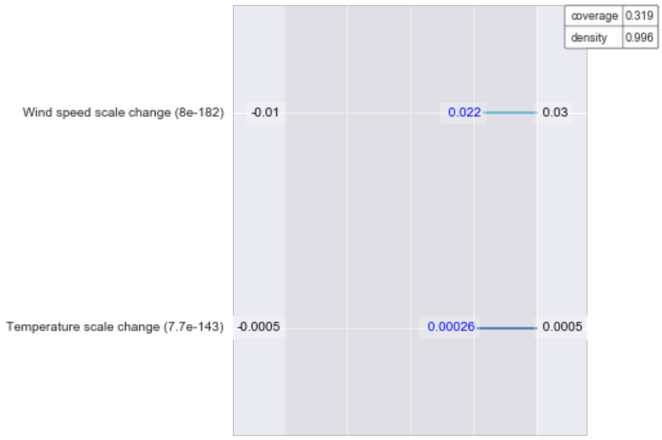
FIGURE 5. An example of PRIM-Analysis. Black dots indicate that the result is an outcome of interest. Grey dots indicate that the result is not an outcome of interest. Adopted from Bryant and Lempert (2009).

A box created with the PRIM, can be further analyzed to identify vulnerabilities in the system. An example of this is provided in figure 6. In this example, a box bound by wind speed change and temperature change is analyzed. With a coverage of approximately 30%, nearly thirty percent of all the critical outcomes are explained by scenarios within this box of uncertainty. At the same time, nearly 100 % of the outcomes within this box are resulting in a situation where the container terminal is under performing. Hence, the terminal is vulnerable to climate change scenarios where the wind speed and temperature change are similar to the change defined by this box.

3. GENERIC APPLICABILITY OF THIS METHOD

By following the blocks proposed in this method, an exploratory model can be created. This model is not suitable for predictive purposes. Due to it's exploratory character, the method can be used for screening of ports, to determine the vulnerability of a container

FIGURE 6. Example of how the vulnerabilities in the container terminal are presented. The horizontal lines represent the size of the box.



terminal and to determine whether more extensive research is required.

In this method, some blocks can be re-used for other container terminals, while others are dependent on the container terminal. The port operations and weather impact can be described for any type of container terminal, and is reusable for most of the container terminals. However, some of the weather impacts may depend on the national legislation. Examples are the maximum temperature for workers outside, and the maximum wind speed before closing the terminal. The weather distribution is related to the location of the container terminal. The weather distributions should be remade for every terminal. However, the method used to create the weather distribution functions are very straightforward, and are very simple to replicate for other locations. Lastly, the exploratory modeling and scenario discovery can easily be reused for other cases, as the uncertainty space in climate change is present for every port.

Although the exploratory character of this method does not enable the user to make predictions with it, the method can be used to screen for container terminals vulnerable to climate change.

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