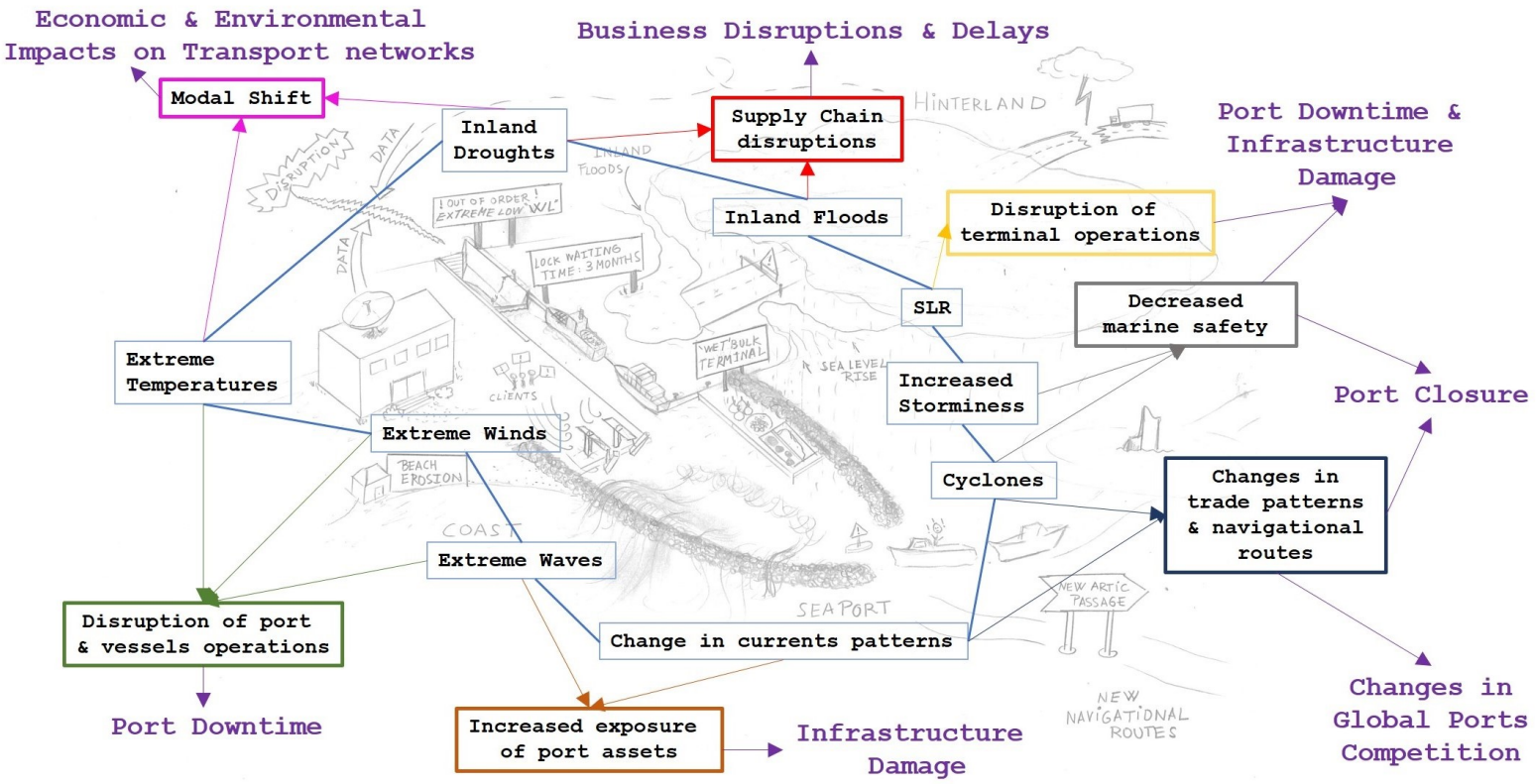
Climate Change Impact Assessment on Ports

Overview & Research Gap Analysis

S. Sellés Valls

Additional Thesis

Delft University of Technology



TUDelft

Climate Change Impact Assessment on Ports

Overview and Gap Analysis

by

Susana Sellés Valls

Additional Thesis for 10 ECTS
at the Delft University of Technology,

Student number:	4582950	
Project duration:	September 10, 2018 – November 16, 2018	
Thesis committee:	Prof. dr. ir. M. van Koningsveld,	TU Delft, supervisor
	Prof. dr. ir. S. N. Jonkman,	TU Delft, supervisor
	Dr. Ir. P. Taneja,	TU Delft, daily supervisor
	Ir. J. Mol,	Royal HaskoningDHV

This thesis is confidential and cannot be made public until November 16, 2018.

TU Delft

Abstract

S. Sellés Valls
Delft, November 2018

In spite of the major and broad consequences of adverse climate change impacts on ports in general, relatively little and relevant detailed research is made available within public domain. Several studies have addressed climate impacts on transportation infrastructure however very few focus on ports and supply chain. Ports are considered critical infrastructure that serve as a catalyst for economic growth and development of a country. Their importance is not only on a national (or regional) level, but they act as gateways to trade and constitute essential nodes in the global supply chain.

The topic of this thesis on *Climate Change Impact Assessment on Ports* is very broad to tackle within only 9 weeks (the length of this research). Therefore, the focus has been set on seaports within the Netherlands and more specifically, the Port of Rotterdam as main example. This thesis aims to advance research on climate change impact assessment on ports and supply chains. To achieve the aforementioned, a few research questions have been defined to help steer the research into the right direction: (1) What is known about the main impacts of climate change on ports and supply chains? (2) Which assets are vulnerable to the main impacts determined in sub-research question 1? (3) What are the state of the art strategies to perform a climate change impact assessment? And what are the available resources (frameworks, methods, software)? (4) Which knowledge gaps have been identified while answering sub-research questions 1,2 and 3? (5) How can one address the gaps identified in sub-research question 4?

The methodology of this thesis has two main parts: The literature study and the expert interviews. The interviews were a very important part of this research. That is because this thesis aims to present the needs from the users perspective, to motivate researchers to continue with the exploration of this topic. Formulating the right questions to ask the experts and identifying which of the 12 experts could provide the best answer to understand the needs from different port users perspective, was the most challenging part of this thesis.

The results of this thesis are research topics on the broad subject of climate change impact assessment on ports an supply chains. Due to time constrains, only 3 research topics are presented in more detail with the corresponding suggested approach. These three topics have been prioritized among the rest based on expert's opinions on what climate change issues are the most urgent (for further details see 2.4.2 & 4.1-4.3). These topics are: (1) Developing an Integrated Stochastic Model to Test Climate Change Resilience on Ports, (2) Investigating Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade effects and (3) Developing a Method to Promote Awareness for Climate Change Resilient Ports. Nevertheless, chapter 6 presents a list of other potential research topics that can also be of interest to researchers. The recommendations for further research on the topic of climate change impact assessment on ports and supply chains are to follow the suggested research topics descriptions in chapter 6. Furthermore, to explore probabilistic models to tackle uncertainty issues and to understand the multivariate dependencies within ports and supply chains. Finally but most importantly, this research should be extended internationally, not only focusing on Dutch experts, to have a global perspective on the problems and the identified knowledge gaps posed on this thesis. Other recommendations can be found in chapter 7.

Contents

1 Introduction **1**
1.1 Background . . . 1
1.1.1 Some Important Definitions . . . 2
1.1.2 Relevant concepts of ports . . . 2
1.1.3 Relevant concepts of supply chains . . . 3
1.2 Research Objectives . . . 3
1.3 Research Questions . . . 4
1.4 Methodology . . . 4
1.4.1 Literature Study . . . 4
1.4.2 Interviews . . . 5
1.5 General Structure of the Thesis . . . 6

2 Climate Change Direct and Indirect Impacts on Ports **7**
2.1 Climate Change Direct Impacts on Ports . . . 7
2.1.1 Sea Level Rise . . . 7
2.1.2 Increase in Storminess . . . 8
2.1.3 Strong wind driven by storms, cyclones and typhoons . . . 9
2.1.4 Limited Visibility Induced by High Fogginess . . . 9
2.1.5 Higher and/or Lower Air Temperatures . . . 10
2.1.6 Increase in the Amount of Rainfall and Snow . . . 10
2.1.7 Changes in Wave climate: Period, Height & Direction . . . 10
2.1.8 Climate Change Compound Events . . . 11
2.2 Climate Change Indirect Impacts on Ports . . . 11
2.2.1 Supply Chain Disruptions . . . 11
2.2.2 Inland Waterways as Source of Supply Chain Disruption . . . 12
2.2.3 Other Climate Change Threats . . . 13
2.3 Current Consideration of Climate Change Impacts: Knowledge & Awareness . . . 13
2.3.1 Historic surveys to Port Industry . . . 14
2.3.2 Critical Port facilities & Interdependence . . . 15
2.3.3 Expert's Perspective on Most Vulnerable Port Elements . . . 15
2.3.4 Some Insight into Policies and Adaptation to Climate Change . . . 17
2.4 Climate Change Impact Overview on Ports & Supply Chains . . . 18

3 Climate Change Impact Assessment through Literature Studies **23**
3.1 Discussion & Conclusions of the identified Methods . . . 23
3.2 Identified Literature Knowledge Gaps . . . 25

4 Expert Interviews on Climate Change Issues **27**
4.1 Climate Change Assessment in Port Development practice . . . 27
4.1.1 Economic Stage: Cargo Volumes & Cargo Routes . . . 27
4.1.2 Master planning: Layout & Terrain . . . 28
4.1.3 Design & Infrastructure . . . 29
4.2 Climate Change Assessment in three-level Port Model . . . 29
4.2.1 Port Infrastructure . . . 29
4.2.2 Port Operations . . . 29
4.2.3 Port Services & Products . . . 30
4.3 Stakeholder Engagement . . . 31
4.3.1 The Big Unknown: Responsibility on the Measures . . . 31
4.3.2 Raising awareness on the subject of Climate Change Impacts on Ports . . . 32
4.3.3 Port of Rotterdam Pilot Project: Adaptation Strategy for the Botlek Area . . . 33

4.4 State of the Art Software, Methods & Techniques . . . 34
4.4.1 Economic Optimization Method . . . 34
4.4.2 Three-point Method . . . 35
4.4.3 Bow-Tie Method . . . 35
4.4.4 Risk Matrix . . . 35
4.4.5 CIrcle Tool . . . 36
4.4.6 STAIN Tool . . . 37

5 Identified Research Knowledge Gaps 39
5.1 Lack of Integrated Models and General Guidelines to perform Climate Change Impact Assessment on Ports and Supply Chains . . . 39
5.2 Identification & Quantification of Supply Chain Disruptions due to Climate Change Cascade Effects. . . . 40
5.3 Methods to Raise Awareness for Climate Change Resilience on Ports . . . 41
5.4 The lack of Climate Adaptation Policy Action . . . 41
5.5 Other miscellaneous Gaps . . . 42

6 Definition of Research Topics and Corresponding Approach 45
6.1 Developing an Integrated Stochastic Model to Test Climate Change Resilience on Ports . 46
6.1.1 Problem definition . . . 46
6.1.2 Research Objectives . . . 46
6.1.3 Research Questions . . . 47
6.1.4 Proposed Method. . . . 47
6.1.5 Outcome & Final Products . . . 48
6.1.6 Recommended Literature . . . 50
6.2 Investigating Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade Effects. . . . 50
6.2.1 Problem definition . . . 50
6.2.2 Research Objectives . . . 51
6.2.3 Research Questions . . . 51
6.2.4 Proposed Method. . . . 51
6.2.5 Outcome & Final Products . . . 53
6.2.6 Recommended Literature . . . 54
6.3 Developing a Method to Promote Awareness for Climate Change Resilient Ports . . . 55
6.3.1 Problem definition . . . 55
6.3.2 Research Objectives . . . 56
6.3.3 Research Questions . . . 56
6.3.4 Proposed Method. . . . 56
6.3.5 Outcome & Final Products . . . 57
6.3.6 About STAIN . . . 57
6.4 Other Interesting Research Topics. . . . 58
6.4.1 Development of General Guidelines to perform Climate Change Impact Assessment Worldwide . . . 59
6.4.2 Other Research Topics . . . 59

7 Conclusions & Recommendations 61
7.1 On Climate Change Direct Impacts on Ports . . . 61
7.2 On Climate Change Indirect Impacts on Ports . . . 62
7.3 On the Most Vulnerable Port Elements . . . 62
7.4 On Climate Change Impact Assessment . . . 63
7.5 On Identified Knowledge Gaps . . . 63
7.6 On How to Address the Identified Knowledge Gaps . . . 64
7.7 On the Methodology Followed . . . 65
7.8 Recommendations . . . 66

A Expert Answers to the Identified Literature Knowledge Gaps **67**

B Expert Interviews **73**
B.1 Port Field's experts . . . 73
B.1.1 Rotterdam's Port Authority: *Ir. Joost de Nooijer* . . . 73
B.1.2 Adaptative Port Planning expert & Researcher: *Dr. Ir. Poonam Taneja* . . . 76
B.1.3 Port Economic and Inland Waterways & Shipping expert: *Dr. Ir. Cornelis van Dorsser* . . . 78
B.2 Climate Change and Risk Assessment experts . . . 81
B.2.1 Inland Waterways & Climate Change expert: *PhD Candidate Ir. Frederik Vinke* . . . 81
B.2.2 Environmental Risk Assessment expert: *Dr. Matthew Hunt* . . . 83
B.2.3 Flood Risk expert: *Ir. Matthijs Bos* . . . 88
B.2.4 Expert in Modelling of the Economy-wide Consequences of Disasters & Supply Chain: *Dr. Ir. Elco Koks* . . . 91
B.2.5 Leading Professional in Urban Flood & Water Resilience: *Ir. Nanco Dolman* . . . 93
B.3 Stakeholder Engagement experts . . . 95
B.3.1 Product Development Flood Resilience expert: *Ir. Micheline Hounjet* . . . 95
B.3.2 Strategy & Management Consultant expert: *MSc Jarit van de Visch* . . . 98

C State of the Art Methodologies **101**
C.1 The Committee on Approaches to Climate Change Adaptation from November of 2010 [35] . . . 101
C.2 Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies – UNEP & VU (October 1998) [43] . . . 101
C.3 CLIMATE CHANGE IMPACT ASSESSMENT, ACT Government from November of 2011 . . . 102
C.4 Climate Change impact assessment and adaptation strategies for sustainable development of societies – RMSI consultant [18] . . . 103
C.4.1 Escalating impacts of climate extremes on critical infrastructures in Europe – Forzieria et al. (November 2017)[24] . . . 104
C.5 Conducting an impact assessment – Climate Change in Australia: Projection for Australian NRM regions [3] . . . 105
C.6 Development of Climate Resilient Ports – MSc. Thesis Erwanda S. Nugroho [33] . . . 107
C.7 IPPC Report 2007 [36]: Chapter 6, National Systems for Managing the Risks from Climate Extremes and Disasters . . . 107
C.8 Exploring Potential Climate Change Impacts and Adaptation Strategies for Seaport Operability– JUDITH K. MOL [28] . . . 108

Bibliography **111**

1 Introduction

1.1. Background

Climate change is slowly becoming more of a reality instead of pure theory. Significant changes in climate and consequences are already being felt regionally, and these are projected to become more extreme within the next few decades [16]. Natural systems are seriously impacted by climate change. For example, many regions on Earth are starting to show a changing precipitation pattern or melting snow and ice, which is causing alterations to the hydrological systems. Consequently, current science and policy discussions are not merely focusing on how and why climate change is happening, but also how fast it will happen looking to the near and far future and what the vulnerabilities of natural and anthropogenic systems on Earth would be [16]. Examples of anthropogenic systems are airports, ports and (global) supply chains [37].

Ports are considered critical infrastructure that serve as a catalyst for economic growth and development of a country. Their importance is not only on a national (or regional) level, but they act as gateways to trade and constitute essential nodes in the global supply chain [30]. Due to the changing climate over the next few decades, ports, harbors and marinas will need to adapt to these regional impacts of climate change.

In spite of the major broad consequences of adverse climate change impacts on ports in general, still relatively little and relevant detailed research is made available within public domain. Several studies have addressed climate impacts on transportation infrastructure however very few focus on ports and supply chain[44]. The typical lifespan of port infrastructure, port master-planning and development is on the order of 40-50. Because of the long-term projections and the potential climate-change impacts which may not been seen for several years, the majority of ports rarely plan to adapt now for future climate change events. Often, only when facilities are actually being threatened or damaged, port authorities and clients act on mitigation measures.

This thesis aims to advance research on climate change impact assessment on ports and supply chains. The topic of this thesis on *Climate Change Impact Assessment on Ports* is very broad to tackle within only 9 weeks (the length of this research). Therefore, the focus has been set on seaports within the Netherlands and more specifically, the Port of Rotterdam as main example. Nevertheless, this thesis also gives some insight on Dutch Waterways and their dependencies within the Port of Rotterdam and supply chains. Despite the focus is set on the Netherlands, the information can be translatable to other countries. The Dutch are widely known for being always one step ahead in terms of water resilience and sustainability hence, is expected that this thesis capture the state of the art concepts and practices within the topic of climate change impacts on ports.

1.1.1. Some Important Definitions

Before getting into any more detail and for the sake of clarity in this thesis, several terms that will be used in this report will be briefly explained forehand.

- **Climate Change** [32]: Climate change is a change in the usual weather (averaged within 30 years) found in a place which could be in the amount of yearly rain or the usual temperature for a month or season. But within this thesis, the term climate change also comprises the change in Earth's climate. Earth's climate is always changing and scientists see that Earth's climate is getting warmer and will continue for at least the next 100 years. The climate is an average of 30 years weather, hence it is considered in this thesis that climate change has been already on for more than 30 years.
- **Hazard** [15]: A hazard is considered to be within this report the potential for harm or an adverse effect to a vulnerable asset. A hazard is used in this thesis to name the physic effects (or factors) of climate change such as sea level rise or extreme weather events.
- **Impact** [19] : The term "Impact" defines a climate change marked effect or influence into vulnerable assets. Hence, impact has been used as a synonym of effect. The impacts itself can represent threats, have negative consequences for the assets; or they can be opportunities, have positive consequences for the assets.
- **Climate Change Impact Assessment:** Impacts can also be directly or indirectly affecting ports. This thesis focuses on supply chain disruptions as main indirect impacts on ports. Hence, the term "climate change impact assessment" refers to ports and supply chains throughout this report.
- **Risk** [15]: The term risk has used to describe the combination of the likelihood of the occurrence of a hazard (harm) and the severity of the consequences in economic units. It can be a function or a combination of hazard, vulnerability and exposure.
- **Vulnerability** [44] : this term is used to describe how susceptible a system is to the adverse effects of climate change.

1.1.2. Relevant concepts of ports

This research addresses ports as existing entities but differentiating the whole (sea)port into three interrelated levels [42]:

1. Port Physical Infrastructure
2. Port Operations
3. Port Products & Services

A port system comprises well defined physical network structure, and physical goods flow through the links and nodes in the system. Figure 1.1 [42], defines the port as a three-layer infrastructure model (inframodel). The model distinguishes three generic layers: a physical infrastructure layer, an operational layer, and a services and products layer. The main distinction among the three layers is based on functionality. Furthermore, the lower layers provide the necessary conditions for the existence and proper functioning of layers on higher levels. Each layer comprises physical, technical, operational, and institutional elements, together with actors and their interactions [42].

Figure 1.1: Three-layer inframodel of a port; by Herder et al. (2008) and adapted by Dr. Taneja [42]

The bottom layer covers the physical infrastructure comprising basic infrastructure, superstructure, and the equipment. The spacial scale of the physical infrastructure is humongous, with many vulnerable elements that can disrupt the entire transport and supply chain. The landlord function of the port authority requires it to build port infrastructure and take responsibility for sustainable land use. The operational layer which also includes the management processes, interacts closely with the maritime and the intermodal transport network. The logistics activities include a wide range of activities: (1) network control, (2) capacity management, (3) workforce scheduling and (4) routing on the network assign capacity to various service providers acting in the top layer. The latter deal with supply and use of infrastructure-based products and services. Finally, the services provided by a port include access, protection, and vessel traffic management for ships. Also nautical services like pilotage, towage, mooring and terminal services which include the physical transfer of goods and passengers between water and land, storage and transfer of cargo to other modes of transport [42].

This thesis makes use of the Three-layer inframodel to asses climate change impacts on ports. In chapter 4, this model is applied to differentiate what is the current practice of experts to assess climate change impacts in each layer. Current expectations are basically the consideration of climate change impacts only on the infrastructure layer. However, what if the effects of climate change are the most harmful on the operational layer, and the delivery of good port services is compromised?

1.1.3. Relevant concepts of supply chains

Mentzer et al. [31] describe the supply chain as:

> ”an integrated system of companies involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer.”

In this thesis, the supply chain is understood as a network that comprises an integrated system of companies from the upstream to the downstream end of the products and service flows. This thesis focuses on port supply chains. On another note, the term ”supply chain disruption” is used in this thesis to describe a disruption (climate change disruptive event) in any node or/and link throughout the entire network. This is of highly relevance to this thesis because these disruptive events are considered major and potential indirect impacts on ports. Chapters 2,4,5 and 6 contain more information on this aspect. Because of the scope of this thesis, the source of disruption is only considered to be climate change.

1.2. Research Objectives

This thesis aims to advance research on climate change impact assessment on ports and supply chains. In order to do so, two objectives must be achieved:

1. To present an overview of state of the art strategies to assess climate change impacts on ports and supply chains.

2. To identify research gaps within the topic ”Climate change impact assessment on ports and supply chains” in order to define future research.

1.3. Research Questions

The main objective of this thesis is captured in the following main research question:

- What is the way forward to advance research related to climate change impact assessment on ports and supply chains?

To answer the main research question, a few sub-research questions have been defined to help steer the research into the right direction:

1. What is known about the main impacts of climate change on ports and supply chains?
2. Which assets are vulnerable to the main impacts determined in sub-research question 1?
3. What are the state of the art strategies to perform a climate change impact assessment?
   What are the available resources (frameworks, methods, software)?
4. Which knowledge gaps have been identified while answering sub-research questions 1,2 and 3?
5. How can one address the gaps identified in sub-research question 4?

1.4. Methodology

To answer the five sub-research questions and contribute to research on climate change impact assessment for ports and supply chains, the following methodology was followed:

1. Literature study and gap analysis. Duration: 2 weeks
2. Formulation of the interview questions. Duration: 2 weeks
3. Interviews with experts. Duration: 2 weeks
4. Gap analysis based on the results from the interviews. Duration: 1 week
5. Prioritization and formulation of 3 research subjects. Duration: 2 weeks

The two most important aspects of the methodology are the literature study and the interviews with experts. The interviews were a very important part of this research and the most challenging. That is because this thesis aims to present the needs from the user perspective to motivate researchers to continue with the exploration of this topic. Formulating the right questions to the experts to identify the latter issue was the most challenging part of this thesis. The rest of the steps were mainly focused on the gathering and analysis of information and data. The following sections elaborate on the literature study and interviews.

1.4.1. Literature Study

The first step was a two-weeks ”quick” literature study on the climate change impacts on ports, and on methods to assess these. The method used to perform the literature review was by introducing certain keywords in Google Scholar and finding papers that could not only be of interest to my thesis, but also that could provide me with new references and bibliography. Some of these key words were: *”climate change impacts on ports, indirect climate change impacts, impact assessment, risk assessment, supply chain disruptions, ports and climate change, climate change resilient ports etc”*. Concerning the impacts, a clear distinction has

been made between direct and indirect climate change impacts. Some of the direct impacts of climate change on seaports are sea level rise, increase of storminess, changes in wave climate, increased frequency of extreme events etc. The indirect impacts have been attributed mainly to the supply chain disruptions which includes for instance, lack of capacity of Inland Waterways due to droughts. It was expected that the main indirect impacts on ports come from supply chain disruptions (see definitions on 1.1.1). Others can be trade diversion and new shipping routes, human migration, shifts in market due to climate policies, changes in labour conditions etc. The focus was not only on identifying these indirect impacts but also to explore the (inter-dependence) links with ports.

Once the knowledge on direct and indirect climate change impacts was investigated, the following step was to explore the state of the art strategies to assess climate change impacts on ports. The final part was to elaborate a list of knowledge gaps identified within the literature study. The idea has been to address the identified gaps during the interviews to experts to see whether the gaps can be filled. Due to time constraints and lack of public resources, the extent of the literature review might not be complete to present a global overview. Hence, the importance of the interviews to gather more information on several fields of expertise.

1.4.2. Interviews

The interviews define the second part of the methodology and aim to address the literature gaps but also focus on discovering other potential gaps within practice. The next question to answer was which ”type” of experts would be the best ones to shed some light on the topics of interest. It was decided to invite experts from mainly three different categories according to the identified literature gaps (for more information on the literature gaps see chapter 3):

1. Port experts: researchers, engineers and port authorities
2. Climate change and Risk assessment experts: consultants and researchers
3. Stakeholder engagement experts: consultants and software experts.

The key was on conducting as many and as different expertise-based interviews as possible within the latter three categories. The set of questions formed a semi-structured semi-open interview which proofed to be a successful and efficient way to gather as much knowledge as possible. The interviewed experts within the mentioned categories are the following:

1. **Port Field’s experts**
    - Rotterdam’s Port Authority: *Ir. Joost de Nooijer*
    - Adaptative Port Planning expert & Researcher: *Dr. Ir. Poonam Taneja*
    - Port Economics and Inland Waterways & Shipping expert: *Dr. Ir. Cornelis van Dorsser*
    - Port Designer & Project Manager Expert: *Ir. Joost Lansen* (*)
    - Professor Emeritus in Ports & Waterways section of TU Delft; Port environmental expert, developer of ”Ports of the future” and ”Green Ports” philosophy: *Prof. Ir. Tiedo Vellinga* (*)

    (*) Interview not recorded and not present in appendix B.
2. **Climate Change and Risk Assessment experts**
    - Inland Waterways & Climate Change expert: *PhD Candidate Ir. Frederik Vinke*
    - Environmental Risk Assessment expert: *Dr. Matthew Hunt*
    - Flood Risk expert: *Ir. Matthijs Bos*
    - Expert in Modelling of the Economy-wide Consequences of Disasters & Supply Chain: *Dr. Ir. Elco Koks*

- Leading Professional in Urban Flood & Water Resilience: *Ir. Nanco Dolman*

3. **Stakeholder Engagement experts**

   - Product Development Flood Resilience expert: *Ir. Micheline Hounjet*
   - Strategy & Management Consultant expert: *MSc Jarit van de Visch*

It is proven that the information gathered from all experts not only has helped to answer the gaps posed after the literature review, but also to identify new ones. The identification of research knowledge gaps has not been easy. The information gathered through the interviews helped to understand what are the interests among the port industry. One of the approaches was to ask experts what gaps they identify in their daily practice. Another way to identify the gaps has been by interrelating the information from different interviews and propose gaps to experts to see their opinion. The final part of this thesis was to present the most promising research subjects topics for future students that would like to embark upon the topic of climate change impact assessment on ports and supply chains.

1.5. General Structure of the Thesis

This research comprises four parts that correspond with the four main chapters of the report (Chapter 2,3.4 and 5). These chapters present findings and results of the sub-research questions 1-5 from the knowledge gathered by the literature review and the interviews to experts (See 1.3 Methodology). This section aims to provide some guidance on how to properly address and understand the order and parts of this report.

- **Chapter 2:** This chapter aims to answer the sub-research questions 1 and 2. To do so, the chapter contains information from both the literature study and the interviews to experts. The first three sections of chapter 2 address sub-research question 1 and the last section gives some answers to the sub-research question 2. At the end of the chapter, the reader can find a table presenting an overview of the potential climate change impacts on port infrastructure, operations, hinterland connections and supply chain. Furthermore, a summarized overview of the latter has been presented in the form of a creative diagram (see Figure 2.7).

- **Chapter 3:** The chapter aims to answer the sub-research question 3 from an academic perspective. The chapter ends with a summary of the gaps identified through the literature study.

- **Chapter 4:** The chapter aims to answer the sub-research question 3 from a more practical point of view. The first and second sections focus on impact assessment on the port as entity. The first uses the perspective of the three-layer inframodel (see explanation on section 1.1) and the second presents the current practices within the stages of port development. The third section addresses some aspects of the stakeholder engagement during the practice of assessing climate change impacts. The final section presents the available and state of the art software, methods and techniques to assess the impacts of climate change.

- **Chapter 5:** This chapter presents the identified research gaps to answer the sub-research question 4. The latter has been addressed with an analysis on the results from the literature study and the interviews presented in chapters 2,3 and 4.

- **Chapter 6:** This chapter answers the last sub-research question number 5. Due to time restrictions, only three research topics are presented with an explanation on the suggested approach. These three topics have been prioritized among the rest based on expert's opinions on what issues are the most urgent. Nevertheless, the chapter ends with a list of other possible research topics for who becomes interested.

2

Climate Change Direct and Indirect Impacts on Ports

Chapter 2 focuses on answering the first and the second sub-research questions:

- What is known about the main impacts of climate change on ports and supply chains?
- Which assets are vulnerable to the main impacts determined in sub-research question 1?

To answer the posed two questions in a clear way, the chapter splits into several sections which only the first two are specially dedicated to the direct and indirect impacts on ports. The third section presents a creative overview of the direct and direct impacts on ports. The last section provides insight on the current knowledge and awareness of experts on climate change impacts on ports. It also presents the results of several historic surveys to the port industry.

2.1. Climate Change Direct Impacts on Ports

There is a widespread believe ports will be directly affected by climate change in the near and far future. Several entities such as IPPC, are currently busy on identifying climate change trends, scenarios and development in time of its consequences. However, what is going happen in reality, when and where is still seen generally as big unknowns.

Climate change most probably will have big direct effects on ports due to their geographic location being close to river, sea or ocean water. Some of the direct effects of climate change are already being felt within the Port Industry [9], such as flooding, extreme and more frequent wind events, heavy rainfall, inland droughts… For the sake of simplicity, these impacts can be explained as direct consequences of climatic variables (extreme weather events, sea level rise, rising air and ocean temperatures, change in water quality, increase in humidity in coastal areas etc.) on port infrastructure, operations and services. The following subsections elaborate on the most relevant climate variables (or climate factors) and their impacts on ports.

2.1.1. Sea Level Rise

There is currently a big debate whether sea level rise itself supposes a hazard, or the hazard itself is the projected acceleration of sea level rise due to climate change. For the sake of simplicity in this thesis, sea level rise itself is considered the hazard.

The substantial impacts of (mean) sea level rise are already being felt by coastal ecosystems and communities around the world. Mean Sea Level Rise changes are interacting with storms and consequently increasing risk of greater storm surges (flooding) which translates into infrastructure damage, erosion and habitat loss [37].

From the interviews, Sea Level Rise (or SLR) is seen as the easiest impact to understand and to mitigate. Experts generally use IPCC projections as boundary conditions (scenarios) for their designs, business plans or risk assessments. The UK for instance, has developed their own regional down-scaling models and gathered SLR predictions for different years and Carbon Emission projections in the UKCP09 reports. Experts within the field of Ports and Waterways see SLR as a long-term future threat and with main consequence, the flooding of port infrastructure [9], [4], [11]. Apart from increasing the risk of flooding, it would also induce larger (and more frequent) overtopping discharges [30] together with structural erosion of beaches nearby.

One of the several direct consequences of flooding would be the ingress of water into sensitive Vessel Traffic System (VTS) equipment systems. The latter would mean consequent power loss which could reduce safety in navigation. If the safety levels go under critical thresholds, flooding could lead to port closure affecting port's reputation. The reliance of the supply chain could be compromised and ports could loose future clients. Conclusively, the main consequences of flooding and structural erosion due to increase in storminess within the port water area and operations are: (1) delay in shipping movements but also to arrivals and departures; transfer of pilots to vessels; vessel handling, (2) reduced need for dredging, increased requirement for surveying and (3) changes in availability of dredgers to undertake works. Moreover, flooding induced by SLR can also have consequences at the terminal areas and within the operations such as (1) inability to operate the terminal causing delays, (2) damage to infrastructure including electricity supply (and backup generators), loss of operation and finally (3) potential knock-on effects to other critical infrastructure.

In short, sea level rise is seen as the main climate change impact for ports. From expert's experience, the potential impacts of sea level rise are relatively well understood. However, experts acknowledge the lack of information on (1) when to start investing, (2) when to start planning and (3) when to start adapting.

2.1.2. Increase in Storminess

Storms and particularly large waves can trigger flooding, causing highly destructive impacts on ocean and coastal ecosystems as well as the human communities, including Ports [37]. Stronger wave action and higher storm surges, especially when coupled with higher sea levels, are the primary threat to ports [27]. Generally, it is expected that extreme weather events (such as storms) will increase in frequency. The low confidence in the climate change projections hinders experts when predicting any changes and also within their impact assessments.

The leading British ABP organization [4] assumes in their most recent reports that extreme weather will become more frequent and the major consequence will be increased risk in the safety of vessels at sea. On the contrary, several experts from the fields of flood and environmental risk and Rotterdam port authority believe that the main and major impacts will be within the level of port operations.

At the interviews, experts related the increase in storminess with flooding and lightening. Both impacts are threats to the port operations and consequently the delivery of services and products. It is still an unknown how climate change will affect lightening patterns. It is believed among experts that severe lightening will increase if the frequency of big storms increase. Experts assume that the impacts of flooding will completely hinder terminal operations. Some of these impacts are expected to be (1) the inability to use cranes and other

Port	Main cause of disruption	Estimated financial loss[1]	Source
A port in Western Australia	Extreme cyclones	3.0 billion AUD	Ng et al. (2013)
Texas ports, USA	Hurricane Ike	2.4 billion USD	FEMA (2008)
Southern Louisiana ports, USA	Hurricane Katrina	1.7 billion USD	Santella et al. (2010)
The Port of Newcastle, Australia	Extreme storms	1.0 billion USD	Port World (2007)

Figure 2.1: This table belongs to the MSc Thesis and findings from Erwanda [33]. It represents a good example on how big economic losses can be due to extreme storms and hurricanes. Which consequently, these economic losses would be much bigger than if no climate change measures are taken.

terminal equipment, (2) flooded warehouses and (3) outdated stacking techniques for containers (and possibly other cargo). Most of the interviewed experts are concerned about bulk terminals. Bulk terminals often store cargo in the open and due to increase in storminess, cargo will be exposed to more rain. If the cargo is sensitive to water, the operators will need to store the cargo somewhere else. That kind of terminal will be forced to invest in different infrastructure to be able to continue operating while keeping the product dry from the rain.

However, when considering the general port infrastructure, literature and experts agree that some assets will become more exposed that they were supposed to be. Hence, the consequences of increased exposure are the need to (1) Review design parameters at asset reviews / refurbishment proposals to include resilience measures; also (2) increase on repair costs and (3) obsolete, outdated infrastructure.

2.1.3. Strong wind driven by storms, cyclones and typhoons

According to IPCC estimates of the potential destructiveness of hurricanes and cyclones, there seems to dominate a significant upward trend since the mid-1970s towards longer lifetimes and greater storm intensity of hurricanes and cyclones (examples on 2.1) [36]. It is likely (greater than 66% probability) that future tropical cyclones will increase in intensity meaning larger peak wind speeds and more intense precipitation [7].

A higher frequency of coastal storms in the same direction as the port entrance channel could affect port operations by causing increased agitation which would decrease marine safety conditions for navigability and berthability [14]. These impacts can also damage bridges, piers, terminal assets, ships and cargo. Infrastructure may need to be raised or reinforced to withstand these impacts. Apart from contributing to storm surge, wind can also have its own damaging impacts. High winds can threaten terminal structures that have not been reinforced. For example, Hurricane Katrina tore roofs and doors off warehouses at the Port of New Orleans. Some possible actions against the mentioned threads are to change design standards for terminals, cranes, lighting systems, and other infrastructure to incorporate the risk of stronger storms.

2.1.4. Limited Visibility Induced by High Fogginess

There is very little information on public sources about the influence of climate change in fog patterns. Nevertheless, if an increase on the frequency of fogginess on several regions was one of the effects of climate change, ports would potentially be affected by it. The waterside and terminal operations would be affected by more frequent and more intense fogginess which is expected to reduce the visibility in waterways and hence the marine safety. If the visibility drops to any level below the safety limit, the speed of incoming and outgoing sea vessels may have to be reduced, such that the flow of goods through terminals could be slowed down causing downtime. In case of extremely low visibility, the waterways would be closed leading to even higher terminal downtime [33] that could compromise the port's reputation.

2.1.5. Higher and/or Lower Air Temperatures

Ports and terminals can be vulnerable to temperature change, specially in northern European regions were high temperatures are not very common. Higher temperatures could create difficulties on ports for plant and equipment designed for temperate regions. Extreme high temperatures could also affect some auxiliary port infrastructure. For instance, paved surfaces might deteriorate faster in hotter climates. Cranes and warehouses made of metal may require design changes to cope with higher temperatures [27]. Higher temperatures may also require more energy for cooling of goods stored at ports that would lead to higher energy consumption for cargo storage and general air conditioning. On the contrary, fewer cold days would reduce the number of frost and ice days leading to safer operational conditions [30].

Higher temperatures could also imply longer shipping season (NSR) and new sea routes such as the Northest-West Passage (NWP). The latter might suggest shorter distance for Asia–Europe trade and less fuel consumption. However, it should be considered that additional support services and navigation aids (such as ice-breaking search and rescue) might be necessary. Newer routes might also imply changes in ports competition, lower passage tolls and reduced transport costs. Moreover, new or diversion of existing trade might arise implying changes in structure and direction of trade, indirectly through impacting on agriculture, fishing and energy [44].

Last but not least, higher temperatures could affect the human and natural environments associated with ports. Many employees at ports work primarily outdoors hence, operational changes may be compulsory to protect workers from extreme heat. Warmer temperatures may also increase the risk of transferring invasive species on cargo vessels from port to port [27].

2.1.6. Increase in the Amount of Rainfall and Snow

If extreme rainfall, wind or tropical storms increase in frequency but also in intensity, coastal and river flooding can have big impacts on ports, specially rainfall. In 2014 there was a big rainfall event at the port of Amsterdam and their drainage systems were not prepared for the event. As consequence, several small disruptions were caused that lasted for a few days that translated into downtime and extra costs for the companies.

Increase in rainfall can imply an increase in humidity at coastal regions. Large humidity can affect certain kind of goods that are stored. The storing techniques would need to be upgraded to the situation derived by climate change.

2.1.7. Changes in Wave climate: Period, Height & Direction

The greenhouse effect and the complex interactions of atmospheric processes may induce changes in near-surface wind and pressure patterns, which will affect the pattern of the wave field [12] that is an important coastal driver. The changes in wave conditions would affect harbour agitation in many ways. On the one hand, variations in wave height would directly influence energy spectrum penetrating into ports. On the other hand, changes in wave direction or period would affect wave propagation processes: shoaling, refraction and diffraction. The latter could leave infrastructure exposed such as breakwaters and quay walls. Sediment transport patterns would also be affected by changing wave climate conditions and could potentially generate siltation on ports.

All the aforementioned wave-driven factors could impact on agitation or wave penetration into harbours. The operational activities in the harbour areas are strongly dependent on wave conditions, especially in relationship with the entrance and exit of the ships in safe conditions, but also for the regular ship mooring and cargo loading and unloading [40].

2.1.8. Climate Change Compound Events

All the aforementioned climate change impacts might occur at the same time, making ports deal with compound events instead of one single event. In general, compound events are not often considered yet in practice, but it is known from literature that can lead to totally different system vulnerabilities. However, very little has been found regarding the topic of climate change compound events within the two-weeks literature study.

Several of these impacts could be correlated because they come from the same main weather event and it should be taken into account in the assessment. Furthermore, flooding can be caused as a combination of SLR, storm surge and extreme river discharges. Probably, the impacts of such combination of events would be different and more harmful than for a single event. Another example of a compound event is the combination of storm surge, very high waves and strong wind. If the water level is higher, waves will be able to propagate longer into the coast as they will feel the seabed later. If these waves are able to enter the port and wind is blowing hard, they would probably feel reinforced instead of damped.

2.2. Climate Change Indirect Impacts on Ports

The title of this section refers to impacts and not hazards because the focus is set on the consequences (or effects) that climate change can have in an indirect way on ports. The main difference with the previous section is that physical forcing and climate factor directly have an impact on port infrastructure or operations. This part aims to present ways in which ports can suffer from downtime or closure due to impacts of climate change in other sectors or networks.

To aim for some clarity in a multidimensional system, the indirect impacts addressed in this thesis fall into one of the following two categories: (1) Supply chain disruption and (2) Critical Port facilities & Interdependence. However, a third category, (3) ”Expected Climate Change triggers”, aims to present several other possible threats that do not fall into the latter two categories.

2.2.1. Supply Chain Disruptions

Climate change is already affecting the financial performance of companies and their suppliers. In the past, the latter issue was a minor business risk for most organizations. However, the increasing frequency and severity of disruptive weather events are creating a new and business-critical context [5]. The situation worsens if one considers the projected changes in long-term average conditions by for instance IPPC sources.

Supply chains have become longer and more complex but at the same time, the severity and frequency of supply chain disruptions seems to be increasing [5]. Natural disasters and extreme weather conditions are not the only threats to supply chains. Also oil dependence and information fragmentation also suppose serious risks. Research from World Economic Forum from 5 years ago already stated that 80 percent of companies worldwide see better protection of supply chains as a priority . Nevertheless, potential impacts on supply chains are among the least recognized of climate change risks. The latter is due to supply chains consisting of many assets and linkages that require a broader and wider risk management approach [21]. The solutions lies in focusing on the resilience of the network as a whole.

Ports play major roles in the global supply chain. So everywhere that has a link to a disruption, the effects will go down or up to ports. For seaports, the main direct impact is sea level rise, however is important to also look at the climate change impact upstream and downstream the supply chain. For instance, droughts can cause reduction in goods like crops which directly depend on the climate. Agricultural production is very much reliant on the climate conditions and there is a direct impact on trade flows. The latter might affect the companies of the port and affect their business. Another main sector is the one providing access to enough cooling water for energy supply.

Routing and delay of ships will become an issue due to the more frequent hurricanes. The current most affected areas are mainly South and East Asia and Centre America together with California and the (South) East coast of United States, basically also Gulf of Mexico. If the weather conditions are changing and hurricanes become more frequent, the ports will have to be prepared for it. Even if the big storms are not directly passing through the port, the impacts will be felt and if not prepared, downtime will increase.

Climate change might also trigger changes in trading routes. If transport routes become different, raw material transportation (which is basically dominant within sea trade) will be affected. The latter might change sea routes and have impacts on global ports. The transport cost might also change, for example there might be a steel decline production in Germany due to problems in the Rinne. Another effect of changing shipping routes might be that adapting to another type of good's transportation might require additional equipment. If the intensity of rain increase, shelter might be essential for loading and unloading docks. It is also worth noticing that due to some of these climatic impacts, ships are already sailing in the Artic channel.

Conclusively, ports are the main nodes in global and regional supply chains. These systems are very complicated and their mutual connections, including with the port, need to be understood better. Therefore assessment of climate change impacts becomes easier when taking these connections into consideration.

2.2.2. Inland Waterways as Source of Supply Chain Disruption

Interviewed experts agree on the vulnerability of port-waterway system due to climate change impacts. There are many impacts on the port operation site; but from the Waterway system, the impact is on extreme low water levels. Rivers will be affected by droughts which is believed to have a great effect on downtime for port terminals.

There is a general feeling that climate change itself is accelerating and the consequences may even come slightly earlier than predicted [37]. This year the drought has been fierce on the Netherlands and impacted Inland Waterways with around 90 days that the water level on the Waal was less than 2.8 meters. The Waterways were designed following the idea that only 20 days per year would be less than 2.8 meters. For these water levels, only the 25% of the transport capacity is left and the latter has direct impacts on the port of Rotterdam. If it happens every year there, reallocation of industrial activities would probably happen. However, what would that mean for the port, the economy and the city still remains unknown. On the contrary, extreme river discharges are not considered hazardous for Inland Waterways disruptions among experts. The period of these large discharges is just a few days contrary to that of several months for very low river discharges (droughts). Most shipping companies and barge operators have a risk acceptance of 7-10 days that their facilities become in-operational. One could say that the performance indicator most appropriate for inland waterways is the % of time the waterway is not navigable.

For seaports, the connection to the hinterland is very important, if that is not available there is no cargo deliver. In that way sea ports need to be up to date with the consequences affecting, roads, railway and inland waterways. Already this year some cargo was left on Rotterdam that could not be transported and had a waiting time of 3 months The capacity of the Inland Waterways was not enough to cover the demand. PhD candidate ir. Frederik Vinke believes that the supply chain will become different due to climate change. If Inland water transport prices become too high, or there is no enough capacity, a modal shift might take place. In the Netherlands, the Port of Rotterdam is already considering the possibilities of other kind of transport like railway and road. If climate change continues to affect the river discharges, the water depth might become too low at some point and the waterway network will not offer anymore the same capacity mostly to transport goods to Germany. Hence, other

solutions in terms of transport modes need to be find. Frederik is looking in his PhD into the affected summer period whether other modes of transport can take what Inland transport cannot, however a modal shift is not wanted for environmental and inland transport aspects.

In literature one can see that everyone is focused on the dry periods and on very wide range of mitigation solutions. However, there is no guidelines that explain how to act on low water levels and neither how to apply the many mitigation measures that are mentioned. The general feeling is that no one seems to be focusing on modeling solutions to see whether they are feasible or not. The state of the art climate solutions seems to be stuck in theory. There are several arguments that mention measures but conclude that due to certain argumentation they would not be feasible. One of the goals of Frederik's research is to find out the most optimal effective measures and model them to see how the system would respond.

2.2.3. Other Climate Change Threats

Climate Change can be explained as a collection of extreme physical events causing all kind of impacts. However, measures taken to avoid or mitigate climate change effects are also responsible for several other economic and social impacts. More specifically, climate change related policies or trends can also trigger economic and social impacts. This subsection aims to exemplify the latter giving some examples of current trends and policies. Experts agree if the fuel industry changes to fully renewable energies, ports will be clearly affected not only by the consumption of fuels but also their trade. The latter have effects on the trade flows and goods going through ports. For instance if all the cars become electric, they might not get through the port but another channel. So, that shows how trading of goods is not (or will not) really change but the flows of those are.

Ports might face changes in insurance coverage and possible higher insurance premiums because of climate change. The insurance industry is one of the leading commercial sectors expressing concern about and exploring adaptive responses to climate change. Several large insurance companies are incorporating additional risks from climate change into their offerings. Some of the consequences are the introduction of strategies to shift a greater share of risk onto customers [27]. Another big indirect threat are the indirect social effects like starvation in areas that might be next to ports. That will also affect what will happen to the port. Health problems will probably increase among the workers and the port will suffer from it.

Some experts expect that prevailing wind direction will change and it might be the case that breakwaters are not in the right position. Erosion patters and sediment flows can change also if wind direction and intensity change. The latter can end in the dunes not being supportive enough anymore. Another effect can be within fisheries if new currents patterns are established.

Finally, globalization and reverse globalization whether climate change effects on migration will exacerbate the feelings of populism and nationalism and lead to Reverse globalization.

2.3. Current Consideration of Climate Change Impacts: Knowledge & Awareness

Most ports are not planning yet for the impacts of climate change. In general, ports have very few policies that specifically address adaptation to the potential impacts of climate change [11]. These statements are presented in a global port industry survey, and will be explained more in detail in the coming sections.

From the perspective of Rotterdam's port authority, flooding due to sea level rise and storm surge are the major climate change hazards. Other hazards such as increase of fogginess, higher winds, higher temperatures and extreme precipitation would not cause significant impacts if compared to flooding. However, the interviewed engineer acknowledges that the latter hazards fall out of his expertise. Nevertheless, some engineers working for the port are considering other hazards such as extreme rainfall. These kind of events behave differently that SLR or flooding because they are localized events with high frequencies of occurrence. SLR and flooding are expected to be globalized impacts with smaller frequencies of occurrence.

2.3.1. Historic surveys to Port Industry

One of the first surveys focusing on climate change in ports was performed by a group from Texas AM during 2005 and 2006 entitled "Port Planning and Views on Climate Change." The goal was to explore whether US ports were already considering climate change within the port planning practices. The results indicated that about half of the respondents showed considerations for the climate change impacts in their ports.

A few years later, Stanford University [11] published a similar survey but with a wider and more international focus on adaptation issues for ports. The purpose of the survey was to set an example on assessing how seaports and other economic sectors such as airports, energy infrastructure, and inter-modal freight systems are dealing with climate change impacts and the urgency act on. The study aim to explore how port authorities were considering adaptation strategies and what was their knowledge base for their long-range plans. Also to identify the information they found essential to plan while addressing possible climate change impacts in the coming century. At the time of the survey (2011) most of the ports who participated in the questionnaire were planning for some expansions on a 5-10 year horizon. However, longer climate change consequences, for instance market shifts or equipment needs, were not very popularly considered at the time of the survey. The last question of the survey ask the participants to list the top three impacts climate change might have on their port's operations. The biggest concern at that time was SLR followed by wave impact, flooding, shifts in the market, sedimentation and dredging (See figure 2.2).

Figure 2.2: Most answered climate change hazards on the survey. The size of the font represents the amount of same answers to the hazards.

A similar survey was performed on behalf of the United Nations Conference on Trade and Development in December 2017 [9]. The survey was conducted among 44 ports representing 29 countries including entities in Europe, Asia and North America. The respondent ports are responsible for the 16% of the global seaborne trade with large ports with more than 20 million of tons annually dominating the sample with 44% of the total. The aim of the survey was to improve the understanding of the potential implications of Climate Variability and Change (CV & C) for ports. A set of questions were designed to identify the 3 following aspects: (1) Availability of relevant information regarding climate change projections and hazards: also the information needed of ports; (2) Assessment strategies of resilience and preparedness amongst ports; (3) Identification of state of the art practice in terms of response measures and adaptation. As in the previous 2 surveys (Texas A&M and Stanford University), the majority of the ports responded that they already include climate related factors in their investment plans. Despite the considerable history of extreme weather events at their ports, the majority of the respondents have not received any claims from their users and clients requesting effective response measures and neither any change in insurance premiums.

Regarding objective (1) of the survey, several important gaps were identified such as the lack of reported information on major port operations and infrastructure design parameters for instance wave height, period and direction and average extreme precipitation. Furthermore, the respondent ports feel there is a need for more information about climatic projections such as extreme sea level rise. However, as for the second part of the survey 40% of the participants reported to not have performed or plan to conduct a vulnerability assessment of the port elements and neither identified or evaluated potential adaptation measures. Finally, the results suggests that with only 20% of the ports having received any financial help to overcome climate change impacts, government and non-government entities expect that the port authorities take care of their own measures to combat climate change.

2.3.2. Critical Port facilities & Interdependence

Port inter-dependencies with basic networks can be defined as critical (or vulnerable) points. If the connection of if one of these networks fails, then the port will be indirectly affected. The connection to climate change can be made in the same way, if an extreme events happens and affects some vital network for the port (such as power or data), the port will suffer in delays or even closure. For instance, if the power station where the port gets all the power is not resilient and it stops functioning during one of these weather events, even if the port itself is resilient, it will not be able to operate because of the power shortage. Hence, the port is not resilient after all.

Following the latter train of thoughts, the port vulnerabilities are not only within its operations but most importantly are on what the port is dependent of. These vulnerabilities are important to detect when managing the port business and to identify where the critical risks are. From the expert's experience shared at the interviews, the most critical elements, networks identified for a regular port are: (1) power and the power station also its transport (cables underground or upper ground); (2) data, which is as important as power nowadays. Information needs to keep flowing in and out of the port. If their servers and bases within the state are not resilience, the port has a problem even if the port itself is completely resilient; (3) clean water and sewage and (4) interconnections; roads, railway and inland waterways. If these are not resilient and cargo cannot come in or out of the port, the port suffers from delays or even closure. Finally, health and safety implications with operational limits in offices, computer systems, telecoms and interconnecting services are also potentially vulnerable.

2.3.3. Expert's Perspective on Most Vulnerable Port Elements

British Environmental and climate change consultant expert, Dr. Ir. Matthew Hunt, believes everything is vulnerable on a port. Very few things come up to be invulnerable in one way or

another depending on where something is and how has been constructed. From his experience, sea structures seem to be vulnerable, such as quay walls, if they are not high enough they will get flooded. If breakwaters do not keep up with sea level rise projections, increase in storminess can also be a point of vulnerability to the port. To this extent, Rotterdam Port engineers agree that the vulnerability of port marine infrastructure is not about the physical failure but the hinder caused to operations when extreme events would happen.

Rail, road, cranes and basically elements that overheat that cannot operate at or higher a specific temperature and are also, to Matthew's opinion vulnerable points mostly depending on where you are. However, Port of Rotterdam engineers and senior port consultants differ on the aforementioned point by stating that the equipment can cope with high temperatures and would only fail if the temperature would rise to an extreme which to their opinion, is unlikely to happen.

Interviewed experts agree on some port elements typically being more vulnerable to effects of climate change than others. The elements identified as being the most vulnerable are quay heights and breakwater overtopping, water drainage services and connecting infrastructure. If the latter are not operative, cargo cannot go in or out of the port. On the contrary, Cranes and mobile plants, if not build as hard standing, can become inoperative. However, they do not represent a risk because their operational period or life time is much lower than other infrastructure such as quays or breakwaters.

Experience from the CIrcle workshop at the port of Rotterdam tells that the biggest impact is the wind. Heavy winds break down communication tools which steer and monitor a lot of issues and activities within the port. The outcome of the workshop suggested a lack of knowledge on related cascade effects of failure in the communication system of a port. Missing communication is even more impactful than shortage of electricity, as everything in a port needs to be at the right moment (ships, VTS, cargo, rail and road entrances…). The ports are very sensitive to individual delays as they comprise several networks and very complicated supply chains with a lot of connections. On another note, expert Ir. Tiedo Vellinga who worked for many years as part of the Rotterdam Port authority, agrees that power shortage is one of the biggest threats to the port, but also the flooding of tunnels and consequent blocking of access and escape routes is also extremely harmful to the port clients.

Does vulnerability of port elements depend on the region and location of the port?

Experts believe that depending on the port and location itself vulnerability expectations change. For instance considering location and sea level rise in the UK, the most realistic projections are based on 1 meter of sea level rise which certainly will have an impact in several elements of the port infrastructure. However, if one looks at ports in Morocco and one assumes that sea level rise projections in 100 years are of 25 cm (source: Dr. Matthew Hunt) that would obviously not be a major issue.

Another example within regional differences in climate change impacts would be the heat impact for very extreme scenarios. The Middle East (Oman, Dubai, Qatar) and south Mediterranean countries (Morocco, Spain) are used to be exposed at temperatures of 50°C. Hence, they would be able to cope with an increase of 5°C. However, northern European countries such as Netherlands and the UK find challenging to operate at temperatures around 40C. If the port transport infrastructure is based on road, railway and hard standing cranes, the inoperable figures will raise. Therefore, the increase of temperature within these countries represents a potential hazard, as the equipment, the roads and railway are not designed to be operative at high temperatures. However do not represent such potential hazards for other regions where the materials are resistant to high temperatures.

Climate change predictions in storminess are irrelevant if the port in question is situated in a sheltered region. However, if the port is exposed to open sea or ocean, the increase of

extreme weather (storms) in coastal areas will lead to full closure which is a very expensive consequence for everyone involved in the port. When talking about climate change impacts on ports, one must refer to different regions and different hazards such as summers being warmer or winters being hotter and wetter, and basically the exposure to extreme weather.

In the UK there are a lot of vulnerability assessments or climate risk assessment being done as it is required by the government however also for ports financed with international money. As closure to this question, Matthew explained that from his experience the expectations change depending on where, how and what the operations will be.

2.3.4. Some Insight into Policies and Adaptation to Climate Change

It is projected at the global scale that 1,000-year and even 100- year events will frequently affect individual large port cities. Hence, even assuming that port cities will be provided with high protection, the large exposure in terms of population and assets would still possibly translate into recurring city-scale disasters. Therefore, it is essential to consider not only disaster planning but adaptation strategies as well, and analyze the consequences of adaptation and especial defences' failure [17]. Nicholls et al. (2010) proposes a few adaptation strategies which comprise a range of policy options that go from a short-term response to some other longer-term options:

- Early warning systems and early evacuation
- Upgraded protection systems
- Management of land subsidence in susceptible cities
- Building regulations such as flood-proof buildings
- Land use planning to reduce exposure focusing on new development away from the floodplain
- Selective relocation away from existing exposed city areas
- Risk sharing through insurance and reinsurance

Following the latter train of thoughts on adaptive strategies, M. Hasnoot et al. (2013) [26] present new dynamic adaptive plans, *Adaptive Pathways*, to deal with deep uncertainties such as the impacts of climate change. These strategies present short-term actions while establishing a framework to guide future actions. The *Adaptation Pathways* approach presents a cluster of possible actions that come after a tipping point (point in time where the strategy followed no longer fulfills the specified objectives) which together form a tree where every route is considered an adaptation pathway (see figure 2.3). This new adaptive plans can be very useful when assessing climate change policies (such as the ones presented above). However, due to time constraints, presenting more information on these subjects falls out of the scope of this thesis. For a deeper insight, it is suggested to read " Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world" [26].

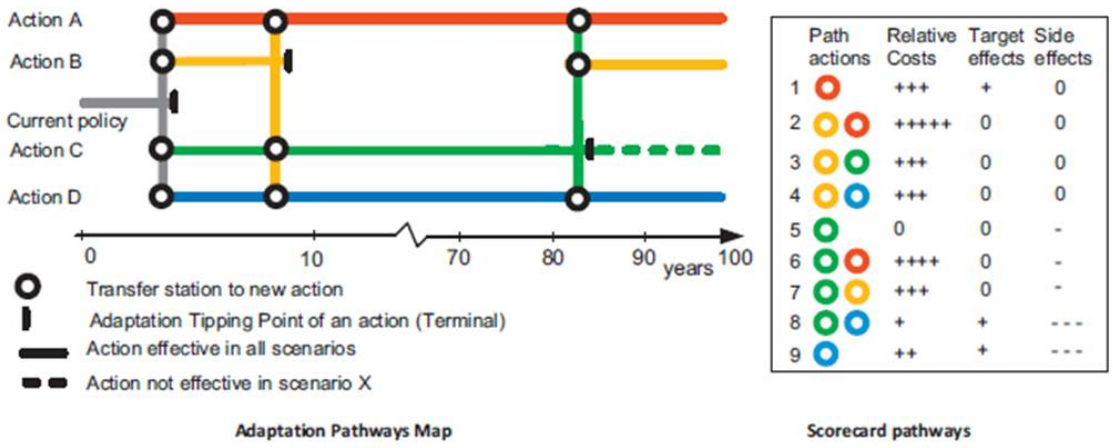


Figure 2.3: An example of an Adaptation Pathways map (left) and a scorecard (right) presenting the costs and benefits of the 9 possible pathways presented in the map [26].

2.4. Climate Change Impact Overview on Ports & Supply Chains

This section provides two different ways of impact mapping with also different formats. The first product is a table that differentiates Hazards, Impacts, Potential Implications and Vulnerable Assets of (or to) climate change within different areas (and operations) of the port field (Water areas, Port Infrastructure, Terminal areas, Hinterland connections and networks and Supply chain (or general)). With some help from experts, the table also provides an idea of what is expected to be short term and what long term.

The second product is meant to provide a more creative overview format. The model presents the most relevant climate change hazards, relates these to the potential impacts on the port and supply chain, and finally suggests the potential implications of these impacts. This diagram (see figure 2.7) aims to present a creative and simple overview to help visualize the complexity of the system.

IMPACTS= Red= short & medium term Blue= long term

Overview of Climate Change Impacts on Ports and Supply Chains

	Hazards	Impacts	Potential Implications	Vulnerable Assets
Water Areas & Operations	SLR	(1) Flooding and inundation (2) Erosion of coastal areas	(1) Delay in shipping movements (2) Reduced need for dredging, increased requirement for surveying. (3) Changes in availability of dredgers to undertake works.	Approach channel, ships in general
	Change in currents and tide patterns	Increase in sedimentation	Increased need to maintain channels	Approach channel, surrounding beaches and port seabed
	Increase Storminess and wave heights	Decrease in marine safety conditions for navigability and berthability	(1) Delay in shipping movements (2) Delays to arrivals and departures; transfer of pilots to vessels; vessel handling.	VTS services, tugs, incoming ships, breakwaters
	Changes in Wave climate (Period, direction)	Wave agitation (oscillations due to wind waves within the port), siltation or structure stability	(1) Decrease in marine safety conditions for navigability and berthability (2) Increased need to maintain channels (3) Damage to structures	Quay walls, ship operations
	Limited visibility induced by high fogginess	Decrease in marine safety conditions for navigability and berthability	Delay in shipping movements, increase downtime of port	All marine operations
	Strong wind driven by storms, cyclones and typhoons	Decrease in marine safety conditions for navigability and berthability	Delay in shipping movements, increase downtime of port	All marine operations
Port Infrastructure	SLR	Flooding and inundation	Damage of port assets	Quays, Breakwaters, Terminal Equipment, Goods and storage
	Increase Storminess	Increase in port infrastructure assets exposure	(1) Review design parameters at asset reviews / refurbishment proposals to include resilience measures. (2) Increase repair costs. (3) Obsolete, outdated infrastructure.	All vulnerable infrastructure
	Changes in Wave climate (Period, direction)	Direct Exposure to the inside port infrastructure	(1) Refurbishment proposals to include resilience measures. (2) Increase repair costs. (3) Obsolete, outdated infrastructure.	All vulnerable infrastructure
	Increase storm intensity	Flooding and inundation	Increasing risk of damage to port infrastructure, stored cargo and transport systems	All vulnerable infrastructure
	Extreme weather events	Increases in soil moisture	Undermine structural integrity of infrastructure	All vulnerable infrastructure

Figure 2.4: (First part) Table mapping climate change impacts on the different port levels and supply chain.

Terminal Areas & Operations	Strong wind driven by storms, cyclones and typhoons	Challenge to goods handling and storing sub-operations	(1) Increase downtime (2)damage to equipment and infrastructure	Bulk gantry, container crane operations and container yard stacking
	Limited visibility induced by high fogginess	Inability to operate	Increase downtime	All terminal operations
	Higher and/or lower air temperatures	(1) Deteriorate goods storing areas (2) Worsening operating conditions for staff (3) Reduction in engine operating efficiencies	(1) Increase operational expenditures (2) Increase green house gasses emissions	Equipment sensititve to temperature: cranes, trucks, storage conditions; & Labour force
	SLR	Flooding and inundation	(1) Inability to operate the terminal causing delays (2) Damage to infrastructure including electricity supply (and backup generators), loss of operation. (3) Potential knock-on effects to other critical infrastructure (4) Salt intrusion to basic equipment and corrosion of infrastructure	Data shortage, all equipment, warehouses
	Increases in the amount of rainfall and snow	Flooding and inability to operate	(1) Increase downtime (2) Damage infrastucture	(1) Container terminals could be closed due to unsafe working conditions. (2) Terminal operations in general (3) Outdated open-storage of bulk material operation.
Hinterland Area & Connections	Higher and/or lower air temperatures	(1) Increases in very hot days and heat waves (2) Large variations (spatial and temporal) (3) Frequent freeze and thaw cycles	(1) Challenge to service reliability (2) Increased maintenance and replacement costs	Railway lines (and roads) sensitive to buckling on extreme temperatures
	SLR (Indirect)	Flooding and inundation	(1) Inability to operate causing big delays and bottle necks within the transport web (2) Failure of electric components, communication and rail infrastructure outside the port.	All transport operations & loss of capacty
	Increase storm intensity	Raise soil moisture level	(1) Instability of slopes in railways/roads leading to bottle necks in transport network (2) Subsidence and landslide	All transport operations & loss of capacty
	Increases in the amount of rainfall and snow	Flooding and inability to operate	(1) Increase downtime due to interruption of road and rail networks leading to the port. (2) Damage infrastucture	All transport operations & loss of capacty
	Strong wind driven by storms, cyclones and typhoons	Inability for vehicles/railway to operate	Increase downtime and potential damage to infrastucture	All transport operations & loss of capacty

Figure 2.5: (Second part) Table mapping climate change impacts on the different port levels and supply chain.

Supply Chains & other Port related Business	Change in climatic regions	Trading patterns and the demand for port services	Modal shift	Inland Waterways (negatively) , Rail & Road (increase demand)
		Changes in Legislation related to working conditions / hours.	(1) Increase downtime (2) Organisational re-arrengenment	Port authorities, clients and port business in general; could also affect regional economy
	Increase Storminess	Several	(1) Reschedule external works to alternative times. (2) Delay in maintenance and emergency repairs (3) Increase in asset maintenance surveys. (4) Damage to VTS structures, infrastructure and access (Spurn). (5) Increase in insurance premium	Supply chain disruptions
	Sea Level Rise, changes in hydrodinamic conditions	Erosion or accretion of the coast surrounding and protecting port structures	Risks for safety of such structures and increase probability of flooding	Supply chain disruptions
	Rising temperatures	(1) Increases in very hot days and heat waves (2) Melting ice (3) Large variations (spatial and temporal) (4) Frequent freeze and thaw cycles	(1) Shorter distance for Asia–Europe trade and less fuel consumption (2) Additional support services and navigation aids such as ice-breaking search and rescue (3) Competition, lower passage tolls and reduced transport costs (4) New trade, diversion of existing trade, changes in structure and direction of trade (5) Longer shipping season (NSR), new sea routes (e.g. NWP) (6) Higher energy consumption in ports, including for cargo storage and air conditioning	Changes in port competition, change in trading routes, possible new supply chains, inverse globalization
	SLR	Flooding and inundation	(1) Relocation of business and migration of people, with further economic repercussions.	labour market, port closures, changes in ship size
	Increase in Cyclones, Tropical Storms	Increases in weather-related delays and traffic disruptions	(1) Change in navigational routes (2) Change in the structure and direction of trade (indirectly through impact on agriculture, fishing, energy)	Supply chain disruptions, changes in port competition, change in trading routes, possible new supply chains, inverse globalization

Figure 2.6: (Third part) Table mapping climate change impacts on the different port levels and supply chain.

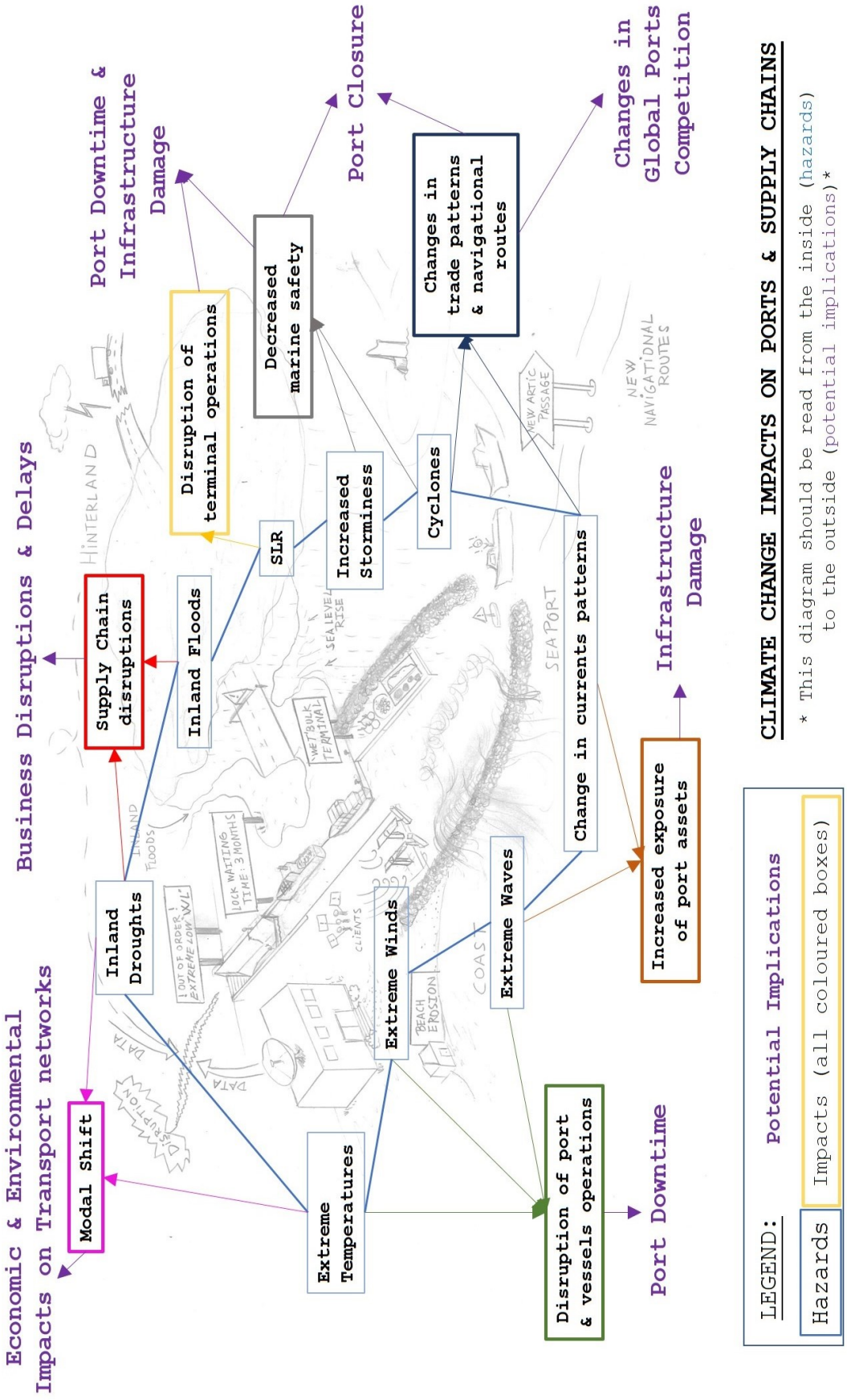


Figure 2.7: ”Climate change impacts on ports and supply chains” model. Overview of climate change impacts. SOURCE: Author

3

Climate Change Impact Assessment through Literature Studies

Chapter three provides answers to sub-research question 3 from an academic perspective:

- What are the state of the art strategies to perform climate change impact assessment?

In Appendix C, the nine state of the art frameworks that this chapter refers to are presented in detail. Only a few of them are specifically addressing ports. The methods that are presented have very different formats. Some of these are set of steps, set of questions and diagrams. It is noticed that most of the methods describe bottom-up approaches. The latter term means that the method starts by defining the climate scenarios and finalize by quantifying the risks and exploring the adaptation measures. There is another approach called top-down which starts by setting the risk tolerance and finalizing with determining the climate impacts. Nevertheless, determining which method is what falls out of the scope of this thesis.

3.1. Discussion & Conclusions of the identified Methods

There was no methodology (apart from MSc thesis from Erwanda & Judith Mol) that was specifically focused on the impacts in ports. The drawback of such is that the climate change potential implications are not directly specified for a port asset or part. Most of them aim for a broader focus and provide general guidelines. It is worth noting the Australian Government seems to be aware and well prepared on the importance to tackle and identify the impacts of climate change.

As in nearly all of the proposed methodologies the availability of information on the variables affected by climate change comes as a must, only one of them (Japanese) presents the need to categorize impacts considering their time scale or appearance in time as short, medium and long term. The studies in general do not assume that impacts would affect the port differently in time; however it is unknown whether in practice that is also a major concern.

Several of the presented methods suggest the need to first identify the physical stressors of climate change (i.e. extreme weather events), then translate them into impacts and finally assess the risk of the port elements to the latter impacts. Nevertheless, some of the sources (Climate change in Australia, MSc Thesis Erwanda) exchange the order of risks and impacts; they firsts propose to investigate the risks due to climate change stressors and then to assess what would be the impacts of such risks within the port elements. It must be noted that both practices are accepted and considered correct according to the Risk Journal; the order

depends on the author's point of view. However the level of detail on how to put into practice both risk and impact assessment seems rather poor. As far as explored within literature, only UNFCCC with their 'Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change' suggests tools, such as software and models to, use within the practice of Uncertainty and Risk Analysis, decision making and forecast of socioeconomic scenarios.

Nevertheless, Erwanda suggests a general classification of climate risk magnitudes for ports by Connell et al. (2015, p. 303). Erwanda explains the advantages of performing environmental and social impact assessments as a first step to determine the appropriate risk/opportunity magnitudes of all climate change effects and adverse weather events. The estimation of the impacts can be done by considering the anticipated duration of the associated adverse weather events in a year and the expected reduction in the operability of the terminal during the event. The data is key to perform the risk analysis however it seems that the required data must be gathered specifically for each port. However the question on how to access the data and how to determine such thresholds remains unanswered. Following the theory line of findings from Erwanda, Knowledge for Climate 022D/2010 gives some insight on performing a vulnerability analysis of port infrastructure by means of a workshop among experts. The study is performed for the Port of Rotterdam and is based on a qualitative scoring method which provides a general feeling of the vulnerability of port infrastructure to flooding. The port assets risk assessment defines 3 categories for experts to choose among, that identify whether the vulnerability is low (1%), medium (10%) and high (100%).

A few mathematical models assessing risk are presented in 'Risk and cost evaluation of port adaptation measures to climate change impacts' by Z. Yang et al. Two of them are the 2ER algorithm for the synthesize of climate risk estimates and adaptation costs and A fuzzy Bayesian approach for climate change risk analysis in ports. The aforementioned study proposes a risk and cost evaluation methodology that to analyze port climate change adaptation strategies in situations where high uncertainty data is an issue. Furthermore, for a proper climate change assessment one would have to look how the 100 year wind speed , rainfall etc. change with climate change. The European projects RAIN [2] and BRIGAID [1] have published these hazard maps with and without climate change.

The methods that have been identified during the literature study are the following (for more information Appendix C is referred):

- The Committee on Approaches to Climate Change Adaptation from November of 2010
- Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies – UNEP & VU (October 1998)
- CLIMATE CHANGE IMPACT ASSESSMENT, ACT Government from November of 2011
- Climate Change impact assessment and adaptation strategies forr sustainable development of societies – RMSI consultant
- Escalating impacts of climate extremes on critical infrastructures in Europe
- Conducting an impact assessment – Climate Change in Australia: Projection for Australian NRM regions
- Development of Climate Resilient Ports – MSc. Thesis Erwanda S. Nugroho
- IPPC Report 2007: Chapter 6, National Systems for Man-aging the Risks from Climate Extremes and Disasters
- Exploring Potential Climate Change Impacts and Adaptation Strategies for Seaport Operability– JUDITH K. MOL

3.2. Identified Literature Knowledge Gaps

One could conclude that general recipes and more in detail conceptual frameworks to perform an impact assessment are present within literature. However, only specific (TU Delft) MSc theses address impact assessments related to the field of ports. The potential theoretical climate change impacts affecting ports and its main assets are well known. The level of awareness of primary (or direct) climate change impacts such as SLR, increase in storminess frequency etc. is larger than for secondary (or indirect) impacts such as changes in trading patterns and the demand for port services that could conclude in modal shift. There is no evidence on whether the latter secondary/indirect impacts are considered in practice by engineers, port authorities and experts in general.

None of the studies present a different approach for long term in contrast to short term impacts. Moreover, there is lack of knowledge on which set of temporal scale effects (short term, medium term effects...) should or must be included in a master plan or port related policy and what is considered in practice. The major consequence derived from the lack of knowledge on impacts time-frames is that vulnerability is more difficult to assess. There is no literature suggesting a way to identify what are the imminent consequences of climate change in ports. And therefore, there is no way of identifying which port elements would be the first affected.

As mentioned on the previous section, the level of detail on how to put into practice both risk and impact assessment seems rather poor. Furthermore, the quantification of climate change impacts and risks and their translation into costs seems to remain unknown. A few methods (Erwanda, KfC) assess the risk of several port assets by means of a categorization based on the (very rough) probability of operational, financial and socio-environmental damage. The assessment is based on experts' opinion and is defined as qualitative. However, threshold levels of the hydrodynamics and physical variables affecting each port element are not considered in the studies. Conclusively, the lack of quantification of impacts is the major gap and that leads to inability to rank which assets are most vulnerable and should be a priority for port authorities. Following the latter train of thoughts, studies do not address who is suffering within the port stakeholders and who has to pay or will pay the expenses of adaptation measures.

From the information presented, three categories of knowledge gaps topics can be identified. They comprise the academic point of view of climate change drivers and potential implications for ports, risks and methodologies for impact assessment. The aforementioned categories are (1) Current practice of Port Authorities and experts considering climate change impacts, (2) Vulnerability analysis of ports elements and (3) Quantification of risks and impacts, and damage assessment for climate change in ports. The following list of questions aims to present the gaps identified through the literature study. The answers to these gaps are presented in Appendix A.

1. Current practice of Port Authorities and Port Experts when assessing climate change impacts

- What climate change impacts are currently considered by Port Authorities? And for port consultants?
- Are cascade effects considered within current impact assessment practices?
- How does the Port of Rotterdam currently deal with climate change impacts?
- In which tasks, designs, reports and policies does the Port (as an entity) consider the climate change impacts? Are those impacts categorized regarding timeframe?
- What time scale would be beneficial to consider when master planning? And for other type of planning or designing?

- Who is involved in the process of decision making for climate change measures?
- What are the new developments within the Port & Waterways field (such as IWT Assam)?

2. Vulnerability analysis of ports elements

- How could one best assess the vulnerability of each port asset/element? What performance indicators could be used to efficiently identify the latter?
- What is the relation between the aforementioned performance indicators with the climate factors such as wave height, wind speed, water level, temperature?
- Would it be useful to determine general thresholds (i.e. at a national level) at which integrity and functionality of infrastructure and equipment are significantly impaired? Or should that be a practice for each specific port?
- What is the threshold beyond the individual port elements become considerably affected? What could be described as 'considerably affected'?
- What is the port policy to assess vulnerability? What is the limit accepted and on what base is it measured?
- What method or software one could use to link, identify what climate change impacts affect each port asset or port element? Would that be a general method for every port or should it be used specific technique for each case study?
- Who is responsible for the adaptation or mitigation measures? Who should decide and who should pay?

3. Quantification of risks and impacts, and damage assessment for climate change in ports

- What is the difficulty of making risks and impacts more tangible for decision making?
- How would be the best way to express and to quantify risk? Where can one find the data and information to be able to judge the aforementioned?
- Which software or technique could be relevant to assess impacts and risk within a port scale? And within supply chain scale?
- How could one judge whether an impact is short, medium or long term affecting the port? How could one best describe what short, medium and long term impacts are?
- What can be done to mitigate the risks, what does it cost and when does this need to be implemented?
- How can one best express the consequences of cascade effects?

4

Expert Interviews on Climate Change Issues

Chapter four provides answers to sub-research question 3 from a practical perspective perspective:

- What are the state of the art strategies to perform climate change impact assessments?
- What are the available resources (frameworks, methods, software)?

The climate change impact assessment of ports is a very broad practice. Hence, this chapter presents how climate change impacts are currently considered by experts in each layer (see section 1.1.2) of the port. The sections of this chapter present information that has been gathered during the expert interviews. Hence, one should read the different sections from the perspective of the expert. The first and second sections focus on impact assessment on the port as entity. The first presents the current practices within the stages of port development and the second section uses the perspective of the three-layer inframodel (see explanation in section 1.1). The third section addresses some aspects of the stakeholder engagement during the practice of assessing climate change impacts. The final section presents the available and state of the art software, methods and techniques to assess the impacts of climate change.

4.1. Climate Change Assessment in Port Development practice

4.1.1. Economic Stage: Cargo Volumes & Cargo Routes

There is an undeniable focus on the importance of climate change on ports, specially on infrastructure design. However, port business cases do not include climate change in predictions. The reason is climate change is thought to have effects in a longer period than the one considered in economic stage development for ports. Dr. ir. Cornelis van Dorsser believes the question on climate change effects on port economic stage (or business case building) should be placed within the discount rate factor. Using a low discount rate would mean that climate change is more taken into account in the investment. However, especially in private investment discount rates can be rather high; that means that there is no urgency on climate change adaptation measures.

Furthermore, indirect effects might play a role if coming from the climate change policy part. There is hardly anything written on forecasting of port volumes in general. Forecasting is something done mostly by consultants and some guidance is normally given by econometric experts. Probabilistic forecasting is something missing and could be done using linear models and checking all the parameters to identify the sensitivity of them. But most of the time some of the statistical models do not capture completely the physics of the system.

4.1.2. Master planning: Layout & Terrain

Master planning is a practice that involves several expertise. In this thesis due to time restrictions and for the sake of simplicity, the topic will be addressed from Rotterdam's port authority perspective and consultants (designers and port planners) point of view.

Rotterdam Port authority

As Landlord port, the Rotterdam port authorities have the responsibility to inform the clients of any relevant issues that could affect them as users. From the angle of Rotterdam's port authority, they generally consider very closely what are the risks of flooding at specific areas and terrain heights. As the Port of Rotterdam is situated in an outer dike part, there is no law about flood protection as there is for inner dike areas. The only existing policy is that the user of the area is responsible for the damages and protection to flooding. However, they have the responsibility to deliver a terrain which is high enough for the current Sea Level Rise forecasts in IPPC reports.

The way the port deals with impact assessments is through workshops and interviews with the clients. These workshops explore the economic damage caused by extreme flooding events. The port asks the companies about recovery times until full operation after several disasters. Also they are interested to know the economic damages at the companies' facilities. The aim of Rotterdam engineers is to validate their tailor-made risk-damage curves with clients data provided through the workshops. Several of the companies at the port make us of a specific method to quantify the impacts of flooding. The method consists of risk-based matrices that categorize (by means of color based approach) the impacts of extreme events on their facilities (see section 4.4.4).

Independently of the risk acceptance of the individual companies, the port authority felt the need to develop a method to dictate the level of risk that is acceptable for the port. Their method is based on comparing the port's risk to inner dike areas risk. In the Netherlands for each inner dike area there are two computed calculations: casualties and economic damage if failure. The port's approach is meant to scale down the results from inner dike acceptable economic damages to the port outer dike areas. The Port of Rotterdam is convinced that their method follows the state of the art approaches to impact assessments which is the quantification of impacts in terms of risk and not only chances (designing for certain return periods). Conclusively, their practice determines the economic damage threshold for every SLR scenario (and storm event). If that is exceeded then measures need to be taken and the Port is able to plan for adaptation.

On the western part of the port, wind becomes more of an issue than water levels. Detailed models for local winds have been developed in collaboration with the University of Eindhoven. These models look at special facilities, ship mooring, cranes etc. However, there is no research on the increased frequency of extreme wind events and its impacts on these areas.

On another note, the Rotterdam port authority feels that sharing the climate change risks with the clients is not that of an easy task. The clients can assume that those risks were known forehand and sue them for not preparing the terrain properly. At the same time, the port authority is only responsible for the terrain height and not for the terminal adaptive capacity to climate change events. The consequences of such dilemma are ignoring the risks, or preparing the companies to adapt to these risks. The second one has been applied at the Maasvlakte 2, the current container companies are preparing themselves and adapting to the potential impacts. For future chemical industries that would like to settle in the Maasvlake 2, the port policy (or contract) obliges the companies to conduct a climate change assessment themselves.

Consultants practice

Expert Ir. Nanco Dolman's practice starts with a vulnerability analysis of the assets. Within the latter, different scenarios but also cascade effects are studied within infrastructure and operations. Cascade effects are important for operations, and hence, assessed by means of a series of software, methods such as CIrcle or Bow-Tie 4.4. The latter is important to prioritize what systems and functions are most vulnerable and to illustrate the relation between systems and locations around ports. The second step within the general assessment method is to perform a stakeholder analysis. The stakeholder dialogue is about raising awareness, improve communications and forecasting and identification of prevention measures. The last step in the method refers to the ambitions of stakeholders. Raising awareness is very difficult but mostly to transmit the feeling of urgency; interviews are conducted to map interests, support and responsibility for different assets. It is done within the port environment but also on how stakeholders outside the port communicate and process information. In many cases, ports are very much business driven hence, that is the focus for most of the people involved.

4.1.3. Design & Infrastructure

Expert Dr. Ir. Cornelis van Dorsser shared that around 8 years ago (when he was working as a port designer) only deterministic values of SLR (increase of water level in meters) were considered in designs, for instance quay wall levels. Other interviewed experts seems to agree to the statement from Dr. van Dorsser. Nowadays, most of the ports around the world still consider this practice efficient because they believe they are designing on the very conservative side. However, only an increase in heights is considered by adding a value for SLR. But what would happen if together with sea level rise, storms and high wind speeds become more and more intense? Are the designs still on the conservative side?

4.2. Climate Change Assessment in three-level Port Model

This subsection focuses on impact assessment in the port as a physical element. The structure is based on the mentioned 3 level port categorization in section **??**. It aims to clarify how port authorities, consultants, researchers and generally port experts feel about climate change impacts on the mentioned 3 levels of the port. It also presents some information about the inclusion of these consequences in practice.

4.2.1. Port Infrastructure

The Rotterdam port authority believes that physical infrastructure, mostly maritime, is not vulnerable to the impacts of climate change. The latter refers to damage in the structure, so considering the structure as the vulnerable element. Mainly because maritime infrastructure can cope with weather impacts (being robust mostly made of concrete structures). Within they experience as a global port, they noticed that the vulnerable elements are operations and the assets of their clients. For example, if the terrain of a terminal floods, the operations will consequently be hindered. Consultants seem to agree with the latter statements (see interviews in the annex). Considering the experts' opinion on this specific topic, climate change impacts causing severe infrastructure damage can be neglected. The focus should be on the impacts on port operations, that are treated on the following subsection.

4.2.2. Port Operations

Assessment in practise

Port of Rotterdam engineers assess impacts within their operations by means of damage curves of flooding. Some interesting fact about these curves is that beyond certain inundation

level the damages become constant. The shape of those graphs is like the (for instance) steel strength diagrams, where there is a rapid increase at the beginning but beyond some threshold, the strain is fixed. The results among years of analysis suggest that installations in general is the most affected where the biggest economic damages are spotted.

The starting point for consultants is the setting of scenarios for fairly conservative future but also for worst case scenario. The input data for the projections mainly come in general from distinguished sources such as IPCC or UK CP09 for climate projections in the UK. Normally, engineers address the resilience of the port together with port operators and other port stakeholders during risk workshops. If during the workshop data suggests that the port would not be resilient to the input scenarios, they altogether identify measures that need to be implemented to ensure the level of resilience. Conclusively, they assess the risks through a risk workshop rather than using any model or simulation. The resilience is described in base of what the port operators thinks is acceptable and what risks they accept to take. In privatized ports, the risk categories depend on the client and he/she is asked to fill in the numbers that will define the thresholds for each category of risks (e.g. financial risk, environmental risk, reputational risk and social risk).

Which port operations are vulnerable?

The answer to this question mainly depends on the nature and location of a port. The latter determines to what weather or climate hazards the port is exposed to. This sections aims to present a general opinion from experts among the field of ports.

If one is moving containers in very windy and stormy places, with containers being fairly water tight, these could be easily stack with help of some innovative techniques. Hence, investments on climate change proofing are on simple operational techniques that might be solved with little money, training and awareness. However, bulk terminals storing cargo in the open under latter same exact circumstances will need to start storing the cargo somewhere else. That kind of terminal will probably need to invest in different infrastructure to be able to continue operating while keeping the product dry from the increase rain. However, in a big global ports such as Rotterdam, every type of cargo (containers, oil, tank farms, bulk etc.) is present there. The vulnerability of such type of global ports is mostly about its superstructure; and the operations come down to what is the cargo and how is moved in and out of the port.

4.2.3. Port Services & Products

When looking at the global picture including ports as major supply chain nodes, the issue that matters is the port's ability to deliver services and products. For that, port infrastructure and operations level need to be resilient and in general, ready to adapt to future market shifts.

Climate change has and will have influence on the global economy in a direct but also indirect way such as through policies. The way experts quantify business and supply chain disruptions (in general) is by economic models. Expert in modelling of economy-wide consequences of disasters, Elco Koks, suggests two ways to assess disruptions:

(1) The macro-traditional economic models are simplistic but very useful models to understand input and outputs of goods in a global supply chain. These models make use of tables (or matrices) to store data. The chains are estimated with UN trade flows data base as source. Some of the global tables are public and accessible: WIOD, EORA, EXIOBASE, UN COMTRADE, OECD TABLES, Asian Development Bank (ADB). From Elco's expertise, these tables definitely help to map out supply chain networks. (2) The second type of models are more focused on finding a new type of economic equilibrium and get new post-measure equilibrium. For supply chain modelling, Elco suggests looking at the field of Industrial Ecology where supply chain climate impacts are better understood.

4.3. Stakeholder Engagement

From British consultant perspective, Matthew Hunt and his colleagues normally ensure to have within risk workshops a climate risk assessment team with about 2 or 3 people. They also make sure the participation of people from the client team like the head responsible for port development, a decision maker for port operations and 2 or 3 experts involved in operations. The suggested team comprises several expertise which are key to a successful risk assessment: development director, a head of port planning, harbor master and head of operations. However, in big global ports such as the Port of Rotterdam, one can find several types of terminals and different port services. Therefore, it is important to include several of the different terminal operators to engage them in the process. The terminal operators are able to detect whether a point of the whole process is vulnerable to the port. There is no point for the Port of Rotterdam operators to have resilience covert if one of their main clients does not understand anything about climate risks and becomes vulnerability for the whole port. That is the reason why from experts perspective, in very big and complicated ports it is important to engage the big clients in the process.

Depending on the magnitude of the project, other stakeholders apart from the ones participating in the port activities might also be involved. If the project requires to identify supply chain disruptions and cascade effects of climate change, experts believe there should be a mix of experts from basically two categories: (1) Experts in crisis management, which in the Netherlands the unit is called “safety regions”. They are responsible for the management of disasters and they know very well from experience the cascading effects. (2) Experts in the different networks that have relation to the port or the region where the port is. These experts will provide the information about the vulnerabilities of the different networks, such as thresholds at which the network is not working anymore. These networks are strictly dependent on the region that is being considered, however most commonly considered are: energy, electricity, drinking water, sewage water, railways, roads, inland waterways and communication. The last being the one with less knowledge but with the biggest and largest impacts to other networks.

4.3.1. The Big Unknown: Responsibility on the Measures

This section addresses the polemic question on ”who is responsible for the measures”. This question was asked to all the interviewed experts and as it was already expected, it generated many points of discussion. There seems to be a general agreement that the answer depends on the country, culture and port organization. Furthermore, This topic is closely related to stakeholder engagement and raising awareness. Expert MSc Jarit van de Visch has provided some insight into a successful pilot project at Rotterdam Port that focused on raising awareness to the impacts of climate change to the port clients. The latter is explained at the end of this section.

From the perspective of the Netherlands, inner dike areas are protected against flooding by law, by the government. However, at outer dike areas every user is responsible for their own damage in case of storm surges and floods. There is no law that enforces a governmental action to protect outer dike areas and the port of Rotterdam is located in one of those. The level of awareness to climate change impacts really differ per company. Big companies in the Port of Rotterdam have very high safety standards and consider as boundary conditions for their assessments storms of 1000 years return period. Nevertheless, smaller companies do not believe those storms are of any hinder to them. So one could conclude that the question about responsibility comes to something like what risks do companies accept.

Another example within the Netherlands is the A15 highway which is managed by the government. If the highway is flooded, the port can suffer from major indirect damage as the cargo would not be able to go in or out. Rotterdam port engineers are currently considering

including climate change clauses in new contracts. As Landlord port, they have the responsibility to inform the clients of any relevant issues that could affect them as users of the port. From their experience, it could take up to 10 years to have a solid (and common) strategy that every company in the Port of Rotterdam follows.

The port organization plays a major role on this equation. Most of the ports in the UK are private businesses however in Morocco or Spain the port is public earned. If the port is public, the responsibility of the adaptation measures would lie in the government in one way or another. Within the UK, ports are more privatized than other European countries and the responsibility is all within the private sector. The port operator or harbor authority would do the investment however, they can pass charges to the shipping companies and the terminal operators; at the same time, the latter can charge larger quantities for their services and products. Like in the Netherlands, some cases if it is not build into the contract, the harbor authority cannot oblige the terminal operators to take care of adaptation strategies. Conclusively, in some cases the harbor authorities can only strongly recommend adaptation measures and hence, getting the adaptation delivered can be a very tricky question.

Within the Inland Waterway sectors seems that everyone is aware that everyone is responsible in financing the measures. The discussions within Rijkwaterstaat (Dutch Government) argue whether they (as Government) should facilitate the inland transport system to the transport companies. However, there is no space to grow in the Netherlands. The shipping industries responsible must find solutions to keep the transport capacity at high levels. Because at some point, there is no possibility to widen and deepen the waterway because of bottom erosion and dike instability.

4.3.2. Raising awareness on the subject of Climate Change Impacts on Ports

Several experts agree that the most effective way to raise awareness (but the least wanted) is to see the real consequences if something bad happens. It worked in the Netherlands when recent floods by Katherina and Sandy hurricanes produced so much damage. Insurance companies are potentially interested in supply chain effects of climate change nevertheless, it is not on their priority list. The latter happens with port clients and port authorities. Hence, the question of what would it take for them to plan ahead for climate change arises.

Interviewed experts within the fields of ports and supply chain modelling agree to raising awareness by understand better not only climate change effects on ports but most importantly general supply chains. Several experts suggest to make use of models and workshops with supply chain stakeholders and with the manufacturing sector. The chain of services comprises big companies that outsource to other companies and so on. These ”outsourcing” chains are a bit hidden within big global supply chains. For instance, an insurance sector can have 8th order of outsourcing but that can also happen in the manufacture field. The focus should be on finding the bottlenecks, the companies that are producing products that are essential to the global supply chain. Research such be conducted on understanding qualitatively but also quantitatively effects of climate change on the entire system. The only way, experts in modelling this kind of aspects think that would be possible is by iterating between workshops and models.

The best way to promote awareness is to explain people what are the consequences of climate change and how these consequences are going to affect them. Use common language to address the impacts of climate change to society rather than using scenarios and technical language. The aim should be to explain the direct impacts on society and make people realize the urgency to act against it.

4.3.3. Port of Rotterdam Pilot Project: Adaptation Strategy for the Botlek Area

The Port of Rotterdam was interested not only in developing a climate change adaptation strategy but also in a way of raising awareness among the companies [34]. The proposal from RHDHV consultants was to join all the experts together to ask them about flooding consequences in their facilities and further come up with an adaptation strategy that was beneficial to all. RHDHV team analyzed the flood hazards and showed them to the companies during a first workshop (see figure 4.1).

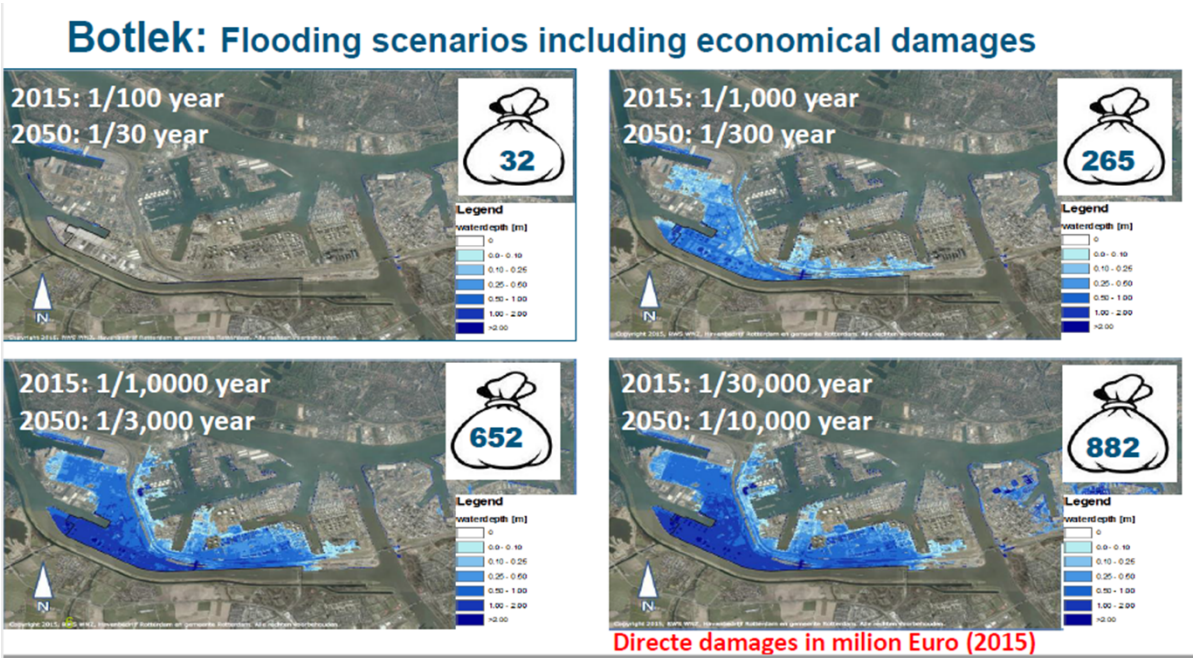


Figure 4.1: Flood hazard maps for the Botlek pilot project. SOURCE: Royal Haskoning DHV & *https://www.portofrotterdam.com/en/our-port/our-themes/a-safe-port/water-safety*

The representative experts were asked what are the water levels (from flooding) to which their facilities are no longer in service (SLS) and completely damaged (ULS). The interesting part about sharing hazards is that experts realized that many other mentioned also applied to them. With this simple acknowledgement, experts are more aware of the consequences their assets can suffer in a flood. At the Port of Rotterdam, the companies settled at the Botlek area are the main (oil and other substances and fuels) suppliers for the entire region of Holland. Many of the port companies mentioned that with only 20 cm of water, the power outage would be ruined (as it is normally placed in the basement). If that happens to all the industries, the question becomes whether there is enough material to replace them all and whether interdependent companies in the region would also fail to produce.

The main challenge within the project was dealing with different risk appetites in a same threatened area. Not only a level of risk tolerance was treated but many according each company assets. So, what point in time the risk becomes unacceptable? The answer lies in using public laws such as inner dike safety and external safety in the Netherlands. During the second workshop, companies could comment on the results of the engineer risk assessment made with reference to pubic laws into the risks previously discussed with them in the first session. Companies became aware about what point in time the risk is no longer acceptable in a general governmental framework. The participants could identify their level of tolerance within the presented time-line.

The final workshop was about the type measures between levels of mitigation, adaptation (learning to live with water) and after disaster action. Experts had to explain what measures

were the most cost-effective for an adaptation strategy. However, leaving the subject of responsibility aside and thinking as a collective. It was noticed that leaving the responsibility question aside, experts become truly engaged and do not see the session as a negotiation. The consequences are that they feel comfortable to open up and share experiences, knowledge and own practical strategies. After some discussion, the team managed to reach an adaptation strategy that had the largest benefit for all the companies.

The pilot project went on for around one year and a half, however they had to create the risk assessment method from scratch. After their second project, these kinds of projects are meant to take in between six months and one year. The most complicated part of the project was to generate the functions that relate risk with serviceability limit state and then relate the risk to adaptation strategies on time. Conclusively, for the project to be successful one should leave the (economic) responsibility question apart and focus on collective risks and measures that benefit everyone. Because if the workshop becomes a negotiation, the experience shows that companies shut down and focus only on their own benefits.

Would it be possible to adapt the general framework of the pilot project in Botlek to be used in other countries?

The general way of working can fit into any other country, however the norm on which is based is only a common language for the Netherlands. For instance, in the Netherlands there is no possibility to insure assets to flooding, therefore the safety measures and levels are higher than in other countries. On the contrary, the UK enables the companies to insure their assets to floods so the measure and safety standards within the companies are much lower. The key is on finding the region's common language in terms of risks. This practice is very possible to insert in any country around the world. The importance is on showing the hazards hey are exposed to. It is not enough to create a map and give it to the workshop participants but the discussion helps to raise awareness. The participants do not understand flood engineer language, it is easier for them to visualize the facts and see images of what can happen instead of reading complicated graphs. The whole process can be explained as stakeholder dialogue, essential to create awareness and commitment.

4.4. State of the Art Software, Methods & Techniques

This section present the state of the art techniques that have been identified through the interviews.

4.4.1. Economic Optimization Method

The derivation of the economically acceptable level of risk can be formulated as an economic decision problem. The total costs in a system can be determined by the sum of the investment for a safer system and the expected value of the economic damage or economic losses. In the optimal economic situation the total costs represent the minimum among all. This method was originally applied by van Danzig (1956) to determine the optimal level of flood protection (i.e. dike height) for Central Holland.

The aim of this method is to find the optimum budget to invest in protection against extreme events or climate change related events. One must monitorize the different risks per different hazards and then protection measures (investment) depending on the event, so the two curves can be summed to find the total optimum. Modelling economic losses for extreme events that have not happened yet is extremely difficult and data mostly need to be validated with port authorities. More information on this method falls out of the scope of this thesis.

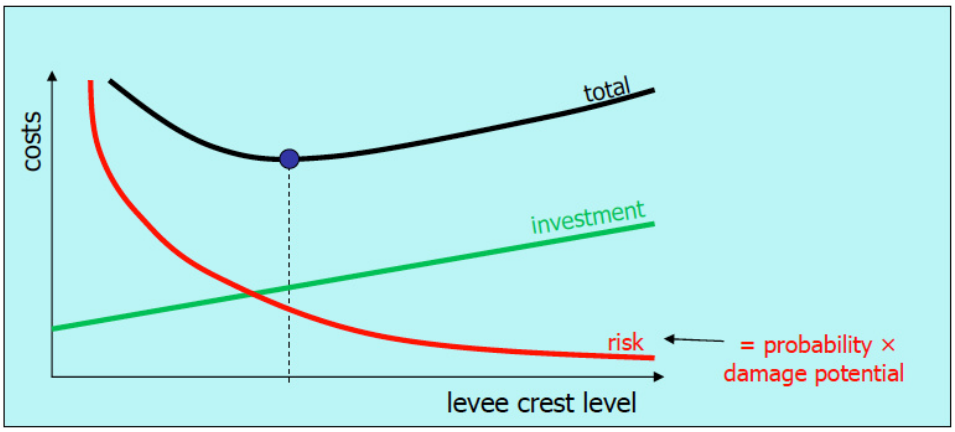


Figure 4.2: Example of the Economic Optimization Method.

4.4.2. Three-point Method

This method consist on modelling with function the consequences for each hazard (rainfall, storm surge, flood, temperature, lightening, wind) with historic events with their respective return periods. Often, 3 stages or categories are considered for events (on the y-axis, as dependent variable) and consequent loses: normal, moderate and extreme situation. These can be defined by means of expert judgment techniques. More information on this method falls out of the scope of this thesis.

4.4.3. Bow-Tie Method

The BowTieXP software is a convenient tool if you would like to create bowtie diagrams and link more information to the bowtie such as documents.

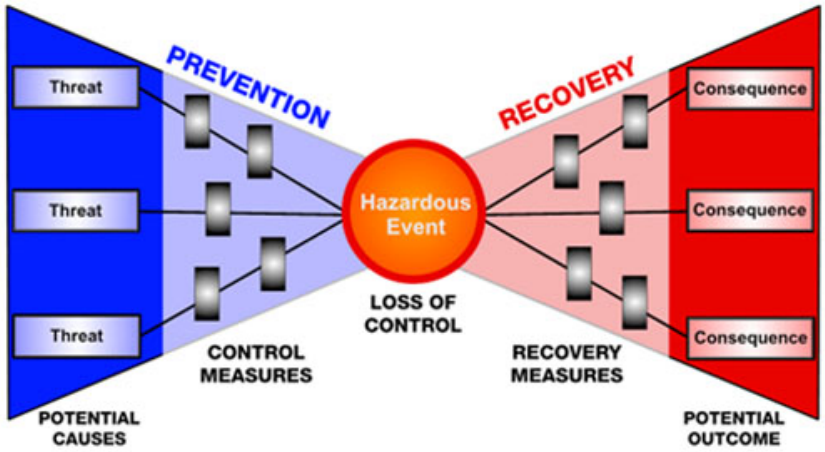


Figure 4.3: Example for the Bow-Tie Method.

4.4.4. Risk Matrix

This approach consist of a matrix providing a rating of the likelihood that the risk will occur together with the severity rating of the consequence (see example in figure 4.4). The “priority” column normally identifies how important the risk is within the collection of risks facing the asset (in this case, the port). The priority scales are broadly narrative, defined as low (L), medium (M) and high (H), and point towards areas of risk for which more detailed analysis

is needed. The level of detail differs among the project, but this risk-based approach enables to define the threshold at which vulnerabilities become a serious threats. More information on this method falls out of the scope of this thesis, it is suggested to look at Msc Thesis of Erwanda S. Nugroho [33].

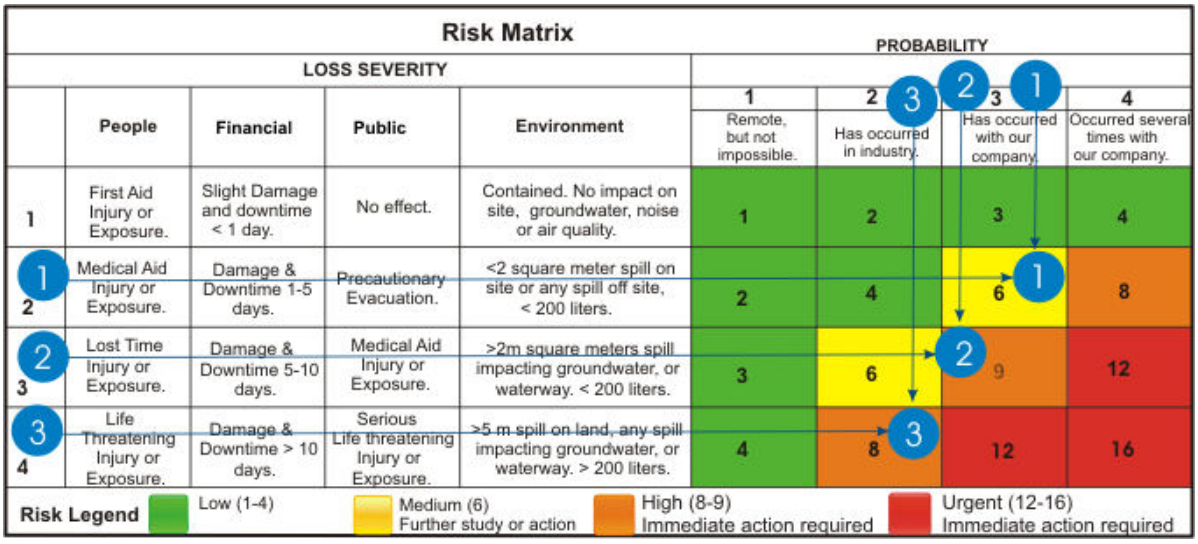


Figure 4.4: Example for the Bow-Tie Method.

4.4.5. CIrcle Tool

The circle tool is performed as a workshop where to gather experts that will be able to give relevant information. Firstly, one formulates the questions to assess, then one thinks which experts will contribute the most, also selection of networks that could be affected or included within the question to answer. The networks chosen to participate in the circle really depend on the area and what is present and valuable there. The idea is to collect information and data talking to the experts during the workshop and then to create the new CIrcle tool; including the networks that were relevant and participated. Then, cascade effects, indirect effects that are connected within the networks are plotted. For ports, the workshop starts by presenting a hazard which most of the times is floods or heavy precipitation. The consequences are drawn in a map of the area that is going to be analyzed. The questions start with who is affected by that hazard and how, up until which threshold (e.g. 25 cm of water). From the gathered consequences, one identifies who of the other networks would suffer if the flooded previously mentioned facility stops functioning. And there is where cascade effects start to be defined by experts. It is also asked to quantify the damages in terms of time (how much tie would you be without for instance electricity), and in terms of money, how much would it cost you to repair it. The major aim is to identify thresholds from the expert's experience.

Software expert, MSc Micheline Hounjet , suggests CIrcle to explore with port experts climate change impacts (heavy rainfall, heavy winds, SLR) and how these could affect different networks, basically to identify cascading effects by means of experts' experiences and knowledge. CIrcle would be very useful to identify which is the network that one needs to protect the most in order to indirectly protect the others.

To create the CIrcle platform (or tool) some relevant data is needed. The data to construct the CIrcle is given by the experts during the workshop. The difficult task is to visualize what are the most relevant impacts that has been said and identified. As not everything can be used to visualize the impacts and the cascade effects. It is open data, only what the network owners feel comfortable to share. The information for the circle is stored within Deltares data

base but it is not open for the public. Another option can be to buy the private version and then start a new database (RHDHV is planning on doing this now).

Sometimes, experts in the workshop do not feel confident enough to reveal their private information. Therefore from Micheline's opinion, is advantageous to explain the experts that the information will not be given to anyone and the effects of climate change on their networks are not their fault. The aim is to make experts in the workshop comfortable on telling their part of the story. First to ask them what are the damages of different hazard and go step by step, connecting all the information of the different network's experts and making them realize that are helping each other.

There is no need to identify a scenario as input. During the workshop the area is exposed to certain hazard (climate physical hazard). Firstly only to one, and then experts start sharing their measures and weak points. Then one can start asking about certain future scenarios and experts will answer in relation to that. As a drawback to this thesis, the workshops start suggesting only one hazard (climate physical factor) that affects the region and their networks, so only introducing other hazards if it is necessary to gather more information about cascade effects.

4.4.6. STAIN Tool

The software STAIN is still in its development phase, however it has already been tested it in a Dutch city and in Singapore. The aim for STAIN is turning this tool available for ports. The next step for the STAIN team is to generate a session for the Port of Rotterdam to identify what measures need to be taken to climate change hazards and what will affect who. The focus is on identifying how different measures influence the networks and stakeholders. The STAIN experience includes opening up a discussion for different type of measures, not only robust but also to explore self-resilience and not only immediate protection. It would be interesting to see what strategies are considered to reinforce each other's goal and explore who benefits from whom.

The availability and practice of STAIN is currently only by means of a workshop (like CIrcle) to gather the information and further process it into a nice outcome for the client. Nevertheless, STAIN experts are exploring the benefits and potential use of an online version that would allow to design and test strategies in the area. This version would add extra value by showing the level of resilience of the area under certain hazards. STAIN could be of use to present designs to other stakeholders and to ask them what measures influence the resilience. Also to make stakeholders score the strategies and quantify the consequences.

5

Identified Research Knowledge Gaps

This chapter answers the sub-research question 4 on identifying what are the knowledge gaps found while answering sub-research questions 1,2 and 3. This chapter presents the results of the gap analysis through the literature study and the 12 expert interviews (see them on Appendix B). It is worth mentioning that this thesis aims to present research knowledge gaps from the point of view of ”end users”, ”port stakeholders”, such as consultants or port authorities. Due to time constraints, only eleven Dutch experts and a one British expert were interviewed. Very little information has been gathered that has more of a global perspective which is probably the main limitation of this thesis. The information is representative for the Netherlands which on a global perspective, is situated on the right hand side tail of a climate change and water resilience knowledge distribution. The latter means that the Dutch are seen far ahead in terms of adaptation planning, water resilience and climate change awareness than the rest of the world. Positively, there is a chance that Dutch pilot projects become role models and examples for other less developed countries.

On another note, the most urgent topics that were mentioned during the expert interviews are gathered in this chapter under five main categories which are the following:

1. Lack of Integrated Models and General Guidelines to perform Climate Change Impact Assessment on Ports and Supply Chains
2. Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade Effects
3. Methods to Raise Awareness for Climate Change Resilience on Ports
4. The Lack of Climate Adaptation Policy Action.
5. Other miscellaneous Gaps

The last section called ”Other miscellaneous gaps” is meant to include knowledge gaps that are interesting but do not belong to one of the four main categories. These gaps are out of the scope of the research agenda for the section of Port & Waterways of TU Delft. Nevertheless, it was decided to include them in this separate section of the results for other researchers’ interests. The following sections will elaborate in more detail on each of the five categories.

The present chapter contains information that inspired the elaboration of the 3 research topics presented in chapter 6 which are the main outcome of this thesis.

5.1. Lack of Integrated Models and General Guidelines to perform Climate Change Impact Assessment on Ports and Supply Chains

From chapter 2,3 and 4, one could conclude that the potential climate change impacts on ports and supply chains are well known. During the 2 weeks of literature studies, it was

already noticeable the large amount of different approaches to asses climate change impacts. Most of them provided a high level approach but no quantification process. Nevertheless, only specific (TU Delft) MSc theses address impact assessment on ports. In practice, most of the ports in the world do not address climate change with risk based approaches. Normally, these approaches start with a thorough risk assessment and determine (or try to) all the possible threats that the infrastructure could be exposed to. Once these are known, depending on the risk "appetite" of the client the risk tolerance level is fixed and infrastructure is designed according to that. Nevertheless, most of the global port infrastructure is currently designed by fixing a (for instance) historic 100-year return period and then they define the risks after this choice [11]. During the expert interviews, several risk based approaches were mentioned which experts use in their daily practices. These methods are: (1) Economic optimization methods, (2) Three-point methods, (3) Bow-tie methods and (4) Risk matrices. Some of these methods rely on Dutch norms and very on-site specific situations such as the norm based on outer (and inner) dike areas. Regardless, the general approach can be adapted to be used in other projects. Nevertheless, none of these methods present a robust framework which comprises from the identification of climate change impacts to the translation of these impacts to asset's damage curves and economic loses.

The following points present specific gaps within the broader category of *"Lack of Integrated Models and General Guidelines to perform Climate Change Impact Assessment on Ports"*:

- **Impact Identification:** The Rotterdam Port Authority (probably extendable to most of port authorities globally) only considers the impact of sea level rise as potential threat in their risk assessments (see interview with Ir J. de Nooijer in appendix B). They believe that other climate change impacts such as increased fogginess, more frequent and wind speeds, extreme temperatures and extreme precipitation will not cause significant impacts compared to flooding by sea level rise. Sea level rise is expected to be a globalized impact, however current projections on extreme rise in sea water levels have a very small probability of occurrence. On the contrary, projections on other extreme weather events, even if expected to be very localized, have larger probabilities of occurrence. Moreover, these events are expected to occur simultaneously and more than once. As port authority, they believe that flooding due to sea level rise will have a bigger impact in the port's economy. Whether their statement is true still remains unknown due to the lack of integrated models able to simulate impacts of extreme weather events on port infrastructure, operations and services, and supply chains.

- **Risk-based approach:** Chapter 4 presents several risk-based approaches. Unfortunately, whether one would be better than others to assess port's exposure to climate change impacts has not been studied yet. It is also possible to produce a tool that is a combination of all or some of them. Another gap, goes back to the thresholds and the tolerance of risks. The tolerance for each port regarding the acceptance of certain risks is different. Not only the impacts of climate change will be different for each port but also the levels of tolerance to those changes might be difference. That is related to the nature of the port and the capital and finance of the port, the incoming and out goings. Hence, how would it be possible to define global general risk acceptance thresholds?

5.2. Identification & Quantification of Supply Chain Disruptions due to Climate Change Cascade Effects

A big gap is the knowledge on business recovery after extreme weather events. Dr. Elco Koks is looking at temporal aspects of flood impacts, how companies recover and how quickly they do it. His research is focused on finding ways to optimize the recovery time process of industries after a disaster or extreme event happens. Also, he aims to explore the possibility that further on the supply chain businesses have an inventory so they can continue going as usual in case of flood impacts on other part of the supply chain. There is a little bit of information within Germany about recovery after the earthquake and in Japan. It is important to

understand the way business can recover before one can understand and focus on ways to "softly" adapt. Elko's research can also be translated to port businesses and supply chains.

Another gap within this topic is the lack on understanding bottlenecks throughout supply chains and also, what type of businesses and infrastructure can have big impacts on ports when affected by extreme weather events. More specifically, the essential parts within the supply chain that if disrupted, could have massive impacts on ports. Ports require a lot of inputs such as electricity, cooling water and waste treatment. If these essentials are not met, ports will not be delivering cargo or other services. The question then becomes how ports will be affected by other network disruptions; and how that would translate to downtime or closure.

The outcome of the CIRcle workshop at the Port of Rotterdam suggested there was knowledge missing on climate change cascade effects on ports, such as power and data shortage. Missing communication is even more impactful than shortage of electricity. Everything in a port needs to be dealt at the right moment (ships, VTS, cargo, rail and road entrances). Ports are very sensitive to individual delays as they comprise several networks and very complicated supply chains with a lot of connections.

5.3. Methods to Raise Awareness for Climate Change Resilience on Ports

All interviewed experts believe that promoting awareness is very important as often they find that getting adaptation to climate change on the clients agenda is still hard. That is because most of the ports worldwide have a lot of risks (fire, chemical hazards, oil spills) to care about before they think about climate change. One of the most common answers of the port users (see interviews in appendix B) are that within the time they have in the port, they have better worries to fix instead of climate change projections for 2050. Also, once people start investing and protecting against climate change they do not really get anything in return. Basically, only once port users see that they are being threaten by climate change effects, they start acting and planning on it. Hence, there is a need to raise the sense of urgency to adapt to changing climatic conditions within the port industry. An example of raising awareness is risk communication. This practice has been explored within the port of Rotterdam (see [29] and interview with Ir. M. Bos & Msc J. van de Visch in appendix B). Nevertheless, as mentioned in the beginning of this chapter, Netherlands is way ahead as a country in terms of sustainability and adaptation planning and hence this projects are considered as pilot projects by their authors.

On another note, it would also be valuable to know where in the world ports are already being affected by climate change and to find a way to trigger them to act on it and be open for dialog. The knowledge gap is not about general available data on climate change effects, but it is about on-site specifications. There has been situations (according to experts) where port users do not believe the information on climate change impacts because of the extremely long timescale. Experts agree that the best way to raise awareness is when something bad happens (such as hurricanes, big floods...), of course that is not wanted either. Would it be an alternative to explore the possibilities of an online tool to test ports under extreme events to simulate the "*something bad happens*"?.

5.4. The lack of Climate Adaptation Policy Action

This section contains information from Ad Hoc Expert Meeting on Climate Change Impacts and Adaptation: A Challenge for Global Ports [44] in Geneve 2011 by United Nations Conference in Trade And Development (UNCTAD).

During the interviews, experts agreed that one of the gaps is the lack of action to bring the theoretic solutions into practice. However, this topic is considered to be out of the scope for

a hydraulic engineer student and also for the civil engineering section of Ports & Waterways of TU Delft. Hence, none of the proposed topics on chapter 6 will address the lack of climate adaptation policy action. Nevertheless, this section provides information for the interested readers.

Climate change adaptation seems less at the centre of public attention than climate change mitigation. Relevant international instruments haven been developed to support effective adaptation action The Nairobi Work Programme on impacts, vulnerability and adaptation to climate change (NWP) is one example. The NWP was adopted by the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC). Their aim is to assist countries, in particular developing countries, to the following: (1) improve their knowledge and assessment on impacts, vulnerability and adaptation; and (2) make informed decisions on practical adaptation actions and measures to respond to climate change considering also future possible climate variability.

Adaptation action is also important on the political agenda of many advanced economies. For instance, in 2010, the European Commission created a dedicated Directorate to focus on climate change to make adaptation to a priority of all EU-level policies. In 2009, the EU issued a White Paper on Climate Change Adaptation which - following completion of the consultation process - is expected to lead to a European strategy by 2013. At the country level, many EU countries are developing specific adaptation strategies to help when coping with the expected impacts of climate change.

Not only development on adaptation strategies is important but also implementation of any strategy is crucial. A few countries have already developed adaptation plans or are in the process of finalizing them [13]. However some forecasts assume significant additional resources will be needed for the purposes of implementation, especially in developing countries [10].

5.5. Other miscellaneous Gaps

The following gaps do not belong to any of the above categories. In spite of the classification's mismatch, these gaps are out of the scope of the research agenda for the section of Port & Waterways of TU Delft. Nevertheless, it was decided that they could be included in this separate section for other researchers' interests.

To experts' opinion, the biggest knowledge gap is the lack of accuracy on the climate change predictions. The latter are getting more precise but there is no way to know yet whether they are getting more accurate. Models seem very focused on variables that are easy to predict such as temperature, rainfall and sea level rise. Several coherent models exist that can predict the aforementioned three fields. However, what is really hard to model and has a very big impact on ports, airports and lots of other critical infrastructure is variables like wind, lightening and fog. Existing models for these variables are not great but only because is incredibly hard to model well their behaviour. Furthermore, no one knows yet how climate change is or will be affecting fog, lightening or wind. There seems to be very little knowledge about that. These variables appear in lower layers of the models, which already present results in big bounds of uncertainty. For instance, if the peak wind speed threshold for port operations is 70 km/h the uncertainty width bands go from 0 to 200 km/h.

The following expectation gap goes back to the determination of physical thresholds and risk tolerance which is different for each port. Not only the impacts of climate change are and will be different depending on the port's location, but also the levels of tolerance to those changes might differ. That is related to the nature of the port but also the capital and finance, the incoming and out goings.

Within the field of Inland Waterways, most of the literature focuses on the dry periods as the only potential climate change impact. One can also find a wide range of mitigation

solutions however, there are no (public) guidelines that explain how to act on low water levels and neither how to apply the many mitigation measures that are mentioned. The general feeling is that no one seems to be focusing on modeling solutions to see whether they are feasible or not. The state of the art climate change solutions (or measures) seem to be stuck in theory. There are several papers available that mention measures but conclude that due to certain argumentation they would not be feasible. One of the goals of PhD candidate Ir. Frederik Vinke's research is to find out the most optimal effective measures and model them to see how the system would respond.

6

Definition of Research Topics and Corresponding Approach

The previous chapter contains information on the research knowledge gaps that inspired the elaboration of the 3 research topics which are the main outcome of this thesis. This chapter on "Definition of Research Topics and Corresponding Approach" aims to answer sub-research question 5 and presents the main outcome of this thesis. Due to time constrains, only 3 research topics are presented in more detail with the corresponding suggested approach. These three topics have been prioritized among the rest based on expert's opinions on what climate change issues are the most urgent (for further details see 2.4.2 & 4.1-4.3 and Appendix B). The first topic was chosen due to the lack of integrated models that assess resilience in ports. The latter statement is one of the conclusions of the literature study, but also one of the topics that the interviewed experts seemed most interested into. Furthermore, the second topic aligns with the interest of the Ports & Waterways section at Delft University of Technology and according to Dr. Ir. Elco Koks and Ir. Joost de Nooijer, the Port of Rotterdam is also very interested in the topic. On another note, during the expert interviews there was a general feeling that raising awareness for climate change adaptation and resilient ports was very urgent. Hence, the proposal for the third topic.

The idea for the prioritized research topics is that TU Delft Master students continue on advancing research on the subject of climate change impacts on ports and supply chains during their graduation. The three selected research topics are the following:

- Developing an Integrated Stochastic Model to Test Climate Change Resilience on Ports
- Investigating Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade effects
- Developing a Method to Promote Awareness for Climate Change Resilient Ports

Each section presents a research topic and comprises a few common parts to define the topic in some detail: (1) Problem Definition, (2) Research Objectives, (3) Research Questions, (4) Proposed Method, (5) Outcome & Final Products and (6) Recommended Literature. It is worth mentioning that these proposals aim to be the very first description of the research topic. The main focus is on establishing the general idea of the research subject, so the students can elaborate further based on their own interests. The topics presented in this chapter can seem to be very detailed at first sight because is part of the scope of my thesis. However, once they are advertised it should be stressed that they are only suggestions for the student, and he or she should decide based on their interests how to further elaborate on the chosen topic.

Nevertheless, the chapter ends with a list of other potential research topics that can also be of interest to researchers. One of them is formulated more in detail than the others as requested by several consultants at Royal Haskoning DHV for their current practice.

6.1. Developing an Integrated Stochastic Model to Test Climate Change Resilience on Ports

6.1.1. Problem definition

Port stakeholders acknowledge the lack of integrated models to quantify things like the resilience of a port. For the sake of simplicity in this thesis, resilience accounts for the capacity of an asset to recover from a destructive event. More specifically, an asset is resilient if its recovery time (and recovery costs) are low (or the lowest possible). The lack of integrated models is probably due to the lack of knowledge on the consequences of climate change on each part of the port system, and the big bounds of uncertainty of these. It seems that the port system (which is part of global supply chains) is so complex that the relationships between elements are very difficult to model. If the system is not well understood, neither the impacts of climate change on it.

On another note, the Rotterdam Port Authority (probably extendable to most of port authorities globally) only considers the impact of sea level rise on their assessments. They believe that other climate change impacts such as increased fogginess, lightening, extreme wind speeds, extreme temperatures and extreme precipitation will not cause significant impacts compared the ones caused by sea level rise because of their localized nature. One could say that if the frequency of ”localized” events increase, the economic risk will also increase. Sea level rise is expected to be a globalized impact but with very small probability of occurrence. On the contrary, projections on other extreme weather events, even if expected to be very localized, have larger probabilities of occurrence. Hence, when dealing with climate change impacts is handier to make use of probabilities to capture uncertainty. That is why many fields within civil engineering are already studying how to introduce stochastic boundary conditions in their models to account for future uncertainty.

On another note, these climate change impacts might occur at the same time, making ports deal with compound events instead of one single event. In general, compound events are not considered yet in practice, but it is known from literature that can lead to totally different system vulnerabilities. Due to the size and complexity of the supply chain system (where ports are considered main nodes), physically based models would not be computationally efficient to simulate the all the existent relationships in an integrated way. Within the last decades, stochastic models using copulas have shown to be highly flexible to represent the multivariate dependence structure and to generate a large number statistically consistent ”flood drivers” variables.

All the arguments in the previous paragraphs elaborate on why probabilistic tools are chosen to model the system and its resilience. In short, probabilistic models are known for capturing well dependencies between systems but also within elements of this systems. In this case, the system is complex and difficult to model with physical relations. Moreover, the impacts considered encompass big bounds of uncertainty which would be more difficult to include in deterministic models. This aforementioned method will be further explained in section 6.1.4.

6.1.2. Research Objectives

The main objective of this suggested thesis is to investigate the performance of integrated stochastic models to test resilience on ports.

In order to fulfill the main objective, the following sub-research objectives have been suggested:

1. To determine the state of the art stochastic models to simulate climate change impacts on ports.
2. To determine the state of the art stochastic models to quantify climate change resilience on ports.
3. To investigate the performance of stochastic models (Copulas-vines & Bayesian Networks) in capturing how (climate change) extreme weather events affect port and supply chain's relationships and interdependencies.
4. To determine a method to asses the recovery times (and recovery costs) of the affected port assets to be able to quantify their resilience to climate change.

6.1.3. Research Questions

The main objective of this thesis is captured in the following main research question:

- How can resilience of ports be analyzed using probabilistic models?

To help accomplish the main and the sub-research objectives a few sub-research questions have been posed to help steer the research in the right direction:

1. What are the state of the art stochastic models to simulate climate change impacts on ports and supply chains? Do these models consider single or compound extreme weather events?
2. What are the state of the art stochastic models to quantify climate change resilience on ports?
3. How do stochastic models (such as vines-copulas) perform when modelling dependencies between climate change impacts and the port asset's recovery time after these impacts? Would Vines perform better than Bayesian Networks?
4. Would these stochastic models serve to determine physical thresholds to which port operations become hindered, or stopped for a period of time?
5. What are the knowledge gaps of the stochastic models and their application after answering research question 3 and 4?

A follow up question of these research topic could be "to explore how to train the stochastic model to optimize recovery time and recovery costs".

6.1.4. Proposed Method

This thesis will explore the possibility of modelling the multivariate dependence structure of ports using Bayesian Networks and/or Vine structures. While Bayesian Networks use the Gaussian copula to model the multivariate dependence structure, Vine structures allow for any type of copula family which is thought to be more realistic when dealing with extreme weather events. That is why research question 3 contains a sub-question on the aforementioned. These probabilistic tools not only help describing dependency but also stochastic variables as input and hence will be the main focus of this research. Some example of the potential of these tools to assess resilience is the following figure from *Seyedmohsen Hosseini, Kash Barker 2016*[41] which assesses the latter in an Inland port.

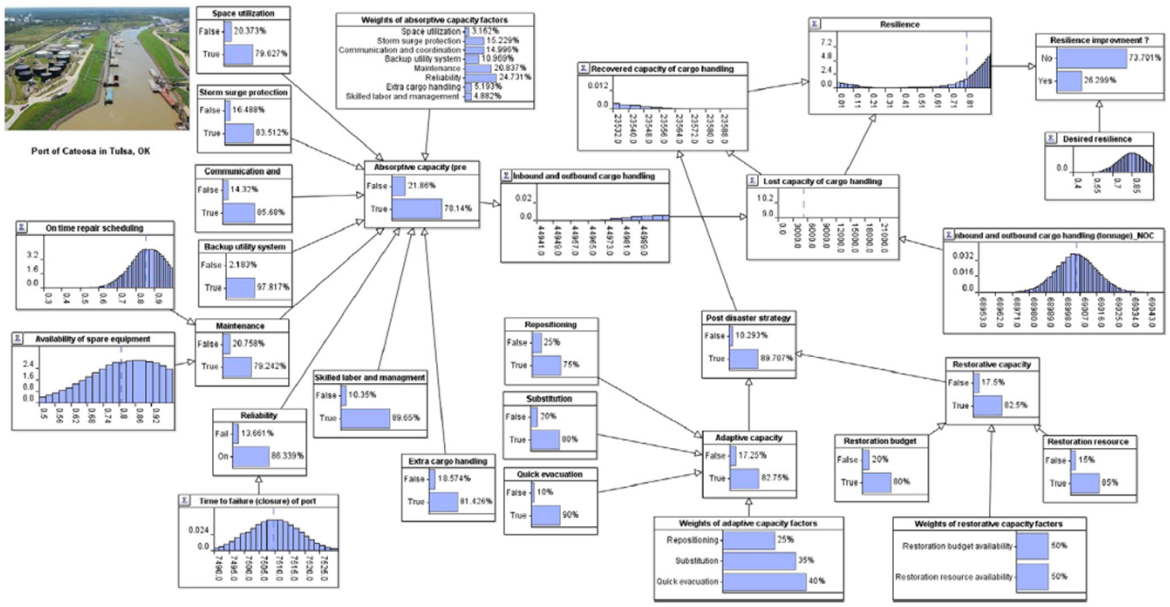


Figure 6.1: Example for the Integrated Stochastic model with a Bayesian Network network for measuring resilience. Source: *Seyedmohsen Hosseini, Kash Barker 2016*[41].

The thesis will start with a thorough literature review on existing integrated models to simulate (multi)extreme weather events on complex physical systems. A strong recommendation is to investigate the possibility to adapt the “Smart service logistics” project from Georgios Leontaris PhD to the port-supply chain system. The project concerns the development of stochastic models in order to include and quantify uncertainties, such that the optimization of the entire ”Offshore Wind Farm installation process” is possible. Instead of Offshore wind farm installation, one could read ”Port Operational System Workability”. It was found that the proposed methodology [23] can help professionals and/or researchers in investigating cost-effective alternatives concerning vulnerable assets. A more detailed explanation of the methodology is out of the scope of this thesis, but with a bit more of research and effort the following suggestion has been made.

Suggestion on Data-base

There is a big possibility that port operational (daily, hourly) data is not available. Hence, expert judgment techniques (via expert workshops) would be used to build the data set. For more information, it is referred to *”TU Delft expert judgment data base, Roger M. Cooke, Louis L.H.J. Goossen”* [39].

Suggestion on Data Analysis & Modelling Techniques

As mentioned on ”Problem definition”, due to the size and complexity of the system that comprise ports, supply chains and other dependent networks; physically based models are not the fastest and most efficient option to simulate impacts on the system. As an alternative, probabilistic, stochastic models offer easier and more efficient opportunities to model dependencies between the individual elements of the system. The idea would be to also present supply chain dependencies, but keeping main focus on the port system. Some suggestions are using (vines-)copulas, Bayesian Networks (Uninet Software) that properly combine data ensuring the dependence between elements. The model can be built using Matlab or Phyton and R. The model should be tested and hopefully validated for a case study to be determined depending on the interests of the student.

6.1.5. Outcome & Final Products

The main product will be an integral, generic, probabilistic tool able to model the most relevant aspects of the port-supply chain system, including other chains such as transport

network. The model should be able to spot vulnerabilities within port activities that can affect services and lead to downtime. This tool aims to reduce risk and subsequently costs to make ports more competitive. For some inspiration, see the two figures below 6.8 & 6.7.

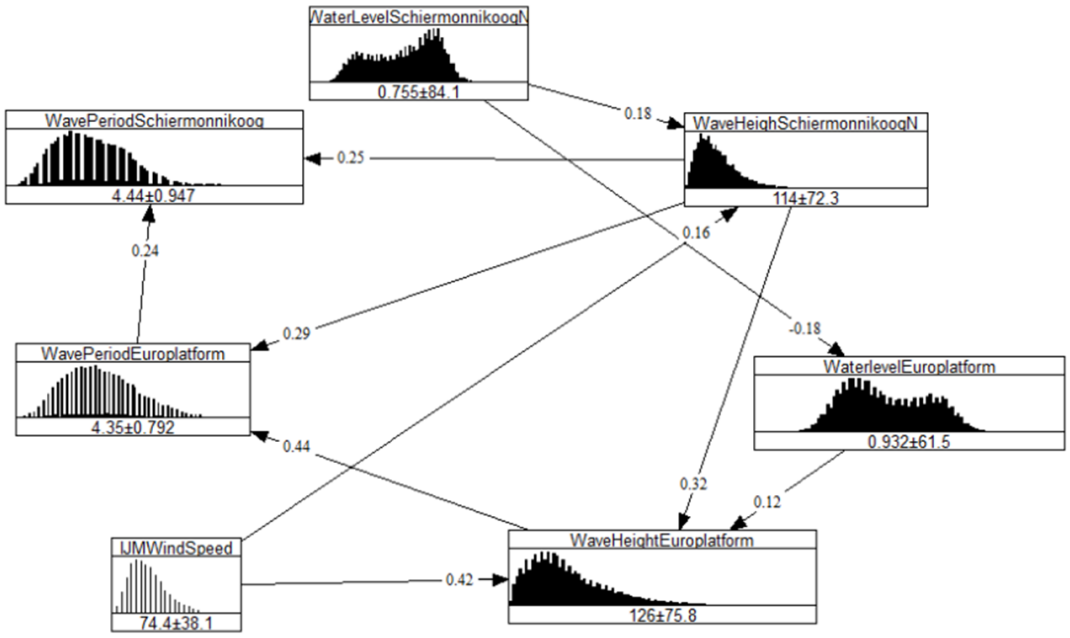


Figure 6.2: Example for the Integrated Stochastic model with a Bayesian Network. The model is based on data-analysis on interdependencies between elements of the system. It delivers the possibility to model the behaviour of elements by dependencies and not physical processes. Source: Author, project for Probabilistic Design in Hydraulic Engineering, TU Delft.

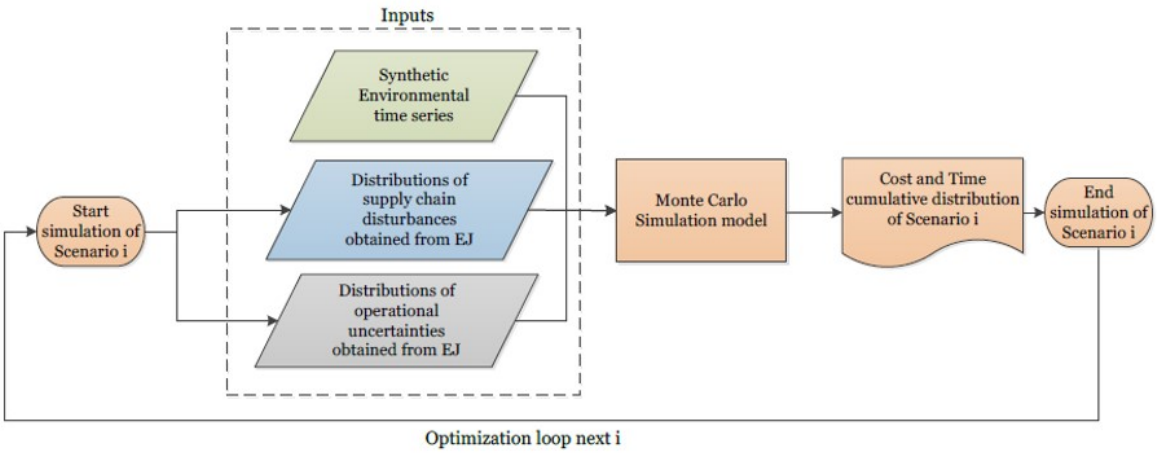


Figure 6.3: Example for the Integrated Stochastic model with an optimized loop process. General framework for the integrated model that already includes optimization. Source: G. Leontaris [23]

6.1.6. Recommended Literature

1. Probabilistic scheduling of offshore operations using copula based environmental time series - An application for cable installation management for offshore wind farms- [23]

Georgios Leontaris, Oswaldo Morales-Nápoles, A.R.M (Rogier) Wolfert

Keywords: Copulas, Environmental time series, Stochastic model applications, Offshore wind farms, Simulation, Project management

2. Planning cable installation activities for offshore wind farms including risk of supply delays [22]

G. Leontaris, O. Morales-Nápoles, A.R.M. Wolfert

3. Inspiration for the model: Compound flood potential in Europe [20]

Dominik Paprotny , Michalis Vousdoukas , Oswaldo Morales-Nápoles, Bas Jonkman, and Luc Feyen

4. Inspiration for the model: Compound flood potential in Europe [20]

Dominik Paprotny , Michalis Vousdoukas , Oswaldo Morales-Nápoles, Bas Jonkman, and Luc Feyen

6.2. Investigating Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade Effects

6.2.1. Problem definition

Supply chains have become longer and more complex but at the same time, the severity and frequency of supply chain disruptions seems to be increasing [5]. Natural disasters and extreme weather conditions are not the only threats to supply chains. Also oil dependence and information fragmentation suppose serious risks. Research from World Economic Forum from 5 years ago already stated that 80 percent of companies worldwide see better protection of supply chains as a priority. Nevertheless, potential impacts on supply chains are among the least recognized of climate change risks. The latter is due to supply chains consisting of many assets and linkages that require a broader and wider risk management approach [21].

Ports play major roles in the global supply chain. So everywhere that has a link to a disruption, the effects will go down or up to ports. Worldwide seaports believe the main climate change impact is sea level rise. However is also important to look at the climate change impacts upstream and downstream the supply chain which can derive in cascade effects. Cascade effects are defined in this thesis to be chain effects. Due to the complexity of the system, the solutions to combat these cascade effects lies in focusing on the resilience of the network as a whole. All the aforementioned arguments support the urgency of the proposed research on supply chain disruption quantification. Some research has been done already, but there is a general feeling that very few concepts has been applied within practice. Some suggested reading is Dr. M. Altamirano dissertation [6].

6.2.2. Research Objectives

The main objective of this suggested thesis is to investigate methods to identify and quantify supply chain disruptions caused by climate change cascade effects.

In order to fulfill the main objective, the following sub-research objectives have been suggested:

- To understand the supply chain system and to determine what is the knowledge needed to identify inter-dependencies between elements and the potential bottle necks.
- To present an overview of the state of the art strategies or tools to identify and quantify supply chain disruptions.
- To identify research knowledge gaps related to the above strategies and tools and their application.

6.2.3. Research Questions

The main objective of this thesis is captured in the following main research question:

- What are the current possibilities to identify and quantify supply chain disruptions due to climate change cascade effects?

To help accomplish the main and the sub-research objectives a few sub-research questions have been posed to help steer the research in the right direction:

1. What are the state of the art strategies or tools to identify climate change cascade effects on port businesses and supply chains?
2. What are the current possibilities for quantifying supply chain disruptions due to climate change cascade effects? Are these being used or investigated?
3. What is the knowledge needed to identify interdependencies and bottle necks within the supply chain and port system?
4. Which knowledge gaps have been identified while answering sub-research questions 1,2 and 3?
5. How can one address the gaps identified in sub-research question 4?

6.2.4. Proposed Method

The research should start with a thorough literature study (see literature recommendations below). The student should focus on determining what are the state of the art methods to identify and quantify supply chain disruptions. The next step would be to continue the literature study to investigate sub-research question 3. However, it is also advised to conduct expert interviews to help answer sub-research questions 1,2 and 3 (for inspiration see figure 6.4). Finally, the methods found should be analyzed and tested in a case study of the student's interest.

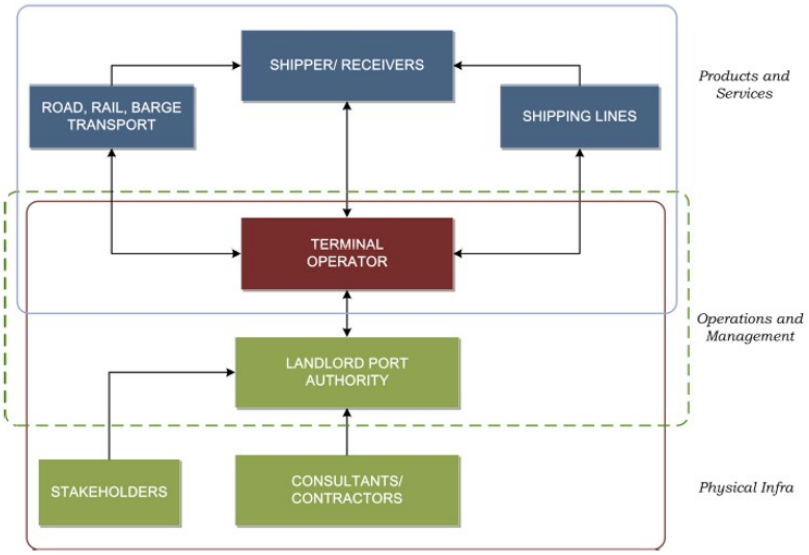


Figure 6.4: Diagram showing the actors that play a role in the port-supply chain system. The diagram distinguishes 3 layers based on functionality, with the lower layers providing the conditions necessary for the existence and proper functioning of the higher layers. Each layer comprises physical, technical, operational, and institutional components, as well as actors and their interactions which can be seen in this figure together with the overlapping boundaries for each pair of layers. Source: Dr. P. Taneja [42] - The Flexible Port

During the expert interviews conducted in this thesis (”Climate Change Impact Assessment on Ports”), the CIrcle tool was mentioned as the state of the art software to identify climate change cascade effects on critical infrastructure. For this study, is suggested to explore the CIrcle software as a potential tool to help achieve the main research objective. The CIrcle tool will be investigated to see whether this model is suitable for the assessment and quantification of supply chain disruptions. It is recommended to contact Ir. Micheline Hounjet (RHDHV) for insight and help on the Circle Tool. See also ”CIrcle – Critical Infrastructures: Relations and Consequences for Life and Environment”, *https://www.deltares.nl/en/software/circle-critical- infrastructures-relations-and-consequences-for-life-and-environment-2/*.

The CIRcle tool is a workshop where to gather experts able to give relevant information on the topic of interest. One firstly formulates the questions for the issue in question and selects the experts that can contribute the most (see suggestions on figure 6.4). The idea is to collect information and data by talking to the experts during the workshop. Then, to create the new CIrcle tool; including all the networks that are relevant. Afterwards, cascade effects, indirect effects that connect networks are identified and plotted. The following questions have been posed to help investigate the potential of CIRcle for the research:

1. What is the potential use of the CIrcle tool to identify cascade effects on supply chains and ports as main nodes of these?

2. What is the potential use of the CIrcle tool to identify interdependencies and bottle necks within the supply chain and port system?

Finally, it is also suggested that the student conducts a few expert interviews to identify the needs of port stakeholders that are part of the chosen case study.

6.2.5. Outcome & Final Products

The main outcome of this research would be an overview of the state of the art strategies to identify and quantify Supply Chain Disruptions caused by climate change cascade effects. Furthermore, this research would also present the results of the identified knowledge gaps within the aforementioned topic, so other subjects can be defined for further research.

On another note, it is suggested to present the results of a CIRcle session able to identify and quantify Supply Chain Disruptions due to climate change cascade effects. And if there is enough time, present some guidelines on how to build such session. Everything above would be tested on a case study of interest for the student and supervisors. The following figures present examples on the CIrcle tool.

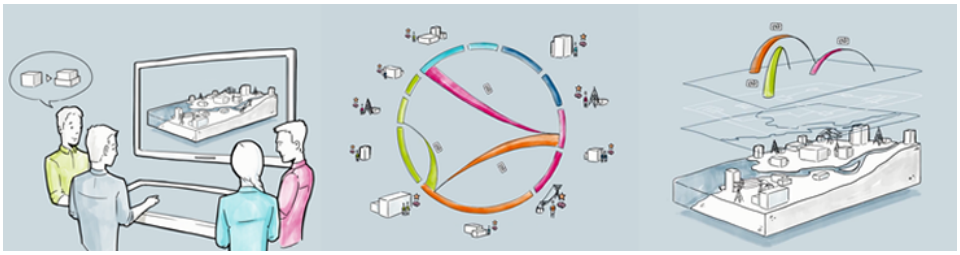


Figure 6.5: Diagram showing the three steps to build a successful CIrcle session. Source: Deltares, https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/

Figure 6.6: Example of a possible outcome for the CIrcle tool. Source: Deltares, https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/

Figure 6.7: Picture taken during a CIrcle workshop with experts. Source: Deltares, https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/

6.2.6. Recommended Literature

It is recommended to contact Ir. Micheline Hounjet for insight and help on the Circle Tool. See also "CIrcle – Critical Infrastructures: Relations and Consequences for Life and Environment", https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/.

It is also advisable to contact Dr. Elco Koks expert in modelling of the economy-wide consequences of disasters and supply chain disruption quantification.

It is also

1. Modeling Disruption Risk in Supply Chain Risk Management [38]

Ragip Ufuk Bilsel, The Boston Consulting Group, Turkey A. Ravi Ravindran, Penn State University, USA

Keywords: Generalized Extreme Value Distribution, Risk Detection, Risk Quantification, Risk Recovery, Supply Chain Disruption.

2. Quantifying the Supply Chain Resilience [8]

A.P. Barroso, V.H. Machado, H. Carvalho and V. Cruz Machado

3. Building Resilience in Global Supply Chains [45]

For more information it is referred to: *http://wbcsdpublications.org/wp-content/uploads/2015/12/building-resilience-in-global-supply-chains.pdf*

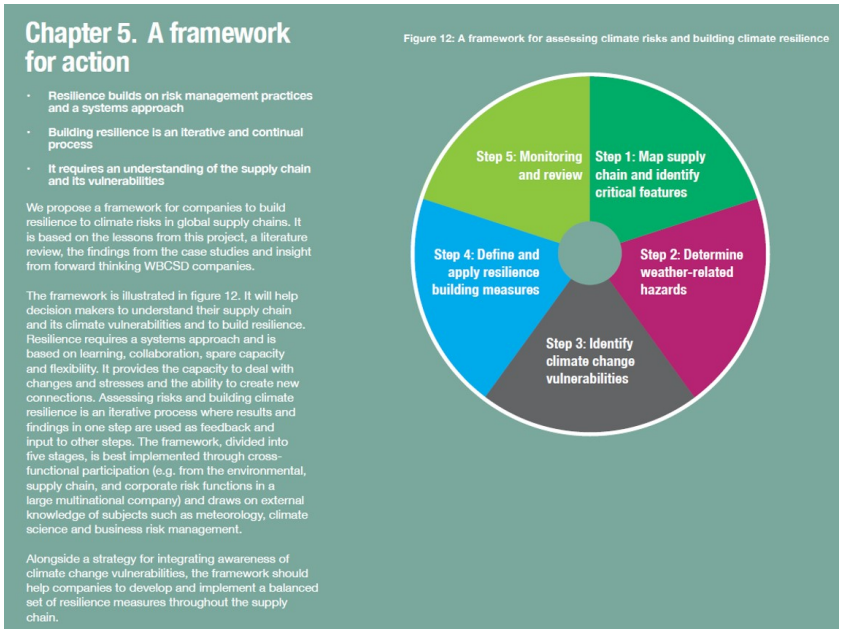


Figure 6.8: Example for general framework to assess supply chain disruptions and resilience. Source: http://wbcsdpublications.org/wp-content/uploads/2015/12/building-resilience-in-global-supply-chains.pdf

6.3. Developing a Method to Promote Awareness for Climate Change Resilient Ports

6.3.1. Problem definition

Experts among the port industry believe that creating awareness on the subject of climate change impacts on ports is of vital importance. Finding a way to get climate change adaptation on the port clients' agenda is still hard. Normally, they have a lot of risks (fire, chemical hazards, oil spills) to care about before they can address climate change and make their assets resilient. One of the most common answers of port users to consultants is that within the time they have in the port, they have better worries to fix instead of climate projections for 2050. However, the impacts of climate change are already being felt in many regions and in order to be prepared for what is coming one needs to think in advance on ways to adapt and be resilient. The problem is that people believe that once they start investing and protecting against climate change they do not really get any money in return. Hence, only once port users see that they are being threaten by climate change effects, they start acting on it. Hence, there is a need to raise the sense of urgency to adapt to changing climatic conditions within the port industry. An example of raising awareness is risk communication. This practice has been explored within the port of Rotterdam (see interview with Ir. M. Bos & Msc J. van de Visch in appendix B). Nevertheless, Netherlands is way ahead as a country in terms of sustainability and adaptation planning and hence this projects are considered as pilot projects by their authors.

Conclusively, the best way to promote awareness is to make the impacts visible to people. But not everyone participating in the port industry understands the engineering and risk language that is normally used on reports. The question becomes: what can we to make climate change impacts more visible and to promote awareness? How can we raise the sense of urgency for port authorities and port clients to start planning and budgeting for the coming impacts? These questions aim to be answered in this proposed research.

6.3.2. Research Objectives

The main objective of this suggested thesis is to explore approaches to raise awareness on the subject of climate change impacts on ports and methods to guide stakeholders on the climate change adaptation process set-up.

In order to fulfill the main objective, the following sub-research objectives have been suggested:

1. To investigate current scientific (or engineering) strategies to raise awareness on natural disasters (climate change, earthquakes, tsunamis...).
2. To explore how to best guide port stakeholders to adapt to climate change.
3. To develop a method (visualization tool, serious game) to help port stakeholders to experiment by themselves how resilient their assets are and raise their sense of urgency to adapt to the possible changes in climatic conditions.
4. To identify knowledge gaps of the methods (found when answering sub-research question 1) and their application that hold back stakeholders from adapting to climate change.

6.3.3. Research Questions

The main objective of this thesis is captured in the following main research question:

- How can one raise awareness on the subject of climate change impacts on ports and guide stakeholders on the climate change adaptation process set-up?

To help accomplish the main and the sub-research objectives a few sub-research questions have been posed to help steer the research in the right direction:

1. What are the state of the art scientific (or engineering) strategies to raise awareness on the subject of natural disasters such as climate change, floods, earthquakes or tsunamis?
2. What would it take for port authorities and port clients worldwide to start adapting for climate change?
3. How can one best guide port stakeholders in the process of adapting to climate change?
4. Which knowledge gaps have been identified while answering sub-research questions 1 to 4?
5. How can one address the gaps identified in sub-research question 5?

6.3.4. Proposed Method

The Port of Rotterdam was interested not only in developing a climate change adaptation strategy but also raising awareness on the subject of climate change adaptation among the companies at the Port, but more specifically at the Botlek area [34]. At the Port of Rotterdam, the companies settled at the Botlek area are the main (oil and other substances and fuels) suppliers for the entire region of Holland. The proposal from RHDHV consultants to the port authority was to join all the experts together to ask them about flooding consequences in their facilities and further come up with an adaptation strategy that was beneficial to all. This approach was very successful and became a pilot project [34]. Nevertheless, this method relies on Dutch norms to set the risk tolerances and damage curves. The question then becomes whether it would be also feasible for other countries and could be studied during this thesis.

During the expert interviews conducted in this thesis ("Climate Change Impact Assessment on Ports"), the STAIN tool was mentioned as the state of the art software to visualize and quantify how different climate adaptation measures contribute to build resilience in a city. For this study, is suggested to explore the STAIN potential to help visualize and understand the impacts of climate change on ports and test the resilience of the port system. One should try to answer the following questions:

- What are the possibilities and limitations of the current STAIN version to help achieve the sub-research objective 3?
- What are the following steps towards the development of an online STAIN session to test resilience on ports to help achieve the sub-research objective 3?

Due to the state of development of STAIN software there is no literature made available publicly yet. Hence, the student should conduct interviews to the STAIN developers to gain knowledge on the tool. The idea is to build a model or a STAIN session that fulfills sub-research objective 3. It might be the case that the tool can be optimized with secondary simpler models in Matlab or Phyton. Or for instance, the use of other techniques for the post processing of the results.

6.3.5. Outcome & Final Products

One of the results of the research would be an overview and gap analysis on the state of the art scientific (or engineering) strategies or methods to raise awareness on natural disasters such as climate change, floods, earthquakes or tsunamis. Moreover, if is decided to study the STAIN tool, the results would be general guidelines on the development of the STAIN sessions so it can be used on future port projects.

6.3.6. About STAIN

For further information of stain it is advised to contact *MSc Micheline Hounjet*.

STAIN aims to visualize and quantify how different climate adaptation measures contribute to the total climate resilience of a city, see figure 6.9. STAIN helps to design the climate resilience strategy of your city as it encourages you to combine robust, flexible and integral measures. These different types of measures can reinforce each other's effects. By playing STAIN you have access to measures of other cities' resilience strategies to help you design your own strategy.

STAINSingapore (figure 6.10) was used in a workshop where climate adaptation experts shared the latest innovative climate adaptation measures and their applicability to different city neighborhoods. The workshop resulted in several strategy optimizations of which STAINscores were obtained and compared.

Figure 6.9: Example of STAIN offline session for the city of ZWOLLE. Source: MSc Micheline Hounjet

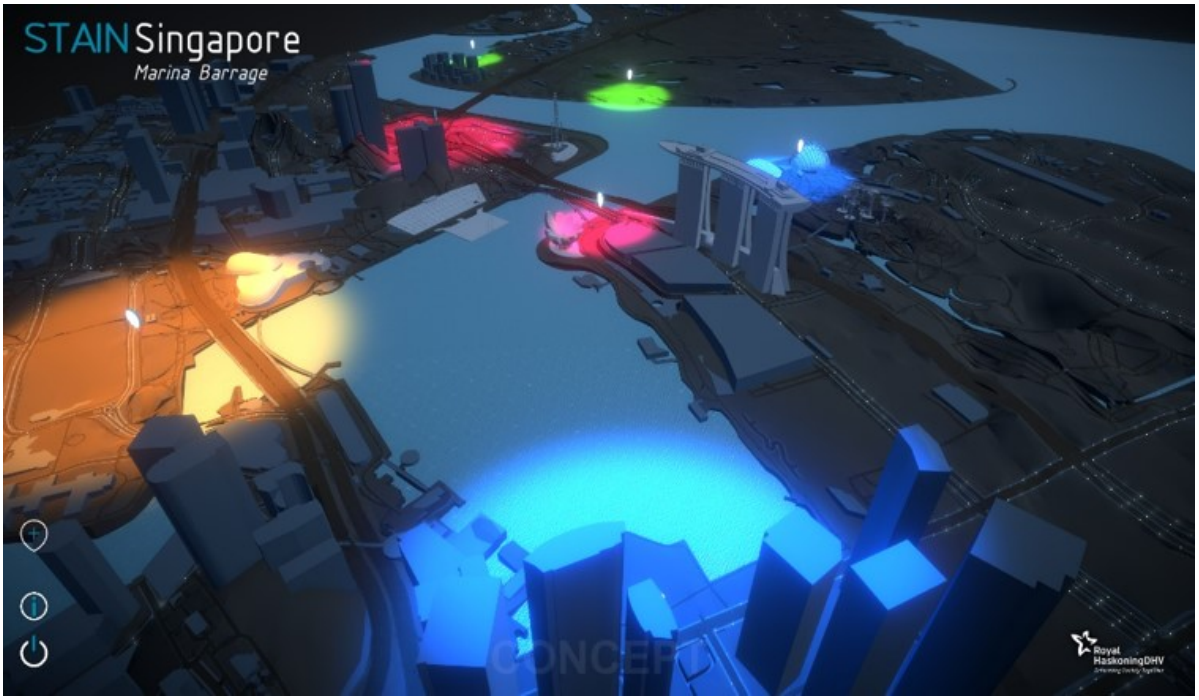


Figure 6.10: Example of STAIN Singapore session for climate resilience startegies. Source: MSc Micheline Hounjet

6.4. Other Interesting Research Topics

This section comprises information on other topics that have been identified during the gag analysis in this thesis. The following subsection provides some insight on the first gap category *"Lack of Integrated models and general guidelines for climate change impact assessment on ports"*.

6.4.1. Development of General Guidelines to perform Climate Change Impact Assessment Worldwide

Problem definition

From chapter 2,3 and 4, one could conclude that the potential climate change impacts on ports and supply chains are well known. Furthermore, general recipes and detailed conceptual frameworks for climate change impact assessment are present within literature. Nevertheless, only specific (TU Delft) MSc theses address impact assessments related to the field of ports. In practice, most of the ports in the world do not address climate change with risk based approaches but design infrastructure with fixed return periods of events. During the expert interviews, several risk based approaches were mentioned which they use in their daily practices. These methods are: (1) Economic optimization methods, (2) Three-point methods, (3) Bow-tie methods and (4) Risk matrices. Nevertheless, none of these methods present a robust framework which comprises from the identification of climate change impacts to the translation of these impacts to damage curves and economic loses.

Research Objective & Methodology

The main objective of this suggested thesis is to advance research on developing a general framework to assess climate change impacts and to determine the consequent economic loses. In order to achieve the aforementioned, it is advised to firstly conduct a literature study and to consult the results of the this thesis *"Climate Change Impact Assessment on Ports"*. The following step would be to choose one (or a combination) of the gathered existent methodologies, and to perform several impact assessments with existing data. In the case the student conducts this thesis with Royal Haskoning DHV, port data will be provided to perform and validate the methodology on a few case studies.

6.4.2. Other Research Topics

This subsections comprises the end of chapter 6 and presents a list of several interesting topics to advance research on climate change impact assessment on ports and supply chains.

- Explore the most optimal measures to combat extreme water levels on Dutch Inland Waterways due to climate change induced droughts; and model them to see how the entire system would respond. *This is one of the goals of PhD candidate Ir. Frederik Vinke's research, it is suggested to contact him if interested.*
- Improve accuracy and precision of models for wind, fog and lightening to be able to assess the impacts of climate change on these variables for future weather events on ports.
- Investigate on how to include climate change impacts on current shipping routes when performing cargo forecasting during port economic stage of development. How would the Origin/Destiny cargo volume matrices look like if climate change impacts on the navigational routes were considered?
- Study what would happen to the Netherlands if sea level rise scenarios of 2,3,5 and 10 meters happen.
- Investigate whether the Netherlands should prepare and adapt for cyclone events in the near future due to climate change.
- Explore where in the world ports are currently being affected by climate change impacts.
- Investigate the possibility to come up with global definitions of climate change risk acceptance and tolerance thresholds.

- Developing financing scenarios for climate change adaptation strategies, specially for the companies settled on seaports.
- A question on responsibility: Who does and pays what in the Landlord Port setting?

7

Conclusions & Recommendations

Conclusions on the main objective, "*to advance research on climate change impact assessment on ports and supply chains*", are presented in this chapter. The conclusions are presented in the following sections which aim to answer the sub-research questions 1-5 (See list below). Furthermore, conclusions on the methodology and further recommendations are also presented at the end of this chapter.

1. What is known about the main impacts of climate change on ports and supply chains?
2. Which assets are vulnerable to the main impacts determined in sub-research question 1?
3. What are the state of the art strategies to perform climate change impact assessment?
   What are the available resources (frameworks, methods, software)?
4. What are the knowledge gaps identified while answering sub-research questions 1,2 and 3?
5. How can one address the gaps identified in sub-research question 4?

7.1. On Climate Change Direct Impacts on Ports

Climate change will probably have big direct effects on ports due to their geographic location being close to river, sea or ocean water. Some of the direct effects of climate change are already being felt within the port industry, such as flooding, extreme and more frequent wind events, heavy rainfall and inland droughts. From the interviews, Sea Level Rise (or SLR) is seen as the easiest impact to understand and to mitigate. However, is currently considered a long-term threat that could cause flooding of port infrastructure and hence, hinder port operations. Experts acknowledge that another big threat of climate change is the increase in storminess seawards (larger waves and wind speeds and extreme storm surges) and landwards (increase in rainfall intensity). The storms could lead to big floods, which could completely hinder terminal operations. Some examples of flood impacts are flooded cranes and other equipment and flooded warehouses. On another note, experts generally agree that large wind speeds can threaten terminal structures that have not been reinforced and wind can blow away containers due to outdated stacking techniques for containers. Nevertheless, the majority of the interviewed experts are mostly concerned about bulk terminals because often the cargo is stored in the open. Due to the increase in storminess the cargo will be exposed to more rain and this will lead to an urgent need to store the cargo somewhere else.

In short, sea level rise is seen as the main and more understandable climate change impact on ports. From port expert's experience, the potential impacts of sea level rise are relatively

well understood on the contrary to other impacts such as extreme winds, lightening, fog and extreme storms.

7.2. On Climate Change Indirect Impacts on Ports

The major climate change indirect impact on ports considered in this thesis is the supply chain disruptions, which affect operations and critical (and basic) networks of the port, such as power, data, drinking and sewage water and transports.

Ports play major roles in the global supply chain and everywhere (in the chain) that there is a disruption, the effects of it will go down or up to ports. For example, droughts provoke reduction in goods like crops and cause direct impacts on trade flows, which might affect the companies of the port and affect their business. Routing and delay of ships will become an issue due to the more frequent hurricanes. Even if the big storms are not directly passing through the port, the impacts will be felt and if ports are not prepared, downtime will increase. All the aforementioned arguments, exemplify how supply chain disruptions can indirectly affect ports and make them vulnerable to climate change.

On another note, climate change might also trigger changes in trading navigational routes, for instance the imminent opening on the Artic Northwest passage, which can change the ports global competition. For seaports, the connection to the hinterland is very important, if that is not available there is no cargo deliver. In that way seaports need to be up to date with climate change impacts on roads, railway and inland waterways. If Inland water transport prices become too high, or there is not enough capacity, a modal shift might take place which is definitely not wanted socially and environmentally. Finally, experts agree that another big indirect impact is that ports might face changes in insurance coverage and possible higher insurance premiums because of climate change.

7.3. On the Most Vulnerable Port Elements

Interviewed experts agree on some port elements being typically more vulnerable to climate change impacts than others; such as quay walls, breakwaters, water drainage services and connecting infrastructure. If the latter is not operative, cargo cannot go in or out the port. On the contrary, cranes and mobile plants, if not build as hard standing, can become inoperative. However, they do not represent a risk because their operational period or life time is much lower than other infrastructure such as quays or breakwaters.

The port vulnerabilities are not only within its operations or critical infrastructure, but most importantly are on what the port is dependent on to be fully operative. These vulnerabilities are important to detect and also is important to identify where the critical risks are for a good port business management. From expert's experience, the most critical elements and networks identified for a regular port are: (1) power and the power station, also its transport (cables underground or upper ground); (2) data, which is as important as power nowadays. Information needs to keep flowing in and out of the port. If their servers and bases within the state are not resilience, the port has a problem even if the port itself is completely resilient; (3) clean water and sewage and (4) interconnections; roads, railway and inland waterways. If these are not resilient and cargo cannot come in or out of the port, the port suffers from delays or even closure. Finally, (5) health and safety implications with operational limits in offices, computer systems, telecoms and interconnecting services are also potentially vulnerable.

Experience from the CIrcle workshop at the port of Rotterdam tells that the biggest impact is the wind. Heavy winds break down communication tools which steer and monitor a lot of issues and activities within the port. On another note, expert Ir. Tiedo Vellinga who worked for many years as part of the Rotterdam Port authority, agrees that power shortage is one of the biggest threats to the port, but also the flooding of tunnels and consequent blocking of access and escape routes is also extremely harmful to the port clients. In short, the general feeling among experts is that the most vulnerable elements on the port are its operations and main activities but most importantly, the networks (or elements) the port is dependent on.

7.4. On Climate Change Impact Assessment

One could conclude that the potential climate change impacts on ports and supply chains are well known. The level of awareness on direct climate change impacts is higher than indirect impacts on ports. On another note, general recipes and detailed conceptual frameworks for climate change impact assessment are present within literature. Nevertheless, only specific (TU Delft) MSc theses address impact assessments related to the field of ports. In practice, most of the ports in the world do not address climate change with risk based approaches. Normally, these approaches start with a thorough risk assessment and determine (or try to) all the possible threats that the infrastructure could be exposed to. Once these are known, depending on the risk "appetite" of the client the risk tolerance level is fixed and infrastructure is designed according to that. Nevertheless, most of the global port infrastructure is currently designed by fixing a (for instance) historic 100-year return period and then they define the risks after this choice [11]. During the expert interviews, several risk based approaches were mentioned which they use in their daily practices. These methods are: (1) Economic optimization methods, (2) Three-point methods, (3) Bow-tie methods and (4) Risk matrices. Apart from these risk based methods, two state of the art software were identified as potential tools to asses climate change impacts: (1) CIrcle tool, to assess cascade effects on critical infrastructure and (2) STAIN, to test climate change adaptation measures mostly on cities, but adaptable to ports. Nevertheless, none of these methods present a robust framework which comprises from the identification of climate change impacts to the translation of these impacts to damage curves and economic loses.

7.5. On Identified Knowledge Gaps

The identification of the research knowledge gaps has not been an easy task. Regardless, the information gathered during the interviews helped to understand what are the interests among the port industry. One of the approaches to identify gaps was to ask experts what gaps they identify on their daily practice. Another way was by interrelating and analyzing the information from the different experts and identifying where knowledge was lacking. Then, proposing the identified gaps to the experts again and see their opinion on them. The four main gap categories that have been identified are the following:

1. **Lack of Integrated Models and General Guidelines to perform climate change impact assessment on ports.** Port stakeholders acknowledge the lack of integrated models to quantify things like the resilience of a port. The lack of integrated models is probably due to the lack of knowledge on the consequences of climate change on each part of the port system, and the big bounds of uncertainty of these. It seems that the port system (which is part of global supply chains) is so complex that the relationships between elements are very difficult to model. If the system is not well understood, neither the impacts of climate change on it.

   Furthermore, sea level rise is expected to be a globalized impact but with very small probability of occurrence. On the contrary, projections on other extreme weather events, even if expected to be very localized, have larger probabilities of occurrence. Hence, when dealing with climate change impacts is handier to make use of probabilities to capture uncertainty. That is why many fields within civil engineering are already studying how to introduce stochastic boundary conditions in their models to account for future uncertainty.

   On another note, these climate change impacts might occur at the same time, making ports deal with compound events instead of one single event. In general, compound events are not considered yet in practice, but it is known from literature that can lead to totally different system vulnerabilities. Due to the size and complexity of the supply chain system (where ports are considered main nodes), physically based models would

not be computationally efficient to simulate the all the existent relationships in an integrated way. Within the last decades, stochastic models using copulas have shown to be highly flexible to represent the multivariate dependence structure and to generate a large number statistically consistent ”flood drivers” variables. Would then probabilistic models such as Bayesian Networks and/or Vine structures be the solution to model the multivariate dependence structure of ports?

2. **Methods to Identify & Quantify Business and Supply Chain Disruptions due to Climate Change Cascade Effects**. The gap is on identifying and addressing indirect effects, cascade effects that cause business and supply chain disruptions. One of the possible approaches to tackle this gap would be to focus on achieving a better understanding of the bottlenecks within supply chains and identifying what type of businesses and infrastructure can have big (direct or indirect) impacts on ports if extreme weather events are frequent.

3. **Scientific approaches to raise awareness of the potential implications of climate change impacts on ports and to raise the sense of urgency to adapt to changing climatic conditions.** Most of the ports worldwide do not consider yet climate change impacts as potential risks to their businesses. Experts believe the latter is due to a lack of understanding on how climate change can impact their facilities. Hence, the importance of engineers to make the impacts more visual and understandable for the port industry.

4. **The lack of Climate Adaptation Policy Action.** Many countries still miss the confidence to make properly informed decisions on practical adaptation actions and measures to respond to climate change, while also considering future climate variability. Not only development on adaptation strategies is important but also implementation of any strategy is crucial. At the country level, many EU countries are starting to develop specific adaptation strategies to help when coping with the expected impacts of climate change. However, there is still work to do for researchers for the these developed countries but also for the many other countries that do not know yet their way to achieve climate change resilience.

5. **Other Miscellaneous Gaps.** To experts’ opinion, the biggest knowledge gap is the lack of accuracy on the climate change predictions. The latter are getting more precise but there is no way to know yet whether they are getting more accurate. Models seem very focused on variables that are easy to predict such as temperature, rainfall and sea level rise. However, what is really hard to model and has a very big impact on ports, airports and lots of other critical infrastructure is variables like wind, lightening and fog. Another gap is on the determination of physical thresholds and risk tolerance which is different for each port. Not only the impacts of climate change are and will be different depending on the port’s location, but also the levels of tolerance to those changes might differ. On another note, within the field of Inland Waterways one can find a wide range of mitigation solutions however, there are no (public) guidelines that explain how to act on low water levels and neither how to apply the many mitigation measures that are mentioned. The general feeling is that no one seems to be focusing on modeling solutions to see whether they are feasible or not. Finally, port experts acknowledge the lack of information on (1) when to start investing for adaptive measures, (2) when to start planning for them and (3) when to start actually adapting, which seems to be relatively high in their priorities.

7.6. On How to Address the Identified Knowledge Gaps

Due to time constrains, only 3 research topics are presented in more detail with the corresponding suggested approach. These three topics have been prioritized among the rest based on expert’s opinions on what climate change issues are the most urgent (for further details see 2.4.2 & 4.1-4.3). These topics have been prioritized among others because there were seen as the biggest ”needs” for consultants and for the Rotterdam Port Authority. The idea

for the 3 prioritized research topics is for TU Delft Master students to continue on advancing research on the topic of climate change impacts on ports and supply chains during their graduation. The three selected research topics are the following:

- Developing an Integrated Stochastic Model to Test Climate Change Resilience on Ports
- Investigating Methods to Identify & Quantify Supply Chain Disruptions due to Climate Change Cascade effects
- Developing a Method to Promote Awareness for Climate Change Resilient Ports

Consultants seem to be very interested in methods to perform climate change impact assessments, therefore the following research topic is suggested and presented in some detail:

- Development of General Guidelines to perform Climate Change Impact Assessment Worldwide

Furthermore, chapter 6 ends with a list of other potential research topics that can also be of interest to researchers; these are the following:

- Explore the most optimal measures to combat extreme water levels on Dutch Inland Waterways due to climate change induced droughts; and model them to see how the entire system would respond. *This is one of the goals of PhD candidate Ir. Frederik Vinke's research, it is suggested to contact him if interested.*
- Investigate the time-line of climate change adaptation measures for port assets. When is the right time to invest, plan and adapt for climate change?
- Improve accuracy and precision of models for wind, fog and lightening to be able to assess the impacts of climate change on these variables for future weather events on ports.
- Investigate on how to include climate change impacts on current shipping routes when performing cargo forecasting during port economic stage of development. How would the Origen/Destiny cargo volume matrices look like if climate change impacts on the navigational routes were considered?
- Study what would happen to the Netherlands if the worst projected sea level rise scenario (water level increase of 60 meters) happens.
- Investigate whether the Netherlands should prepare and adapt for cyclone events in the near future due to climate change.
- Explore where in the world ports are currently being affected by climate change impacts.
- Investigate the possibility to come up with global definitions of climate change risk acceptance and tolerance thresholds.
- Developing financing scenarios for climate change adaptation strategies, specially for the companies settled on seaports.

7.7. On the Methodology Followed

The two main methods forming the methodology of this thesis are the literature study and the expert interviews. The interviews were a very important part of this research. That is because this thesis aims to present the needs from the users perspective, to motivate researchers to continue with the exploration of this topic. Formulating the right questions to ask the experts and identifying which of the 12 experts could provide the best answer to my questions so that I could grasp the needs from different port users perspective, was the most challenging part of this thesis. The remaining steps have been the gathering and analysis of information and data which were easier tasks than the aforementioned.

7.8. Recommendations

This thesis aims to advance research on climate change impact assessment on ports and supply chains. The following is recommended with regard to continuing the research on this thesis topic:

- Very little information has been gathered that has more of a global perspective which is probably the main limitation of this thesis. Hence, it is recommended to extend this research internationally not only focusing on Dutch experts; to have a global perspective on the problems and identified knowledge gaps posed on this thesis.
- Climate Change is to a certain extend also a great deal of uncertainty to people or maybe people are not able to accept the truth. However, when decisions need to be made on how to invest in port infrastructure, maybe there is a difficulty to deal with making decisions under these uncertainties. Therefore, it is recommended to explore probabilistic models (Bayesian Networks, vines) to tackle these uncertainty issues and to understand the multivariate dependencies within ports and supply chains.
- It is recommended to not only study the individual climate change impacts but also the Climate Change Compound Events to have a better and more realistic insight on the impacts.
- It is recommended to study and analyze the lifetimes of infrastructure and its functions together with time horizon of climate change.
- The concepts in this thesis often stay at a rather high conceptual level probably due to lack of time and the broad topic. Examples, or an overarching case study or example could be done in a future to make some of the general issues and ideas more specific.
- It is recommended to continue this study with the suggested research topics in chapter 6 and to set up pilot projects to address the topics that have been identified.
- If interested in one of the research topics, it is highly suggested to contact the suggested experts.

A

Expert Answers to the Identified Literature Knowledge Gaps

The approach to answer the following literature gaps has been the interviews to experts. To conclude this section, it seems that several questions arise from literature that can definitely be answered by practice: (The interview transcripts can be found in Annex X)

1. Current practice by Port Authorities and port experts when considering climate change impacts

- What physical hazards and impacts are currently considered by Port Authorities? And for port consultants?

From the point of view of port authorities, only SLR and storm surge (extreme) water levels are considered in their risk assessments. Port of Rotterdam engineers believe that other consequences such as increase of fogginess, higher winds, higher temperatures and extreme precipitation would not cause a very significant impact compared to flooding. However, the interviewed PoR engineer acknowledges that the latter hazards fall out of his expertise. The same response was given by the RHDHV expert who worked apart from the Port of Rotterdam in several other countries such as Oman as risk assessment engineer.

On the contrary, Matthew Hunt (RHDHV risk assessment expert) believes that different hazards will affect particularly to each region. For instance, extreme temperatures would for instance affect in a larger scale in Northern European countries rather than South Mediterranean ones. RHDHV software expert Micheline Hounjet suggested from her experience with CIrcle at the port of Rotterdam the worse hazard is the wind. Heavy winds break down communication tools. Electronics of communication steer and monitor a lot of things and activities. There is a lack of knowledge on related cascade effects of failure in the communication system of a port. Missing communication is even more impactful than shortage of electricity, as everything in a port needs to be at the right moment (ships, VTS, cargo, rail and road entrances...). The ports are very sensitive to individual delays as they comprise several networks and very complicated supply chains with a lot of connections.

Within the news powerful titles of climate change disasters can also be found. Middle East Eye reveals presents an article where the relentless global rise in temperatures are seen as another cause for concern. Increases in temperature have a profound impact at sea because whenever seawater warms it expands. The warming also causes more frequent and intense storms.

- Are cascade effects considered within current impact assessment practices?

Cascade effects are not considered by RHDHV risk consultants and neither included by port authorities in risk assessments their assessments. Still, consultant software expert in cascade effects express the importance of analyzing this indirect affects that relate not only to port operations and infrastructure, but to essential networks feeding the port in a way or another. Within her practice, it was clear how useful tracking cascade effects can be to identify which is the port network that needs the most protection to indirectly protect the others.

- How does the Port of Rotterdam currently deal with climate change impacts? Do other ports follow also this practice?

The way the Port of Rotterdam deals with impact assessments is through workshops and interviews with the clients. Rotterdam Port's engineer, explains that through these workshops they explore the economic damage caused by extreme flooding events. They ask the company questions like how many days would it take you to recover until full operation again and, what is the economic damage the latter event could cause to your facilities. They validate the risk-damage curves with the data clients provide them through the workshops.

The Port of Rotterdam's engineers developed a method to quantify the impacts of flooding. The method consists of a risk matrix that categorize by means of color based approach the impacts on the company facilities. Independently of the risk acceptance of the individual companies, the port authority felt the need to develop a method that dictates whether the level of risk is acceptable for the port or not. They compared the risk to inner dike areas. For each inner dike area, there are two computed calculations about casualties and economic damage if failure. With the latter information, the port engineers scaled the results from inner dike acceptable economic damages of certain storm frequencies to outer dike areas. So that is the base for the Port of Rotterdam risk acceptancy policies. Joost stresses that their method follows the state of the art approaches to impact assessments that is quantify in terms of risk and not only chances.

Basically, the practice within port of Rotterdam engineers is based on determining the economic damage threshold for every SLR scenario (and storm event). If that is exceeded then measures need to be taken. Based on the framework, the Port can plan for adaptation.

- In which tasks, designs, reports and policies does the Port (as an entity) consider the climate change impacts?

The answer certainly depends on the type of port administration, the country and culture. For instance, the Port of Rotterdam is situated in an outer dike part, there is no law about flood protection as there is for inner dike areas. The only existing policy is that the user of the area is responsible for the damages and protection to flooding. The way the port deals with impact assessments is through workshops and interviews with the clients. Through these workshops they explore the economic damage caused by extreme flooding events. They ask the company questions like how many days would it take you to recover until full operation again and, what is the economic damage the latter event could cause to your facilities. They validate the risk-damage curves with the data clients give them through the workshops. Furthermore, the Rotterdam port authority acknowledges that including climate change clauses in new contracts is a practice that is being considered. They have the responsibility as Landlord port to inform the clients of any relevant issues that could affect them as users of the port. However, the port authority believes that could take up to 10 years to have a solid strategy that every company follows.

In the UK, vulnerability assessments or climate risk assessments are required by the government and that also includes for ports financed with international money. In these cases, the harbor authorities can only strongly recommend adaptation measures to their clients and hence, getting the adaptation delivered can be a very tricky question.

- What time scale would be beneficial to consider when master planning? And for other type of planning or designing?

Unfortunately, there is no common practice in risk assessment that categorize climate change hazards (physical forcing) in certain time scales affecting the port. The latter becomes an issue when adaptive planning.

- Who is involved in the process of decision making for climate change measures?

From a consultant point of view, there is not a fix committee that is in charge. Consultants from RHDHV Netherlands suggest that the responsible could be consultants, knowledge institutes but also Universities. Furthermore, having someone that knows about indirect effects such as business disruptions is very valuable. From interviews, involving owners and users in the port is also important to build tailor made solutions. For instance, is not the same to assess risk for container terminals than a bulk or oil refinery.

RHDHV English colleagues perform risk workshops with a climate risk assessment team with about 2 or 3 people. They also make sure the participation of people from the client team like the head responsible for port development, a decision maker for port operations and 2 or 3 experts involved in operations. The team suggested comprises several expertise which he believes are key to a successful risk assessment: development director, a head of port planning, harbor master and head of operations. However, in big global ports such as the Port of Rotterdam, one can find several types of terminals and different port services. Therefore, it is important to include several of the different terminal operators to engage them in the process as they can detect whether a point of the whole process is vulnerable to the port. An example of the latter by Matthew Hunt, there is no point for the Port of Rotterdam operators to have resilience covert if one of their main clients does not understand anything about climate risks and becomes vulnerability for the whole port. That is the reason why in very big and complicated ports is it very important to engage also the big clients (so the terminal operators) in the process.

However, the RHDHV software expert (Micheline Hounjet) believes should be a mix of experts from basically two categories: (1) Experts in crisis management, which in the Netherlands the unit is called “safety regions”. They are responsible for the management of disasters and they know very well from experience the cascading effects. (2) Experts in the different networks that have relation to the port or the region where the port is. These experts will provide the information about the vulnerabilities of the different networks, such as thresholds at which the network is not working anymore. Those networks are strictly dependent on the region that is being considered for instance, energy, electricity, drinking water, sewage water, railways, roads, inland waterways and communication. The last one, being the one with less knowledge but with the biggest and largest impacts to the other networks.

2. Vulnerability analysis of ports elements

- How could one best assess the vulnerability of each port asset/element? What performance indicators could be used to efficiently identify the latter?

Consultants and port authority agree that vulnerability is quantified as damage in terms of money. Hence, the most relevant performance indicators are downtime and closure of client facilities (or full port closure).

- What is the relation between performance indicators and physical forcing like wave height, wind speed, water level, temperature?

Unfortunately, there seems that no general guidelines to assess this matter are available.

- What is the port practice to assess vulnerability? What is the limit accepted and on what base is it measured?

Both consultants and port authority engineer agree that the answer to this question depends on the client standards. The way the Port of Rotterdam deals with vulnerability assessments (or impact assessments) is through workshops and interviews with the clients. Through these workshops they explore the economic damage caused by extreme flooding events. They ask the companies questions like how many days would it take you to recover until full operation again and, what is the economic damage the latter event could cause to your facilities. They validate the risk-damage curves with the data clients give them through the workshops. However, the level of awareness to climate change impacts really differ per company, client. Big companies at Port of Rotterdam have very high safety standards and consider storms of 1000 years return period. However smaller companies do not believe those storms are of any hinder to them so the limits come to something like what risks do companies accept.

From a consultant point of view, the most successful way to assess vulnerability of port elements is by working together with people that operate in the port, with a senior team from the port operator section. The senior operational team sets the boundaries for the impacts in terms of money and all the risks are translated in their language. The consultant team make sure that risks in the categories financial, operational, environmental and reputational are considered within the assessment.

- What method or software one could use to link, identify what climate change impacts affect each port asset or port element? Would that be a general method for every port or should it be used specific technique for each case study?

The answer depends on which impacts one is looking at. If the interest is specifically on a hazard (such as impacts of flooding events) there is no need of any software from the point of view of both consultants and port authority. They have already developed their own methods to assess the risks. However, from the interviews one could notice that some knowledge on how to define thresholds, beyond the risk (damage produced) is not acceptable, is missing. To answer the latter gap, the Port of Rotterdam engineers build a method that dictates whether the level of risk is acceptable for the port or not. They compare the risk to inner dike areas. For each inner dike area in the Netherlands, there are two computed calculations about casualties and economic damage if failure. With the latter information, Joost and his team scaled the results from inner dike acceptable economic damages of certain storm frequencies to outer dike areas.

- Who is responsible for the adaptation or mitigation measures? Who should decide and who should pay?

Consultants, researchers and port authorities agree that answering the question “who is responsible for the damages” can be very tricky and the answer depends on the region, the country and the organization of the port. For instance, most of the ports in the UK are private businesses however in Morocco or Spain the port is publicly earned. In the latter case, the responsible to pay is the government in one way or another, however within ports in the UK as are more privatized than other European countries the responsibility is all within the private sector. For instance, if the port operator or harbor authority does the investment it passes charges to the shipping companies and the terminal operators which at the same time charge larger quantities for their services and products. However, in some cases if it is not build into the contract, the harbor authority cannot oblige the clients to take care of adaptation strategies.

Within the Netherlands, inner dike areas are protected against flooding by law, by the government. However, at outer dike areas every user is responsible for their own damage in

case of storm surges and floods. So, there is no law that enforces a governmental action to protect outer dike areas, only the mentioned policy.

3. Quantification of risks and impacts, and damage assessment for climate change in ports

- What is the difficulty of making risks and impacts more tangible for decision making?

From a consultant point of view, determination of thresholds and tolerance to risks are great expectation gaps that make difficult the risk assessment practice. The tolerance for each port regarding the acceptance of certain risks is different. Not only the impacts of climate change will be different for each port but also the levels of tolerance to those changes might be difference. That is related to the nature of the port and what they do but also the capital and finance of the port, the incoming and out goings.

The availability of methods that quantify the impacts of climate change really depends on where you are in the world. Port of Rotterdam engineers are confident in their risk assessment practice. However, they felt the need to develop a method that dictates whether the level of risk is acceptable for the port or not. For each inner dike area, there are two computed calculations about casualties and economic damage if failure that they use to scale down the acceptable economic damages to outer dike areas.

Furthermore, UK consultant believe the biggest gap and challenge to really get a handle on all risks is the accuracy of the predictions. The latter are getting more precise but there is no way to know yet whether they are getting more accurate. However, port authorities and consultants are very focused on easy predictable variables and model such as temperature, rainfall and sea level rise.

Currently several coherent models exist that can predict the three fields. However, what experts find very hard to model and has a very big impact on ports, airports and lots of other critical infrastructure is things like wind, lightening and fog. For instance, there is dense fog in the port this has to close down. The models for the aforementioned variables are not great but because in his opinion is incredibly hard to model. Also, one does not know how climate change is affecting fog, lightening or wind, he stresses that there is very little knowledge about that. Furthermore, those variables appear in lower layers of the models which already present results with big bounds of uncertainty. For instance, he explains that if the peak wind speed threshold for port operations is 70 km/h the uncertainty width bands are from 0 to 200 km/h.

- How would be the best way to identify climate change impacts and to quantify climate change risk? Where can one find the data and information to be able to perform risk assessment?

From both perspectives of port authority and climate risk expert, the practice of risk assessments must be done with cooperation of senior port operators and other main port stakeholders for instance, someone responsible for the access roads and/or waterways; and also for clean and sewage water.

There are some public sources of risk based approaches available. Port engineer, Joos Nooijer, explained during the interview that of a report from the 90's that define the % of damage for each asset per m2 that could be a way to define the ranking and is still on use these days. The report differentiates each damage function by the type of cargo. Moreover, the risk assessment reports for the Botlek area in the Port of Rotterdam are available on their webpage.

- Which software or technique could be relevant to assess impacts and risk within supply chain scale?

From the conversation with software expert Micheline Hounjet, there are currently being developed two potential tools for integral assessment of climate change impacts and adapation measures which are STAIN & CIrcle (see sention (....))

B

Expert Interviews

B.1. Port Field's experts

B.1.1. Rotterdam's Port Authority: *Ir. Joost de Nooijer*

1. Knowledge on impacts of climate change

I would like to ask you these first part of questions from the point of view of port authorities.

1.1 What physical port elements do you think are vulnerable to the impacts of climate change? For instance, quay walls, breakwaters...

Joost believes that physical infrastructure, mostly maritime, is not vulnerable to the impacts of climate change. The latter refers to damage in the structure, so considering the structure as the vulnerable element.

1.2 What port operations are directly vulnerable to climate change hazards (e.g. extreme weather events)? And what port operations will be indirectly affected because the impacts on physical infrastructure?

Within their practice, they assess impacts by means of damage curves. Some interesting fact about these curves is that beyond certain inundation level the damages become constant. The shape of those graphs is like the (for instance) steel strength diagram, there is a rapid increase at the beginning but beyond some threshold, the strain is fixed. The results of the analysis suggest that installations are the variable most affected by flooding, the biggest economic damages.

1.3 Do you expect impacts on the port due to climate induced changes to the following elements? Would they be short term, medium term or long term?

- Migration trends and population settlement patterns
- Demand for energy
- Agricultural production
- Industrial production
- Investment in ports

- Modal shift
- Trade diversion to other ports
- Supply chain disruption, Yes and that is a very important one.
- Labor shortage
- other?

Joost explains while performing the risk assessment in the Botlek area (where the big oil companies and nitrogen producers are situated), the indirect risks are some order of magnitude higher than in other areas. The port authority tries to quantify the indirect risks with the help of the VU Amsterdam by means of economic models.

2. Knowledge on the vulnerability of port elements to climate change

2.1 In your opinion, which port elements need an urgent action against climate change impacts in general? Could you please rank them from the most to least urgent? And in the Port of Rotterdam?

Joost do not agree on the fact that physical infrastructure is the most vulnerable to floods. He explains that maritime infrastructure can cope with weather impacts however the vulnerable part are operations and the assets of their clients.

Joost mentions the existence of a report from the 90's that define the % of damage for each asset per m2 that could be a way to define the ranking and which is still on use these days. The report differentiates each damage function by the type of cargo.

2.2 What would be the most relevant performance indicators to assess the impacts in the form of damage/costs? Example: %time per year the overtopping discharge over breakwaters exceeds a certain value.

The most relevant impact to Joost opinion as port authority is damage in terms of money. Hence, the most relevant performance indicators would be downtime and closure of client facilities.

2.3 From the point of view of a port authority, would it be useful to have a tool that relates duration of climate hazards (e.g. waves, wind, fog, surge) to consequences in physical elements (breakwaters, quays walls) and then effects to duration of downtime or closure?

However, Joost explains that they only consider flooding due to sea level rise and storm surge as climate change hazards. He believes that other consequences such as increase of fogginess, higher winds, higher temperatures and extreme precipitation would not cause a very significant impact compared to flooding. Joost acknowledges that the latter hazards fall out of his expertise.

Nevertheless, one of Joost colleagues is looking at extreme rainfall (and others) and those kinds of events behave differently that SLR or flooding. He explains that high temperatures or extreme rainfall are localized events with high frequencies of occurrence. However, SLR will be a more globalized impact but with smaller frequencies.

3. Practice: impact assessment and stakeholder's engagement

3.1. Could you briefly explain how does the Port of Rotterdam currently deal with climate change impacts? Are there any policies?

Joost explains that as port authority they consider very closely what are the risks of flooding at specific areas. As the Port of Rotterdam is situated in an outer dike part, there is

no law about flood protection as there is for inner dike areas. The only existing policy is that the user of the area is responsible for the damages and protection to flooding.

The way the port deals with impact assessments is through workshops and interviews with the clients. Joost explains that through these workshops they explore the economic damage caused by extreme flooding events. They ask the company questions like how many days would it take you to recover until full operation again and, what is the economic damage the latter event could cause to your facilities. They validate the risk-damage curves with the data clients give them through the workshops.

Joost explains several companies make us of a method to quantify the impacts of flooding. The method consists of a risk matrix that categorize by means of color based approach the impacts on the company itself facilities. Independently of the risk acceptance of the individual companies, Joost and his colleagues felt the need to develop a method that dictates whether the level of risk is acceptable for the port or not. He explains that they compared the risk to inner dike areas. For each inner dike area, there are two computed calculations about casualties and economic damage if failure. With the latter information, Joost and his team scaled the results from inner dike acceptable economic damages of certain storm frequencies to outer dike areas. So that is the base for the Port of Rotterdam risk acceptancy policies. Joost stresses that their method follows the state of the art approaches to impact assessments that is quantify in terms of risk and not only chances. Basically, their practice determines the economic damage threshold for every SLR scenario (and storm event). If that is exceeded then measures need to be taken. Based on the framework, Joost explains that the Port can plan for adaptation.

3.2 Who pays or will pay for responsive or adaptive measures to climate change within the Port of Rotterdam?

Joost agrees that answering the question "who is responsible for the damages" can be very tricky. Within the Netherlands, inner dike areas are protected against flooding by law, by the government. However, at outer dike areas every user is responsible for their own damage in case of storm surges and floods. So, there is no law that enforces a governmental action to protect outer dike areas, only the mentioned policy.

To Joost opinion, the level of awareness to these kinds of impacts really differ per company. Big companies in the Port have very high safety standards and consider storms of 1000 years return period. However smaller companies do not believe those storms are of any hinder to them. The question about responsibility comes to something like what risks do companies accept.

Another example, the A15 highway is managed by the government. Joost explains that if the highway is flooded, a lot of indirect damage will be caused to the port.

Joost agrees that including climate change clauses in new contracts is a practice that is being considered. He mentions that they have the responsibility as Landlord port to inform the clients of any relevant issues that could affect them as users of the port. He believes that could take up to 10 years to have a solid strategy that every company follows.

3.3 Even if the consequences of climate change are not visible right now but will be felt in a couple of decades; in your opinion as port engineer, what would it take for port authorities (in general) to include climate change impacts while budgeting, or in master plans or investment plans? Is the port of Rotterdam already considering it?

Joost explains raising awareness is one of the most difficult practices. Most of the average-size companies plan for the next 5 or 10 years and hence the port authority finds difficult to get the message across. The large companies also do not have a very large horizon in terms of planning however, they do investments. Mostly the investment are for robust measures and not budgeting or planning for adaptation measures. Joost acknowledges the (current) awareness to climate change impacts is barely minimum among the port of Rotterdam clients.

Rotterdam's port authority is currently busy building a website, to inform companies so that they can be more aware of the impacts they would face. With their strategy, the port

authority intends to encourage companies to invest more in the longer term so to consider climate change impacts.

3.4 Regarding what consultants or experts can do for port authorities related to assessing climate change impacts: What gaps do you think the port experiences and what would they like to see differently?

The biggest gap Joost and his colleagues experience is raising awareness as managers. Also, the question of who will pay to which consultants could help by developing financing scenarios specially for the companies. A method to approach the decision-making process and the ter.

From Joost experience, other ports do not have a risk based approach which he believes is essential to quantify and analyze impacts. He explains that some consultants only consider chances of events happening and not risks associated with that. They lack to translate impacts into costs and also they fail to look further into risk based approach. To his opinion, other ports might not consider cascade effects.

Joost explains that another big issue is the cultural approach to impacts that countries have. Netherlands have a culture of adapting and planning far ahead but in Joost opinion, other countries might just apply mitigation measures. He finds that is important to validate data by interviewing people.

4. Contacts

Would you recommend me any expert that would be willing to contribute with an interview to my thesis?

Joost suggests Elko Koks as expert in economical modelling of indirect effects; Matthijs Bos and Jarit de Visch as experts within RHDHV and Mathijs van Ledden also from RHDHV, who works with World Bank.

B.1.2. Adaptative Port Planning expert & Researcher: *Dr. Ir. Poonam Taneja*

1. Knowledge on impacts of climate change

1.1. Could you briefly describe what climate change impacts (say 2 or 3) do you think will affect ports the most?

Poonam believes that port operations are vulnerable to impacts of climate change. Within this field, she mentions landside operations together with navigability and accessibility are likely to be the most significant for ports. In her opinion, extremmay result in closure and downtime to the port by impacting the latter mentioned set of port operations.

Furthermore, she explains that due to increased frequency of extreme weather events cargo routes might change. The latter would imply that competition between ports might be affected.

1.2. Do you expect impacts on the port due to climate induced changes to the following? Yes or no question.

- Migration trends and population settlement patterns: Yes, but in the long term
- Demand for energy: Yes, but in the long term
- Agricultural production: Yes, but in the long term
- Industrial production: Yes, but in the long term
- Investment in ports: Yes

- Modal shift: In certain situations, such as due to a higher sea level the bridge clearance may be reduced
- Trade diversion to other ports: Possible direct impact due to decrease in accessibility
- Supply chain disruption, Yes and that is a very important one.
- Labor shortage: Yes, on the long term related to point a) for some ports
- other? Changes in ship size: on the longer term might be changes in design of inland ships to adapt them for more robustness or for shallower draft.

2. Knowledge on the vulnerability of port elements to climate change

2.1. What port elements, infrastructure or equipment you think will be vulnerable to the impacts of climate change? For instance, quay walls, breakwaters, cranes, rail and road connections, inland waterways etc.

Poonam refers to the three-layer model she adapted for ports in her PhD thesis to answer this question. She explains that a port can be divided in three layers (from bottom to top): physical infrastructure, operations and management and lastly product and services. All the layers are interconnected and dependent of each other. Basically, each layer needs its bottom layer.

Following the latter train of thoughts, for a port to provide services and products, the operations and the physical infrastructure must fulfill their functions. For example, climate change may affect the operations due to overtopping or more frequent high winds speeds. This will require adaptation of physical infrastructure and equipment.

2.2. In your opinion, which of the aforementioned elements need an urgent action against climate change impacts? Could you please rank them from the most to least urgent?

Poonam acknowledges that she does not know the answer to this question. However, she explains that the most important is that port services function and cargo flows in and out. She agrees that communication is one of the most vulnerable elements as nowadays data is essential for managing a port. Communication within a port is essential to keep every part functioning well and without delays, if the latter is hindered the whole port suffers. She also suggests that climate change impacts be considered right from the masterplanning stage of a port project.

2.3. For the elements mentioned in question 2.1 what would be the most relevant performance indicators, say 2 or 3 (that you use or plan to use), to further assess the impacts in the form of damage/costs? Example: %time per year the overtopping discharge over breakwaters exceeds a certain value.

Poonam suggests that the answer really depends on the specific port. However, closure of port or terminal and downtime of equipment are obvious indicators of climate change impact.

3. Practice: risk analysis and impact assessment

3.1. In your opinion, what stakeholders should be involved in decision making process for climate change measures on ports?

Poonam believes that people responsible for elements present in the supply chain should be present when assessing climate change impacts and for decision making process. However, she also mentions terminal operators should also be part of the process as they know what is going on day to day and what effects could hinder the operation site of the port.

3.2. Who do you think should pay for adaptation measures in ports: the port authority, the terminal or shipping companies, the government...?

From Poonam's opinion, everyone should pay their fair share. So the cost of any adaptation measure should be split throughout the supply chain.

3.3. What do you think the best way to promote awareness to terminal operators and other port clients is, regarding the impacts of climate change in ports?

Poonam suggests that the best way to promote awareness is to make the impacts visible. So, port authorities start considering climate change adaptations in their master plans and budgeting for it to adapt when the time is right.

3.4. What knowledge gaps could you identify within your experience that resolve around the topic of climate change impacts and assessment?

Poonam agrees that the one of the biggest gaps is on how to promote awareness within ports to start budgeting for future climate change adaptations.

However, she explains that the biggest gap I her opinion is the lack of methods for the quantification of supply chain disruption.

B.1.3. Port Economic and Inland Waterways & Shipping expert: *Dr. Ir. Cornelis van Dorsser*

1. Knowledge on impacts of climate change on ports

In the lecture notes for Ports Waterways 2, you suggested that there is evident effect of climate change on global weather system, already affecting incidence of extreme weather events. Nevertheless, major impact on ports and inland waterways are expected from 2050 onward.

1.1. What impacts do you believe are expected from 2050 onward in ports?

The effects of climate change were meant to be moderate until 2050 and increasing exponentially onward. However, Cornelis feels that climate change itself is accelerating. It may even be slightly earlier. He explains that 2050 was meant for inland waterways. Nowadays already the drought has been fierce on the Netherlands with 89 days that the water level on the Waal was less than 2.8 meters. The Waterways were designed following the idea that only 20 days per year would be less than 2.8 meters. Cornelis explains that for this water levels, only the 25% of the capacity is left. It has direct impacts on the port of Rotterdam so if the latter happens every year there will probably be reallocation of industrial activities.

Cornelis believes there are many impacts on the port operation site due to climate change. From the Waterway system, the impact is on changing water levels, because rivers will be affected by draughts, but also changing wind conditions. The latter has a great effect on downtime for terminals.

Routing and delay of ships will be hindered due to the more frequent hurricanes. The most affected areas are mainly South and East Asia and Centre America together with California and the (South) East coast of United States. If the weather conditions are changing and hurricanes become more frequent, the ports will have to be prepared for it. Even if the big storms are not directly passing through the port, the impacts will be felt and if not prepared, downtime will increase.

Another changing variable will be humidity and will affect certain kind of goods that are stored. Climate change will induce more rain in coastal areas which might influence the humidity content. The storing techniques will have to be upgraded to the situation derived by climate change.

1.2. How do you think climate change will affect to the following issues?

- Supply chain: There are many trends and they depend on how countries develop for instance changes in climate policies. Agricultural production is very much reliant on the climate conditions and there is a direct impact on trade flows.
- Trading navigational routes:

  If transport routes become different raw material transportation which is basically dominant within sea trade will be affected and might change sea routes and have impacts on global ports. The transport cost might change and for instance there might be a steel decline production in Germany. It might be the case that due to problems in the Rinne, the throughput of Port of Rotterdam might decrease considerably but that does not mean that you require less space.

  Another effect of changing shipping routes might be that adapting to another type of good's transportation might require additional equipment. If the intensity of rain increase, shelter might be essential for loading and unloading docks. Ships are already sailing in the Artic channel.
- Ship size and type (e.g. 0 emissions ships)

  Is it climate change causing it or are the measures taken to avoid climate change? It is important to realize whether the impact is via the climate change policies or due to climate change effects.

  If the fuel industry changes to renewable energies then ports will be affected. These have effects on the trade flows and goods going through port. For instance, if the cars are electric they might not get through the port but another channel. So, trading is not really changing but the flows are.
- other relevant?

  Indirect social effects such as starvation in areas that might be next to ports. That will also affect what will happen to the port for instance, if health problems increase among the workers the port will suffer from it.

  Wind impacts on ports, measures and how can affect your business case. Also, if prevailing wind direction changes it might be the case that breakwaters are not in the right position. Erosion patters and sediment flows can change if wind direction and intensity change. What if the dunes are not supportive enough anymore. Moreover, fisheries can change due to different currents. Globalization and Reverse Globalization might be affected indirectly by climate change. So, the question would be, do climate change effects on migration, that would affect feelings of populism and nationalism that leads to Reverse globalization might affect trade routes.

  Currently, most of the methodologies make use of climate change scenarios as input or base to assess the consequences in a sector (for instance ports). However, within the lecture of Ports Waterways 2 at TU Delft you make sure to stress the difference between scenarios and forecasts, being a forecast the projected or most probable thing to happen.

1.3. Would you recommend using forecasts (even probabilistic forecasts) instead of climate change scenarios for climate change impact assessments?

Cornelis explains there is a big difference between forecasts and plausible scenarios. The shift on drivers complicate the ability to forecast because the different type of activities could take place. The current period requires a different method to identify what is possible but not as much as forecasting. Later, if a kondratiev wave has set in and the system is further evolving and one has ahead a period of 30 years what you know which direction is moving and then forecast is very useful.

What happens often is that people do not know what they do and then they derive several scenarios. So, the best way to move forward would be to reduce what is considered plausible by gaining for information about the system and understanding how trends are inter-related.

The idea of the study is to scale down the uncertainty of different scenarios to levels one can work with.

We are currently about 10 years on the way of shifting to the next kondratiev wave. The new system will become more visible around 2030-2040 and then forecasting tools will be useful.

2. Knowledge on Climate Change effects on Port Economic Development Stage

2.1. How port engineers and experts nowadays consider climate change during the economic development stage?

Cornelis believes there is not much yet done. There is a focus on the importance of climate change on ports, on how this may change operations and what it may require. But specially on infrastructure but business cases are not considering climate change. The reason is because climate change will have effects in a much longer period than the one considered in economic stage development. The question is within the discount rate. If using a low discount rate, climate change would be taken more into account. But especially when is private investment discount rated are rather high and to this kind of practical applications climate change is taken into consideration. So that means that there is no much urgency on climate change adaptation measures.

If considering energy transition and change in the kondratiev wave. Port authorities would be the ones thinking how climate change might affect the activities in the port and resettle for it. But then, these studies are on the forefront which climate change is not considered.

From the economic side, indirect effects might play a role coming from the climate change policy part.

2.2. Is there any guidance on how to introduce or consider climate change in estimating cargo volumes on Origen/Destination matrices?

Cornelis believes there is hardly anything written on forecasting of port volumes in general. Forecasting is something done mostly by consultants and some guidance is normally given by econometrics. Probabilistic forecasting is something missing which could be done for instance using a linear model and checking all the parameters to identify the sensitivity of them. But most of the time some of the statistical models do not capture completely the physics of the system.

3. Practice

3.1. Have you ever considered climate change within your engineer practices?

Cornelis has been out of the engineering sector for around 8 years. However, at that moment only deterministic values of SLR (increase of water level in meters) were considered in designs, for instance quay wall levels.

3.2. What knowledge gaps could you identify that resolve around the topic of climate change impacts in ports?

What happens if we get 60 meters extra water, what would be the impacts for the extreme worst scenario. What are the options to adapt? Climate change trends affecting ports and what of the climate change impacts are affecting cargo flows, port operations. How can energy transitions, geopolitics of climate change affect ports? Interaction of the system ports and climate change impacts. Considering an economic model instead of financial might give input on what benefits and what impacts climate change might have on society on a broader view that affect the ports.

4. Contacts

Would you recommend me any expert that would be willing to contribute with an interview to my thesis?

Chapter 9 – Cornelis dissertation & shipping scenarios page 393, quantification of throughput volumes (chapter 13-14). Ronald Stieve from RHDHV.

B.2. Climate Change and Risk Assessment experts

B.2.1. Inland Waterways & Climate Change expert: *PhD Candidate Ir. Frederik Vinke*

1. Knowledge on impacts of climate change on ports

1.1. Could you briefly describe what climate change impacts (say 2 or 3) do you think will affect Waterways the most?

Frederik is mainly focusing on extreme low water river discharges during dry season (July, August and September). He is analyzing whether the water depth is enough. SLR is also one of the impacts Frederik is considering in his PhD but mostly for the area nearby the Port of Rotterdam and the connection to Inland Waterways.

Extreme highwater discharges are not considered within Frederik research. He believes is more related to flood defenses. The period those large discharges take place is just a few days to the contrary of several months of very low river discharges. Therefore, he believes is not a main concern for navigational issues.

The shipping companies and barge operators do not believe is a problem since what they believe is the threshold for inability to sail is around 7-10 days. One could say that the performance indicator most appropriate for inland waterways is the % of time the waterway is not navigable.

1.2. How do you think climate change will affect to the following issues?

- Supply chain & b) Trading navigational routes

  The connection to the hinterland for the sea port must be available if not there is no cargo delivered. In that way sea ports need to be up to date with the consequences affecting also Inland Waterways.

  Frederik believes supply chain will become different. If Inland transport prices become too high, or there is no enough capacity, a modal shift might take place. However, he does not believe it will happen. He mentions that Port of Rotterdam ask him to consider other kind of transport in his research like railway and road. If climate change continues to affect the river discharges, the water depth might become too low at some point and the waterway network will not offer anymore the same capacity and become too low to transport goods to Germany. Hence, other solutions in terms of transport modes need to be find. Frederik is looking into the affected summer period whether other modes of transport can take what Inland transport cannot. A modal shift is not wanted for environmental and inland transport aspects.

  Already this year some cargo was left on Rotterdam that could not be transported and had a waiting time of 3 months, because the capacity of the Inland Waterway was not enough. The Port of Rotterdam is going to choose another main sea port that has more capacity to transport inland cargo.

- Ship size and type (e.g. 0 emissions ships) Frederik is not considering this topic. However, the length and the width of the ships have a great influence on the Waterway capacity. Frederik is looking to bulk transport barges if the water depth is not sufficient what would be the solution.

- other relevant? Frederik explains that he has been asked by the government to explore other modes of transport available within the extreme dry seasons that can take over the cargo of the Inland Waterway.

2. Knowledge on the vulnerability Ports Waterways elements to climate change

2.1. What elements of the Waterways you think will be vulnerable to the impacts of climate change?

The vulnerable elements are mainly the water depth of the waterways at the dry periods.

2.2. In your opinion, which of the elements need an urgent action against climate change impacts? Could you please rank them from the most to least urgent?

The most important issue is the deficient capacity of certain parts of the Dutch Waterways due to absence of minimum water depth.

At the Waal, the bottom layer is going down because of erosion. One may say that stability of the dikes will become affected. Hence, deepen the canal would not be an option anymore at some point.

2.3. Do you know of any regulations, guidelines that provide guidance on how to quantify and consider climate change impacts when designing, planning?

In literature, one can see that everyone is focused on the dry periods and a very wide range of mitigation solutions is also existent from many research sources. However, there is no guideline that explains how to act on low water levels and neither how to apply the many mitigation measures that are mentioned in the literature. Neither PIANC propose a general methodology to tackle the impacts of climate change to Waterways. No one seems to be focusing on modeling solutions to see whether are feasible or not. The state of the art climate solutions seems to be stuck in theory. There are several arguments that mentions the measures but conclude that due to certain argumentation the measures would not be feasible. Within the field of Inland Waterways, the actions against climate change impacts can be characterized mitigation measures, as adaptation measures also consider the far future into account. One of the goals of Frederik research is to find out the most optimal effective measures and model them to see how the system would respond.

3. Practice: impact assessment

3.1. Have you ever considered climate change in any of your practices? If yes, in which way?

When he was an engineer he never considered climate change.

How are you considering climate change in your PhD? What are you focusing on?

Frederik believes that climate change is a fact and that there is some people that have done some research. For instance, he mentions that research has been done (and is ongoing) for Inland Waterways. The economic impact studies focus only in two bottle neck points located in the Dutch corridor to Germany as seem to be the main hazards to navigation in dry periods. However, Frederik explains that most of the research on how climate change affects to Inland Waterways is done for bottlenecks. There is no focus on which stretch of the river is available during those situations.

Frederik aims to find out which mitigation measures would be efficient to apply, to achieve a high capacity to transport cargo. He believes it is important to know which parts are available and not only the ones are not available. He wants to apply that vision in his research. He is looking whether is possible to transport the cargo to Lobit (Germany) even in dry periods, so focus only on the river stretches that are affected by the lack of water depth.

3.2. Who do you think should pay for adaptation measures in Ports or Waterways: the port authority, the terminal or shipping companies, the government…?

Frederik believes the cost must not be specially only for one. In Frederik's research, there are a lot of partners involved (Rijkwaterstaat, Port of Rotterdam, Shipping companies…). He explains that everyone is aware that everyone is responsible in financing the measures. The discussions within Rijkwaterstaat argue about whether thy should facilitate the inland transport system to the transport companies. However, there is no space to grow. The shipping industries responsible must find solutions to keep the transport capacity at high levels. Because at some point, there is no possibility to widen and deepen the waterway because of bottom erosion and dike instability.

3.3. What do you think the best way to promote awareness (in general and considering authority, clients, engineers) of the impacts of climate change in Ports and Waterways?

The best way to promote awareness is to explain people what are the consequences of climate change and how these consequences are going to affect them. Use common language to address the impacts of climate change to society rather than using scenarios and technical language. The aim should be to explain the direct impacts on society and make people realize the urgency to act against it.

3.4. What knowledge gaps could you identify (already) within your PhD that resolve around the topic of climate change impacts in Ports and Waterways?

Climate scenarios are very uncertain. From Frederik's opinion, there should be translated into forecasts to have a better understanding of what would really be an issue in the future to be able to wisely act on. The lack of models and research on the mitigation measures is also an issue that researchers, shipping companies and authorities are facing. Building of general guidelines to act on climate change impacts should be approach by researchers.

Regarding sea ports, the gap is within the effect of climate change in operational activities. For instance, winds and rain climate extremes how do they affect inside the port in the operations side. Port authorities do not seem very concerned about it, but is that really the case?

4. Contacts

Would you recommend me any expert that would be willing to contribute with an interview to my thesis?

Rolien van der Mark (Deltares)

B.2.2. Environmental Risk Assessment expert: *Dr. Matthew Hunt*

1. Knowledge on the vulnerability of port elements to climate change

1.1. What port elements, infrastructure or equipment that would be vulnerable to the impacts of climate change? For instance, quay walls, breakwaters, cranes, rail and road connections, inland waterways etc.

From Matthew's expert opinion, everything is vulnerable within a port. Very few things come up to be invulnerable in one way or another depending on where something is and how has been constructed. He explains from his experience sea structures seem to be vulnerable, such as quay walls. If they are not high enough they will get flooded. If breakwaters do not keep up with sea level rise projections, increase in storminess can also be a point of vulnerability to the port. Rail, road, cranes and basically things that overheat that cannot

operate at or higher a specific temperature, are also, to Matthew's opinion vulnerable points mostly depending on where you are. Matthew believes that healthy and safety implications within operational limits such as in offices, computer systems, telecoms interconnecting services also depending on where they are, are potentially vulnerable.

Conclusively, depending on the nature of it, everything is potentially vulnerable within a port.

1.2. In your opinion, which of the aforementioned elements need an urgent action against climate change impacts? Could you please rank them from the most to least urgent?

Within Matthew's work experience, he identifies several elements that showed to be typically more vulnerable to effects of climate change. They look at a risk assessment as the combination of the nature of the impact, the occurrence and then the sensitivity of the element that gives together likelihood and consequence. The elements that were identified as being the most vulnerable are quay heights and breakwater overtopping, water drainage service in docks where the extra water cannot be released. Also connecting infrastructure outside the port (roads that landslide, are flooded) is not operative, cargo cannot go in or out the port. Cranes and mobile plants, if not build as hard standing, can become inoperative. However, they do not represent a risk because their operational period or life time is much lower than other infrastructure such as quays.

1.3. Do your expectations change for questions 1.1 and 1.2 (vulnerable elements) when you think of specific port categories? (e.g. geographical location, exposed/non-exposed ports, lowlands/highlands, type of cargo). What categories do you relate to what topic (vulnerable element)?

Matthew believes that indeed depending on the port and location itself vulnerability expectations change. For instance considering location and sea level rise, the most realistic projection for the UK are based on 1 meter of sea level rise which certainly will have an impact in several elements of the port infrastructure even though is not certain the level of damage yet. However, if one looks at ports in Morocco, sea level rise projections for a hundred years are of 25 cm which obviously is not an issue.

Another example within regional differences in climate change impacts would be the heat impact for very extreme scenarios. The Middle East (Oman, Dubai, Qatar) and south Mediterranean countries (Morocco) are used to be exposed at temperatures of 50‘C so they would be able to cope with an increase of 5‘C. However, northern European countries such as Netherland and the UK find very challenging operating at temperatures around 40C. If the port transport infrastructure is based on road, railway and hard standing cranes, the inoperability figures will of course raise. Therefore, the increase of temperature within these countries represents a potential hazard, as the equipment, the roads and railway are not designed to be operative at high temperatures; but do not represent such a hazards for other regions where the materials are resistant to high temperatures.

For instance exposed and non-exposed ports, climate change predictions in storminess are irrelevant if the port is situated in a sheltered region. Matthew gave some examples on exposed ports in the UK which have to close due to the increase storminess.

Matthew believes when talking about climate change, one refers to different regions and different impacts such as summers being warmer or winters being hotter and wetter, and basically exposure to extreme weather. If one is moving containers, with containers being fairly water tight and in windy places, containers can be stack easily with help of some techniques. So the only investments are on simple operational ways can be solved with little money with training and awareness. However, bulk terminals that store in the open and will be exposed to more rain or wind need to start storing the cargo somewhere else. That kind of terminal will need to invest in different infrastructure to be able to continue operating while keeping the product dry from the increase rain. However, in a big port such as Rotterdam, every element of ports (containers, oil, tank farms, bulk etc.) exists there. The vulnerability

of such type of global ports is about the superstructure and the operations come down to what is the cargo and how is moved in and out of the port.

In the UK there are a lot of vulnerability assessments or climate risk assessment being done as it is required by the government however also for ports financed with international money. As closure to this question, Matthew explained that from his experience the expectations change depending on where, how and what the operations will be.

» Adaptation reporting powers is the governmental legislation that requires for ports. Also he recommended a green code by PIANC for climate adaptation.

1.4. For the elements mentioned in question 2.1 what would be the most relevant performance indicators, say 2 or 3 (that you use or plan to use), to further assess the impacts in the form of damage/costs? Example: %time per year the overtopping discharge over breakwaters exceeds a certain value.

The two most relevant performance indicators are damage costs and the bigger one is close down cost, the inability to operate as ports are not sensitive structures, normally full of concrete so there are not very sensitive to damage by extreme events. For instance the cost is not associated with the flooding event but with the time that the element cannot be operated and needs to be closed down.

2. Practice: risk analysis and impact assessment

One of the goals of my additional thesis is to explore what is the state of the art software to assess and quantify climate change impacts in ports. The knowledge gaps identified so far (from Academia perspective) are the lack of methods to quantify the impacts and the risks and further translate the data into cost.

2.1. Do you agree with the later statement? What methods do you use to perform climate change impact assessments? What is the line of action you follow? Such as first assessing drivers and risks, then impacts on ports and finally quantifying damage or adaptation measures.

Matthew explained that when working with an existent port, this will have an operational risk assessment where they will look at every associated risk and rank these usually by 5 categories of likelihood and also 5 of consequences. Their practice consists of translating climate risk with people that operate in the port, with a fairly senior team from the port operator section. The senior operational team sets the boundaries for the impacts in terms of money and all the risks are translated in their language. Matthew and his team make sure that risks in the categories financial, operational, environmental and reputation are considered within the assessment. For the reputation risks, actions that affect the reputation and future trade are considered, like if the port closes several times because of the weather, is going to achieve a reputation of being non-reliable and clients will eventually use another port to call.

Nevertheless, Matthew also talked about the struggle that suppose defining thresholds beyond there is an impact. In practice, several climate models succeed to provide an estimation of future scenarios and variables data. However, Matthew confirm that defining such a threshold is not easy and neither precise, the variance can be considerably large. Furthermore, he explains that is very difficult to associate a cost to a specific threshold (e.g. temperature at which the asphalts starts to melt considerably hindering traffic). He suggests in his practice that resilience should be built through time as the dangerous thresholds will not be trespassed in the near future but the end of the century.

Basically, he suggests working close with the port authorities to explain that at some point some adaptation measure will be needed and how and when the best moment to invest in it is. The latter is due to the existing concept of over adaptation, which for instance means that adapting your port right now to a hazard that could occur in 50 years will lead to inoperability of the upgraded element (such as heightening a quay wall about 2 meters)

as the clients (ships) will not be technically prepared for it. Matthew is convinced that port operators should be involved within risk assessments. He believes that the operators should suggest the amount of times that is acceptable a close down due to the climate effects as they will be the clients will be the ones suffering the close down.

Basically port operators should identify at what point there is too many close downs per year and define the value as a threshold for the consultant or engineer. Matthew concludes that for each adaptation measure is important to look when the most cost effective time to carry out the work is. However, for things that there is no significant down side of present adaptation are better to be done now in the present.

2.2. Do you make use of any software/model such as to quantify risks or damage in terms of cost?

Matthew explained that he does not make us of anything in particular. His team uses model outputs for what the climate changes will be (UK CP09) which are the single point of information for climate projections in the UK.

The starting point for climate impact assessment is the set of scenarios or projections for a fairly conservative future situation and then also the worst case scenario. His team ask themselves how resilient will the elements be in the specific year for both scenarios. The answers to those questions are provided by port operators and other port stakeholders during risk workshops performed for each project. If the outcome indicates that the port will not be resilient, the next phase for them is to identify with help from the port operators the measures that need to be implemented to ensure the level of resilience. Conclusively, they assess the risks through a risk workshop model rather than using and model simulation. The resilience is described in base of what the port operators thinks is acceptable and what risks they accept to take. Furthermore, within Matthew's practice of risk assessment, he explains that the categories he uses to quantify a risk are dependent of the client and the latter is asked to fill in the numbers that will define the thresholds for each category of risks (e.g. financial risk, environmental risk, reputation risk…).

2.3. In your opinion, what stakeholders or experts should be involved when assessing climate change impacts on ports? Does your opinion change for stakeholders involved in decision making process for climate change measures on ports?

Matthew and his colleagues normally ensure to have within the risk workshop a climate risk assessment team with about 2 or 3 people. They also make sure the participation of people from the client team like the head responsible for port development, a decision maker for port operations and 2 or 3 experts involved in operations. The team he suggests comprises several expertise which he believes are key to a successful risk assessment: development director, a head of port planning, harbor master and head of operations. However, he explains that in big global ports such as the Port of Rotterdam, one can find several types of terminals and different port services. Therefore, he finds important to include several of the different terminal operators to engage them in the process as they are able to detect whether a point of the whole process is vulnerable to the port. An example of the latter, there is no point for the Port of Rotterdam operators to have resilience covert if one of their main clients does not understand anything about climate risks and becomes vulnerability for the whole port. That is the reason why in very big and complicated ports is it very important to engage also the big clients (so the terminal operators) in the process.

Furthermore, Matthew explains that depending on the magnitude of the risk assessment and the project itself and what they can do, they would also suggest including somebody from the local authorities who is responsible for the house sewage system and the access roads into the port. Those interdependencies are really critical points so for instance how the port gets the cargo in and out together with basic facilities such as electricity. He explains that there is no point for the port to be 100% resilient to all weather effects of climate change. However, if the power station where the port gets all the power is not resilient and it stops functioning during one of these weather events then even if the port itself is resilient within infrastructure and operations, at the end it cannot operate because of the power shortage. Hence, the port is not resilient after all.

The port vulnerabilities are not only within its operations but most importantly are on what the port is dependent of. Matthew also assesses the later dependencies within his practice and has detected several critical points to which the port depends of. Those critical elements are: (1) power and the power station where the port gets it from; how it is transported into the port and if the medium is resilient to those weather events (cables underground or upper ground); (2) Data is as important as power nowadays as the information need to keep flowing in and out of the port. For instance, servers and telecommunications which are the channels where the port gets the weather information, how they transfer information around the port. If they servers and the bases within the state are not resilience the port has a problem even if the port itself is completely resilient. Matthew stresses that those vulnerabilities are important to detect when managing your business to identify where the critical risks to your business are. (3) Clean water and sewage are also very important within the port and seen from practice that are major points of vulnerability. The last one (4) are interconnection, roads, railway and inland waterways, if those are not resilient and cargo cannot come in or out of the port the port.

2.4. Who do you think is responsible for the payment of these measures: the port authority, the terminal companies, the government...?

Matthew is convinced that the answer to the question depends on the region, the country and the organization of the port. For instance, most of the ports in the UK are private businesses however in Morocco or Spain the port is publicly earned. In the latter case the responsible to pay is the government in one way or another, however within ports in the UK as are more privatized than other European countries the responsibility is all within the private sector. For instance, if the port operator or harbor authority does the investment it passes charges to the shipping companies and the terminal operators which at the same time charge larger quantities for their services and products. However, he stresses that in some cases if it is not build into the contract, the harbor authority cannot oblige the terminal operators to take care of adaptation strategies.

Conclusively, in some cases the harbor authorities can only strongly recommend adaptation measures and hence, getting the adaptation delivered can be a very tricky question.

2.5. What knowledge gaps do you experience within your practice of climate change impact assessment, your methodologies or software? Could you rank the aforementioned gaps from descendent order of relevance, urgency?

The biggest gap and challenge to really get a handle on this is the accuracy of the predictions. The latter are getting more precise but there is no way to know yet whether they are getting more accurate. However, they are also very focus on things that are easy to predict and model such as temperature, rainfall and sea level rise. He reasons that currently several coherent models exist that can predict the aforementioned three fields. Matthew explains that what is really very hard to model and has a very big impact on ports, airports and lots of other critical infrastructure is things like wind, lightening and fog. He uses the example as fog to explain that if there is dense fog in the port this has to close down. The models for the aforementioned variables are not great but because in his opinion is incredibly hard to model. Also, one does not know how climate change is affecting fog, lightening or wind, he stresses that there is very little knowledge about that. Furthermore, those variables appear in lower layers of the models which already present results with big bounds of uncertainty. For instance, he explains that if the peak wind speed threshold for port operations is 70 km/h the uncertainty width bands are from 0 to 200 km/h.

To Matthew's opinion, the hazards that become an issue to ports are sea level rise and temperature for operations, however the things that really have an impact cannot really be answered by experts right now. Some of the questions they get from port authorities are how many times in a year the port will have to close down due to fog in 2050 which Matthew stresses are impossible to know now.

Matthew's opinion about waves is that several model cover the field well, however like any model it has uncertainty. However, he agrees that modeling changes in wave period and direction should also be considered.

The second gap that Matthew points out is an expectation gap and goes back to the thresholds and the tolerance of risks. The tolerance for each port regarding the acceptance of certain risks is different. Not only the impacts of climate change will be different for each port but also the levels of tolerance to those changes might be difference. That is related to the nature of the port and what they do but also the capital and finance of the port, the incoming and out goings.

B.2.3. Flood Risk expert: *Ir. Matthijs Bos*

1. Knowledge on the vulnerability of port elements to climate change

1.1. What port elements, infrastructure or equipment that would be vulnerable to the impacts of climate change? For instance, quay walls, breakwaters, cranes, rail and road connections, inland waterways etc.

Matthijs suggests it is important to make a division between the operational aspects of the port and the vulnerable assets. His experience as flood risk expert has given him a good insight on the effects of sea level rise (SLR) and probabilities of inundation at a port. Climate change predictions on SLR come from the IPCC for international projects and from KNMI for project in the Netherlands. Hydraulic numerical or statistical models will be used to calculate the inundations levels.

He explains that within the Port of Rotterdam, there are areas that have a probability of flooding. These areas are mainly older parts of the port in the lowest elevation. For instance, he highlights the fact that warehouses are usually not as elaborated as other parts of the terminal where high capital assets are and in this port are more vulnerable to inundations. He suggests that normally the level of maintenance and protection are positively correlated to the capital of the renting company.

He concludes by saying that everything is vulnerable and that because ports can develop in time, the level of vulnerability within different areas of the port could differ.

1.2. In your opinion, which of the aforementioned elements need an urgent action against climate change impacts? Could you please rank them from the most to least urgent?

Matthijs believes that the owners of the port should be completely aware of the vulnerable areas and the exposure of their port. The most urgent element in Matthijs' opinion should be awareness on the responses of several port assets to the exposure of climate change hazards. Several measures can be done first such as changing the stacking way or heightening the warehouses ground level. He believes that protecting the first 1 meter is already quite effective.

1.3. Do your expectations change for questions 1.1 and 1.2 (vulnerable elements) when you think of specific port categories? (e.g. geographical location, exposed/non-exposed ports, lowlands/highlands, type of cargo). What categories do you relate to what topic (vulnerable element)?

Matthijs believes that in time the expectations and opinions about climate change will change. However, he also suggests that an important factor that determines how a country responds to for instance floods, is the culture of the country. The Netherlands is very well prepared for floods due to its history. As a country, they are used to raise awareness and plan for adaptation responses. However, in other areas such as USA, policy makers try to keep it as far as possible and let the private industry to take care of it. In Asia for instance,

they attempt to create awareness but they do not always have the funds or the policies in place to achieve resilience. Matthijs suggests that the vulnerability of elements depends on the region and the port itself. However, it is not only about having the capital to invest in measures but also about the ability to act on it politically. For instance, the Port of Rotterdam is not obliged by law to provide protection, it has no governmental safety standard for the port area because it is situated at an unembanked area. So, no one is instructing the port to protect their site owners. They do it, because they want to be the safest port in the world. The risks are within the users of the port.

1.4. For the elements mentioned in question 2.1 what would be the most relevant performance indicators, say 2 or 3 (that you use or plan to use), to further assess the impacts in the form of damage/costs? Example: %time per year the overtopping discharge over breakwaters exceeds a certain value.

Matthijs looks in his practice to water levels, (combination of high sea and river levels because of extreme discharge). He links that possible inundation levels to the economic value of the sites and assets to further build damage graphs that are related to the inundated depth to economic loses or costs. The idea for him is to end up with a risk graph that contains several probabilities of events that could happen and relates them to the economic damages per square meter at different sites of the port.

2. Practice: risk analysis and impact assessment

One of the goals of my additional thesis is to explore what is the state of the art software to assess and quantify climate change impacts in ports. The knowledge gaps identified so far (from Academia perspective) are the lack of methods to quantify the impacts and the risks and further translate the data into cost.

2.1. Do you agree with the later statement? What methods do you use to perform climate change impact assessments? What is the line of action you follow?

Matthijs believes that the availability of methods that quantify the impacts of climate change really depends on where you are in the world. He explains that if one has resources and some capital to invest in more research, one should be able to come up with a quantitative analysis of the impacts and could always say something sensible about it. He agrees that the first steps are normally rough and high level but as soon as one can gather enough data, they can narrow down and present more details.

Matthijs explains that within their analysis, he and his colleges first select several scenarios and then calculate the inundation level and generate the data to assess the exposure within the port. However, they also look at the economic benefits and then for different scenarios the increase of these. Further, they use all the information to calculate the cost benefit ratios after having performed a very thorough risk analysis for several probabilities of an event happening.

2.2. Do you make use of any software/model such as to quantify risks or damage in terms of cost?

His team does very thorough and detailed risk assessments on economic damage on what is being protected for clients with also detailed cost assessment.

His method consists on a simple but useful flow chart which relates land use, and flood maps where from different return period the inundation level is calculated. With the latter information, they can calculate the damage for each land spot.

He explains that he is not used to looking at the operations but more at the physical infrastructure.

He concludes saying that in general is more like a methodology that is used among experts. It is a multiplication of several aspects (algorithms): water depth times land use times damage

(as a factor for different return periods). All the costs are calculated in present net value to consider what is it available to spent on infrastructure to protect. The scenarios are normally for 2050 and they do not develop their own assumptions but they use well known projections like from IPPC on climate change and sea level rise.

2.3. In your opinion, what stakeholders or experts should be involved when assessing climate change impacts on ports? Does your opinion change for stakeholders involved in decision making process for climate change measures on ports?

The experts could be consultants, knowledge institutes but also Universities. He suggests that having someone that knows about indirect effects such as business disruptions is very valuable. He adds that involving owners and users (stakeholders) in the port is also important to build tailor made solutions. For instance, is not the same to assess risk for container terminals than a bulk or oil refinery.

2.4. Who do you think is responsible for the payment of these measures: the port authority, the terminal companies, the government...? Do you think it would differ per port?

Matthijs believe this is a joint responsibility between the port authority which is leasing and has contracts with the users and the users themselves; but at the same time there is no government act obliging the port to protect the sites. However, the clients know that forehand and therefore they are already considering the risks of choosing a port or another. Matthijs thinks that the clients of the port should be the ones responsible to pay for the measures and the port authority should be the one making sure that the basics are safe such as safe road access and resilient breakwaters. The terrain height, in Matthijs opinion, should in principal not be dealt by port authority but should be a responsibility for operators of the port. However, he suggests that once a site is not used anymore, the site should be made appropriate for the new client to come.

2.5. What knowledge gaps do you experience within your practice of climate change impact assessment, your methodologies or software? Could you rank the aforementioned gaps from descendent order of relevance, urgency?

Matthijs believes that awareness creation is very important. To find a way to get adaptation to climate change in their agenda is still hard. Because the ports have a lot of risks (fire, chemical hazards, oil spills) to care about before they think about climate change. One of the most common answers of the port users are that within the time they have in the port, they have better worries to fix instead of some projections for 2050.

Also, once people start investing and protecting against climate change they do not really get anything in return. Basically, he suggests that only once port users see that they are being threaten by climate change effects they start acting and planning on it.

Moreover, he thinks that it would be valuable to know where in the world ports are currently being affected by climate change and to find a way to trigger them to act on it and be open for the dialog to adapt to climate change. It is not about the general data available of climate change effects but it is the specifications to the location and make sure one is able to translate the message into their language. He was found in situations where the port users do not believe the information about the effects of climate change because of the super long periods of time.

3. Contacts

Would you recommend me any expert that would be willing to contribute with an interview to my thesis?

Prof. Jeroen Aerts and Associate professor Elco Koks expert in Business interruptions and indirect damages and her colleague Jarit de Visch for stakeholder engagement.

B.2.4. Expert in Modelling of the Economy-wide Consequences of Disasters & Supply Chain: *Dr. Ir. Elco Koks*

1. Knowledge on impacts of climate change on ports

1.1. How do you think climate change will affect supply chain? Could you give some examples?

For seaports, the main direct impact is SLR but is quite interesting to look at the climate change impact upstream and downstream the supply chain. For instance, droughts can cause reduction in goods for instance crops that directly depend on the climate. The latter might affect the companies of the port.

If extreme rainfall, wind or tropical storms increase in frequency but also in intensity, coastal and river flooding can have big impacts on ports. Elco believes specially rainfall might have a very big impact. For instance, in 2014 there was a big rainfall event at the port of Amsterdam and their drainage systems were not prepared for the event. As consequence, several small disruptions were caused that lasted for a few days.

1.2. From your experience, what other businesses, infrastructure are sensitive to climate change that will have indirect impacts on ports?

One main sector that will be of influence for port will be critical infrastructure. Access to enough cooling water for energy supply will be an issue. Reduction in energy supply will cause disruptions in ports. Therefore, is either more downstream on the supply chain (linkages), business that are dependent on goods coming but also on the other side which is quite interesting of ports is that they play major roles in the global supply chain. So everywhere that has a link to a disruption, the effects will go down or up to ports.

In Europe, Inland Waterways are crucial in the supply chain. These year droughts have been harmful to Waterways' water level which caused delays. The shipping companies are probably not insured for these kinds of disruptions.

Elco mentions that road or railway disruptions already can cause business disruptions in ports.

1.3. If you think about possible climate change related business or supply chain disruptions that affect ports; what section/element(s) do you believe need(s) most urgent action?

Mostly awareness and better understanding of the supply chain effects. Elco explains that three years ago several workshops (part of the adaptation program) were carried out at the Port of Rotterdam which included several clients. It was noticed that climate change was very low on their risk matrices which makes sense because the probability of SLR and flooding is very low. So it could be said that companies do not really plan for adaptation as they do not see climate change as a big hazard.

Another aspect which would require a better understanding on the climate change effects on supply chain before thinking about what kind of measures one can input. He suggests a cooperation between Academia and industry.

The best way to raise awareness would be if something happens. It worked in the Netherlands with the recent floods by Katherina and Sandy hurricanes. Insurance companies such as Lloyds are potentially interested in supply chain effects of climate change however it is not on their priority list. If we could rise the understanding maybe they would be more interested.

2. Quantification of climate change impacts on ports

2.1. Have you ever considered climate change economic impacts within your practice? If yes, how and related to what?

Elco mainly looks at coastal and river flooding but also surface flooding and the economic impacts of these. He also did some research on hale and wind extreme events and the economic consequences.

2.2. What models or techniques would be useful to quantify business supply chain disruptions due to climate change impacts?

Elco explains there are two main economic models. The macro-traditional economic models are more simplistic but very useful to understand input and outputs, also many produced global input and output tables to gain better understanding of global supply chain. They are all estimated by means of UN trade flows data base and some of the global tables are public and accessible (WIOD, EORA, EXIOBASE, UN COMTRADE, OECD TABLES, Asian Development Bank (ADB)). These tables would definitely help out to map out supply chain networks. The second type of models are more focused on finding a new type of economic equilibrium and get some new post-measure equilibrium.

For supply chain, he suggests looking at the field of Industrial Ecology where they do more the impacts of supply chain climate impacts. I have been told by Matthijs Bos (RHDHV) that you are also involved assessing climate change impacts on the Port of Rotterdam. I am aware they consider SLR and flooding as main hazards.

2.5. Could you explain me a bit what indirect impacts are you considering apart from SLR or flooding?

There is no other direct impact in ports considered apart from SLR, however he is involved in looking the wider economic impacts and supply chain disruptions due to flooding.

2.6. From your experience, how are ports in general preparing for climate change?

He acknowledges that is not sure whether ports in general are preparing for climate change. He mentions C40, a document related to global cities climate change initiatives. He does not think there is a lot within literature that is not related about SLR and increasing probabilities of flood events.

2.7. Are you aware of any current standards and regulations related to the practice of climate change adaptation? What would it take to raise awareness?

He is not aware of any climate change adaptation guidelines. There might be some building adaptation standards in the US at the main flooding areas but not port specific.

To raise awareness and understand better the supply chain effects of climate change, models and workshops within supply chain should be conducted also within the manufacturing sector. The chain of services comprises big companies that outsource to other companies and this chain is a bit hidden. For instance, an insurance sector can have 8th order of outsourcing and can happen in the manufacture field. The main interest would be finding the bottlenecks, the companies that are producing essential products that are essential to the global supply chain. The research such be focused on understanding qualitatively but also quantitatively. So, iterating between workshops and models.

2.8. Within your practice and research, what knowledge gaps could you identify that resolve around the topic of climate change impacts in ports?

A big question mark within literature is how business recover after a big flooding event in ports. Elco is looking at temporal aspects of flood impacts and how companies recover and how quickly they do it. He is very interested in finding ways to optimize the recovery time and process of businesses after a disaster or extreme event. Also, whether they can find substitution of their inputs and the final costumers if they cannot reach them. Whether they should make sure that further on the supply chain they have a final inventory so they can continue going as usual if a flood event has severe impacts further in the supply chain. He

is focusing in soft adaptation measures. There is a little bit of information within Germany about recovery after the earthquake and in Japan. It is important to understand the way business can recover before one can understand and focus on ways to "softly" adapt.

Another gap would be better understanding of the bottlenecks within the supply chain, what type of businesses and infrastructure can really have big impacts on ports due to extreme events such as flooding. Hence, find the essential parts within the supply chain to avoid massive impacts also in ports.

Interdependencies between industries and businesses with critical infrastructure and the wider economic impacts is also a current knowledge gap. For instance, how ports and the businesses settled in ports are dependent on Inland Waterways, roads and railway. Furthermore, ports as infrastructure require a lot of inputs such as electricity, cooling water and waste treatment. If these essentials are not met, the question is how will ports be affected and how that would relate to downtime or even closure.

3. Contacts

Would you recommend me any expert that would be willing to contribute with an interview to my thesis?

Marjolijn Haasnoot – expert in adaptive pathways

B.2.5. Leading Professional in Urban Flood & Water Resilience: *Ir. Nanco Dolman*

1. How do you consider climate change in your work?

Climate change is starting to become normal as discussion topic. Climate is changing and we can see that outside. However, it is not only climate change, but specially around cities, airports and ports, population is growing and people consume more and want to travel. The latter is also related to fast urbanization; there are currently more people living in cities than in rural areas. It is projected that by 2050, ¾ of the global population will be living in build environments. It is not only climate change, but the accelerated population growth and urbanization that are current interrelated challenges experts face on a daily basis. Airports and ports can be very easily adapted to climate change, but their operations (airlines, aircrafts, ships…) are more vulnerable to big changes in weather. Nanco's daily work involves all of climate change issues, but also very related to water challenges. Many cases of airports but also ports are built in flat and low-lying areas, even reclaimed locations. Therefore, droughts, floods, extreme rainfalls, sea level rise, all influence the challenges of making assets resilient. Currently, competition between airports is mainly based on being green. They can win/ gain certain certifications about being green, energy and water resilient (e.g. LEED and BREAAM). This matter triggers terminals to be sustainable and resilient, for instance with natural air flow - climate conditioning or rain water harvesting.

2. Have you done any project on quantification of climate change impacts?

For ports, quantification of impacts was based on water levels, sea level rise and extreme rainfall. Nanco Dolman has worked with the port of Rotterdam, Westpoort Amsterdam and some companies active in ports like New Orleans and Bangkok, which the latter was more about water coming from behind (the North) rather than the sea. Nanco is also an expert on airport climate change resilience. He is working on a thorough study for Schiphol airport were hazard spectrum is very broad with sea level rise, rainfall, temperature, wind and lightening. In the case of airports, there are some international flight association normative for flight safety. It considers all the mentioned variables and set thresholds beyond which safety is compromised.

3. Do you address risks in terms of damage curves?

Nanco's practice starts with a vulnerability analysis of the airport or port assets. Within the latter, different scenarios but also cascade effects are studied within infrastructure and operations. Cascade effects are important for operations, and hence, assessed by means of a series of software, methods such as CIrcle or bow tie. The latter is important to prioritize what systems and functions are most vulnerable and to illustrate the relation between systems and locations around airports and ports. The second step within the general assessment method is to perform a stakeholder analysis. The latter is about awareness, improve communications and forecasting and prevention measures when an event is coming. The last step refers to the ambitions of stakeholders. Because raising awareness (feeling of urgency) is very difficult and mostly to transmit the feeling of urgency, interviews are conducted to map interests, support and responsibility for different assets. It is done within the airport or port but also how stakeholders outside communicate and process information. In many cases, ports and airports are very much business driven hence, that is the focus for most of the people involved.

4. How do you perform stakeholder analysis? How do you raise awareness?

Nanco agrees that raising awareness/ support is much easier if something bad happens, specifically 99 percent of the cases people understand the urgency of preparing in advance. However, that should not be the case just to wait for a disaster to happen to start acting. Nanco suggests having an area within ports and airports only dedicated to emergency situations; well equipped, climate proof and able to keep functioning even if a disaster happens. An example from the latter is the port of Hamburg which has different elevations and some areas prepared for extreme situations of sea level rise, storm surge etc. He suggested several possibilities for the Netherlands (Schiphol, Rotterdam-The Hague) but also for New York after the experiences of hurricane Sandy. In New York, Nanco explains there is a very big company (interstate NYNJ Port Authority) that owns the airports and the port, but also other infrastructure. They suggested already to apply the "emergency airport/port plan" there. He explains the organization for the latter is Landlord based. The stakeholder analysis is not only meant for the challenges of ports and airports itself, but for the surrounding area, cities, people and communities. The stakeholder dialogue is meant to address a joined team above people's own goals. You mention in one of your papers that cities around the world are developing measures around climate change issues.

5. Which measures are cities developing and why is difficult to implement the measures?

Every city is affected in a certain way by climate change. There are currently 3 international agreements related to climate change: Paris agreement CO2, sustainable development goals (SDG), and Sendai Framework for Disaster Risk Reduction Prevention. Some cities are already developing as role model cities and several networks are currently part of campaigns accelerating example cities and best example is the 100 Resilient Cities network. The cities forming the networks believe in the idea of role model cities and they have and assignment to develop a resilient strategy. In many cases, that is just some sort of book as guidance but still far from implementation. According to the WEF (World Economic Forum, January 2018) extreme weather and climate change are among the top risks that can trigging a world's next financial crisis. Airports, as well as seaports and large industrial areas, have an important role to play because of their roles in the economic development of countries and their potential to take a lead. 'They have to understand that they are in a position to be ambassadors in making more climate resilient areas'.

6. Do you think any other hazard apart from water is potentially harmful?

Nanco believes earthquakes and tsunamis can be potentially dangerous. However, he does not know whether any other (besides water) extreme natural events can be related to climate change.

7. Do you think it is possible to generate or build a method, software that links hazards, to consequences of extreme events and to costs?

Nanco explains the latter is possible by means of a risk analysis. The four categories of protection levels that are considered are: design stage, extreme events and interconnection with different systems, historic events and the latter but least considered is mixture of several systems, compound extreme events in combination of several systems, networks. There are 4 type of risk analysis approach that Nanco as an expert uses:

1. Benchmark method: finding the optimum budget by relating investment cost for protection and cost (economic losses) per disaster event. One must monitorize the different risks per different hazards and then protection measures (investment) depending on the event, so the two curves can be summed to find the total optimum. Modelling economic losses for extreme events that have not happened yet is extremely difficult and data mostly need to be validated with port authorities.
2. Three-point approach: plotting a function for each hazard (rainfall, storm surge, flood, temperature, lightening, wind) with historic events that happened and their respective return periods. There can be 3 stages for events (on the y-axis, as dependent variable) and consequent loses: normal, moderate and extreme situation. These can be defined by means of expert judgement techniques.
3. Bow tie method: The approach takes its name from the shape of the diagram that is generated, which looks like a man's bowtie. A bowtie diagram mainly gives a visual (qualitative) summary of all plausible incident scenarios that could exist around a certain hazard; and secondly represents what are the possible measures to control those scenarios also post event.
4. Risk Matrix: method that explore the risk and rates them referring to a specific color code categories. Some important issues to consider are the setting of normative scenarios, the horizon (year) one is looking at, the levels of risk acceptance for the client and study recovery processes.

8. What knowledge gaps can you identify within your practice?

Lack of adaptation planning and conflicts between business support and stakeholder awareness. Lastly the lack on sense of urgency to adapt to climate change. Although one will act after a disaster strikes.

B.3. Stakeholder Engagement experts

B.3.1. Product Development Flood Resilience expert: *Ir. Micheline Hounjet*

About Circle

The Deltares webpage about CIrcle stresses that the increasing frequency and intensity of extreme climatic events is affecting critical infrastructure and society. One of the most affected fields is transport to which sea ports are identified most of the times as the major nodal points throughout supply chain (Ports and terminals book). It is also mentioned in the webpage that knowledge and experiences that have been collected with the CIrcle tool are stored in the CIrcle knowledge database.

1. What are the major inputs and outputs from CIrcle tool? How does it work in one or two sentences? (i.e. numerical inputs, CC scenario inputs, a near future question…)

The circle tool is meant to be as a workshop where to gather experts that will be able to give relevant information. Firstly, one formulates the questions to assess, then one thinks which experts will contribute the most, also selection of networks that could be affected or included

within the question to answer. The networks chosen to participate in the circle really depend on the area and what is present and valuable there. The idea is to collect information and data talking to the experts during the workshop and then to create the new CIrcle tool; including the networks that were relevant and participated. Then, cascade effects, indirect effects that are connected within the networks are plotted. For ports, the workshop starts by presenting a hazard which most of the times is floods or heavy precipitation. The consequences are drawn in a map of the area that is going to be analyzed. The questions start with who is affected by that hazard and how, up until which threshold (e.g. 25 cm of water). From the gathered consequences, one identifies who of the other networks would suffer if the flooded previously mentioned facility stops functioning. And there is where cascade effects start to be defined by experts. It is also asked to quantify the damages in terms of time (how much tie would you be without for instance electricity), and in terms of money, how much would it cost you to repair it. The major aim is to identify thresholds from the expert's experience.

2. What data is it used (e.g. climate change predictions from IPCC, a database of climate change predictions per region and port-specific information on assets)?

The data to construct the CIrcle is given by the experts during the workshop and the difficult task afterwards is to visualize what are the most relevant impacts that has been said and identified. As not everything can be used to visualize the impacts and the cascade effects. It is open data, only what the network owners feel comfortable to share, the information for the circle is stored within Deltares data base but it is not open for the public. Another option is to buy the private version and then you can start the database yourself (RHDHV is doing this now).

3. Does CIrcle work for the short term (5-10 years) or does the data belong to long term future scenarios (50-100 years)?

You don't need to identify a scenario as input. During the workshop the area is exposed to certain hazard (climate physical factor), firstly only to one, and then people start sharing their measures and the weak points. Then one can start asking about certain future scenarios and people will answer in relation to that.

As a drawback to this thesis, their workshops start suggesting only one hazard (climate physical factor) that affects the region and their networks. They basically let the people talk and only introduce other hazards if it is necessary to gather more information about cascade effects.

4. Are there already general conclusions from former case studies regarding climate change impacts (i.e. extreme weather events) on ports? If there is, which kind (impacts, vulnerabilities of port elements…), say briefly described in one or two sentences?

Experience from the CIrcle at the port of Rotterdam is that the worse hazard is the wind (heavy winds) that breaks down communication tools. Electronics of communication steer and monitor a lot of things and activities. There is a lack of knowledge on related cascade effects of failure in the communication system of a port. Missing communication is even more impactful than shortage of electricity, as everything in a port needs to be at the right moment (ships, VTS, cargo, rail and road entrances…). The ports are very sensitive to individual delays as they comprise several networks and very complicated supply chains with a lot of connections.

The CIrcle also investigates cascade effects within infrastructure web that includes the transport chain. (Ask for her confirmation to the latter statement). Cascade effects could also be seen as secondary or indirect effects of a major impact.

5. Could you give me any example of cascade effects that have consequences on ports?

She believes it really depends on the region and the network that are present nearby the port.

6. Are ports as entity or element included within any chain of cascade effects that already exists or is included in CIrcle database? If yes, to which?

Not included as an entity but some CIrcle workshops have been performed for instance at the port of Rotterdam.

7. Would CIrcle be a useful tool to forecast possible indirect or secondary effects of climate changes within trade, economy on ports?

Yes, depending on how open the experts are with their private information. It is always matters of how willing are the experts on telling their strategies and struggles.

Micheline explained that sometimes the experts that are participating in the workshop do not feel confident enough and feel scared to reveal their private information. Therefore from Micheline's opinion, is advantageous to explain the experts that the information will not be given to anyone and the effects of climate change on their networks are not their fault. The aim is to make all the experts in the workshop comfortable on telling their part in the story. To ask them what are the damages of different hazard and go step by step, connecting all the information of the different network's experts and making them realize they are actually helping each other.

8. Would CIrcle be adequate to model supply chains?

Yes but depending on the information experts share, with the same answer above.

Two of the main goals from Circle tool are to bring all stakeholders together and help them learn from their shared knowledge and experiences to help them make critical infrastructure more resilient. Ports are known for including multiple stakeholders from different sectors and for being a critical nodal point in the economy of the region.

9. Do you think that including say, Port of Rotterdam, in CIrcle as part of infrastructure web (of the region or if the region is already modelled) would be relevant for both CIrcle and the port in question? Could you give me one or two reasons?

Yes, to talk about different impacts and how some climate factors (heavy rainfall, heavy winds, SLR) could affect different networks and to identify the cascading effects by experts' experiences and knowledge. Moreover, CIrcle would be very useful to identify which is the network that one needs to protect the most in order to indirectly protect the others.

10. What stakeholders should be part of decision making process regarding impacts of climate change within port field? And therefore would be asked to participate in CIrcle workshop.

There should be a mix of experts from basically two categories:

1. Experts in crisis management, which in the Netherlands the unit is called "safety regions". They are responsible for the management of disasters and they know very well from experience the cascading effects.

2. Experts in the different networks that have relation to the port or the region where the port is. These experts will provide the information about the vulnerabilities of the different networks, such as thresholds at which the network is not working anymore.

Those networks are strictly dependent on the region that is being considered. She suggested the following: energy, electricity, drinking water, sewage water, railways, roads, inland waterways and communication. The last one, being the one with less knowledge but with the biggest and largest impacts to the other networks.

About impact assessment software

One of the goals of my additional thesis is to explore what is the state of the art software to assess and quantify climate change impacts in ports. The knowledge gaps identified so far (from Academia perspective) are the lack of methods to quantify the impacts and the risks and further translate the data into cost. That is the reason I have showed a sincere interest in CIrcle.

11. Considering this information, do you know of any other software, tools developed or still in development process that could be adequate for impact assessment? For instance, STAIN? Would STAIN have opportunities for application for a port climate change impact assessment?

The software STAIN is still in its development phase, however Micheline's team already tested it in a Dutch city and in Singapore. Micheline explained their aim of turning this tool available for ports. Within Royal Haskoning DHV, there is data stored from the port of Rotterdam about flood risk scenarios affecting the port.

Micheline explains that their aim is to generate a STAIN session for the Port of Rotterdam to identify what measures need to be taken to climate change hazards and what measures affect who. The idea is to see how different measures could influence the different networks and stakeholders. Also to make sure to open up a discussion to different type of measures, not only robust but also to explore the self-resilience and not only protection. They would like to see what strategies are considered for the entire area to reinforce each other goal and explore who benefits from whom.

The availability and practice of STAIN is currently only by means of a workshop (like CIrcle) to gather the information and further process it into a nice outcome for the client. Nevertheless, Micheline and her team are exploring the benefits and potential use of an online version of STAIN that would allow designing and testing the strategies in the area. This version would add extra value by showing the resilience of the area under certain hazards.

STAIN could be of use to present designs to other stakeholders to ask what measures they think influence the resilience and make them score and quantify the consequences.

12. And any software adequate for quantification of risks and impacts to further translate the data into damage in the form of costs? If there is none, do you think would be a relevant subject to be researched on from the point of view of Royal HaskoningDHV? And from the point of view of a port authority?

Micheline suggests the Ports of the future serious game developed partly by Tiedo Vellinga. However, she agreed that the game is more about exploring ideas and not quantifying which this research focus on. She also advised to contact the RHDHV expert Matthijs Bos as he performed impact assessments on the port of Rotterdam. Finally, she also suggests contacting Deltares for their risk tool SIAT which calculates risk by following a scenario and checking the occurrence and further calculating the economic loses.

B.3.2. Strategy & Management Consultant expert: *MSc Jarit van de Visch*

1. Could you explain to me your role in the Botlek pilot project for the Port of Rotterdam?

The Port of Rotterdam was interested not only in developing a climate change adaptation strategy but also in a way of raising awareness among the companies. The proposal from RHDHV consultants was to join all the experts together to ask them about flooding consequences in their facilities. Wind would be treated as part of the storm itself that cause the flooding. RHDHV team analyzed the flood hazards and showed them to the companies during a first workshop. The representative experts were asked what are the water levels (from flooding) to which their facilities are no longer in service (SLS) and completely damaged (ULS). The interesting about sharing hazards is that experts realized that many other mentioned also applied to them. With this simple acknowledgement, experts are more aware of

the consequences their assets can suffer in a flood. In the situation of Rotterdam, the Botlek area is main supplier for the entire region of Holland. Many of the port companies mentioned that with only 20 cm of water, the power outage would be ruined (as it is normally placed in the basement). If that happens to all the industries, the question becomes whether there is enough material to replace them all and whether interdependent companies in the region would also fail to produce. The main challenge to address was what to do when dealing with different risk appetites in a same area. Not only a level of risk tolerance is treated but many according each company assets. So, what point in time the risk is acceptable? The answer lies in using public laws such as inner dike safety and external safety in the Netherlands. During the second workshop, companies could comment on the results of the engineer risk assessment made with reference to pubic laws into the risks previously discussed with them in the first session. Companies became aware about what point in time the risk is no longer acceptable in a general governmental framework. The participants could identify their level of tolerance within the presented timeline.

The final workshop was about the type measures between levels of mitigation, adaptation (learning to live with water) and after disaster action. Experts had to explain what measures were the most cost-effective for an adaptation strategy. However, leaving the subject of responsibility aside and thinking as a collective. It was noticed that leaving the responsibility question aside, experts become truly engaged and do not see the session as a negotiation. The consequences are that they feel comfortable to open up and share experiences, knowledge and own practical strategies. After some discussion, the team managed to reach an adaptation strategy that had the largest benefit for all the companies.

The pilot project went on for around one year and a half, however they had to create the risk assessment method from scratch. After their second project, these kinds of projects are meant to take in between six months and one year. The most complicated part of the project was to generate the functions that relate risk with serviceability limit state and then relate the risk to adaptation strategies on time. Conclusively, for the project to be successful one should leave the (economic) responsibility question apart and focus on collective risks and measures that benefit everyone. Because if the workshop becomes a negotiation, the experience shows that companies shut down and focus only on their own benefits.

2. This new Risk based approach has only been used within the Netherlands so far. Do you think would be possible to adapt the general framework for other countries?

The general way of working can fit into any other country, however the norm on which is based is only a common language for the Netherlands. For instance, in the Netherlands there is no possibility to insure assets to flooding, therefore the safety measures and levels are higher than in other countries. On the contrary, the UK enables the companies to insure their assets to floods so the measure and safety standards within the companies are much lower. The key is on finding the region's common language in terms of risks. This practice is very possible to insert in any country around the world. The importance is on showing the hazards hey are exposed to. It is not enough to create a map and give it to the workshop participants but the discussion helps to raise awareness. The participants do not understand flood engineer language, it is easier for them to visualize the facts and see images of what can happen instead of reading complicated graphs. The whole process can be explained as stakeholder dialogue, essential to create awareness and commitment.

3. Do you know if international ports also apply risk based approaches?

From a consultant perspective, international ports do not ask for flood risk assessments yet. Even if port operators are not yet very interested in knowing the hazards, the multinationals that have assets on the ports are aware of the hazards and interested in risks and adaptation measures. One should be able to explain port authorities that mapping flood hazards do not make the port vulnerable against public opinion. However, caring for these aspects shows a high level of commitment and awareness that companies appreciate and trust.

C

State of the Art Methodologies

C.1. The Committee on Approaches to Climate Change Adaptation from November of 2010 [35]

Background: The methodology in this subsection was presented as a national guideline document to raise awareness of the need to adaptation to climate change valid for multiple sectors in Japan. This report is aimed at national and local government departments responsible for adaptation to climate change.

Methodology: This methodology differentiates two possible approaches to adaptation considering whether the first time that such analysis is conducted and whether information on regional climate change information is available. The report stresses the importance of managing activities with an awareness of the uncertainty of risk that arises with the different time scales. The Committee considers as times scales (1) short term: 0-10 years, (2) medium term: 10-30 years and (3) long term: 30-100 years. The two aforementioned approaches are the followings:

1.The basic approach (Officially named as "Track A") suggests a 5-step method which should always be considered at some point within the process of assessing climate change consequences. The first two steps are related to the stage of assessing climate change impacts which fall within the scope of this thesis. The rest of steps present a link between the identification of the impacts and the adaptive measures to be considered and further implemented.

2.The second approach (Officially named as "Track B") is presented as a detailed methodology that aims to facilitate initial efforts for adaptation strategies by means of using updated and available regional information. The relevant information to impact assessment strategies are the steps 1,2,3 and 4 together with step 10 which is more general.

C.2. Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies – UNEP & VU (October 1998) [43]

Background: The United Nations Environment Programme (UNEP) developed the "Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies" as part of UNEP's contribution to the guidelines and handbooks for Climate Change Country Studies.

Methodology: Chapter 4 of the Handbook addresses the integrated impact assessment of climate change. The suggested approach, called Integrated Assessment (IA), considers the interactions between the diversity of impacts of climate change and identifies which of these effects belong to the other changes context. The aim of an Integrated Assessment is to enable the identification of climate change impacts in a broader context (e.g. natural resource management, sustainability of ecosystems…). The latter would be applicable to the port sector due to its large variate assets (e.g water areas, hinterland connections, terminal infrastructure …) and its regional socio-economic dependence.

The first step consist of a thoughtful analysis of the system (the target port) answering questions such as: "What are the components? What are the links? What are the issues?" Provided the aforementioned information, the integrated analysis can be performed in numerous ways within two extremes: from soft-linking to integrated modelling. Integrated models describe the entire system in one complex and robust code however; soft-linking methods give the possibility to include other than computer models which can be done by linking expert judgments in an expert panel. The step in between would be to use Hard linking models which every model could run in as stand-alone version but would be included in a single code.

The drawback of the aforementioned approach is the lack of practical examples on which software/models are adequate for the IA. The report seems to be presenting only the theoretical guidelines to perform the climate change impact assessment.

C.3. CLIMATE CHANGE IMPACT ASSESSMENT, ACT Government from November of 2011

[25]

Background: The aim of this paper is to provide the framework to address the Government's commitment to perform climate change impact assessments as stated in the 2008 Parliamentary Agreement for the 7th Legislative Assembly for the ACT.

Methodology The proposed impact assessment begins with identifying areas with interactions and inter-dependencies on climate change impact and adaptation. The paper provides (in Attachment 3) a list of climate change scenarios and relevant areas of impact and adaptation response. Furthermore, the report includes a set of questions to guide the impact assessment and also to those responsible of performing the assessment.

PART A: Overall Climate Implications Assessment

What is the overall assessment of climate change implications for the proposal?

a) What is the overall assessment of climate change implications related to the proposal – both positive and negative?

b) Is the nature of the implications that: [may be both] • the proposal's intent/outcomes or risks are impacted by climate change implications?

• other climate change policies,strategies,plans,programs or risks are impacted by the proposal?

• would a modified version of the project make an additional contribution to achieving other Government environmental policies, such as Weathering the Change?

c) How has the proposal addressed the implications? • To what extent have the most significant negative implications been able to be addressed in the proposal, and to what extent are there significant residual implications?

• Are there additional options to further improve either positive or residual negative implications? (Include also possible interventions that could be mainstreamed into other relevant

policies,strategies, plans).
• Have the implications and options been discussed with other relevant agencies/stakeholders, and the feedback taken into account?
• Where there are significant residual negative implications what is the essential trade-off involved and the basis for recommending that the proposal proceed notwithstanding the climate change implications?

d) Does the proposal provide a basis for enhancing the ACT's underlying capability and capacity to respond to climate change through relevant knowledge development (e.g. research, education, and communication), monitoring and evaluation of outcomes, and/or development of relevant government/community partnerships?

PART B: Mitigation Assessment

Are there implications for climate change mitigation?

a) What aspects of the proposal might have greenhouse gas emission implications? For example, will the proposal depend on more or less fossil fuel usage or about the same?

b) What is the estimated impact on the level of 'direct' greenhouse gas emissions in tonnes CO2-e as accounted for under the ACT GHG Inventory?

c) What greenhouse gas emissions offsets have been proposed to reduce the impacts of the proposal; and have they been subject to cost/benefit analysis?

PART C: Impacts and Adaptation Assessment

How does the proposal take account of expected climate change implications? Broadly climate change in the ACT is expected to manifest as more extreme weather events more often, hotter drier summers and longer periods of drought and shifts in rainfall patterns such as drier autumns and wetter springs.

Does the proposal have implications for the ability of the ACT to adapt to changing climate including managing the associated risks and opportunities?

On the basis of a climate trends (see Attachment 3) are there significant (positive or negative) implications for:

a) Current and potential climate change impacts? b) Adaptive capacities/resilience of those communities most impacted? c) The most vulnerable human communities? d) Current and proposed/potential adaptation policies, strategies and other responses?

Considering these climate change implications, and the intrinsic uncertainties in climate projections, what are the characteristics of the decision sought?

a) What level of uncertainty is associated with the implications? b) On what time scale (short/medium/long) are the implications likely to manifest themselves? c) Is there a monitoring/evaluation strategy to facilitate adaptive management? d) Is the proposal readily reversible or flexible if the implications turn out to be unacceptable?

C.4. Climate Change impact assessment and adaptation strategies for sustainable development of societies – RMSI consultant [18]

Background: RMSI is a technical consultant specialist in assessing climate change impacts to developing countries. Their service includes the local and regional development of climate scenarios by means of downscaling techniques, sector-specific vulnerability and risk assessment and cost effective adaptation measures.

Methodology:
The method is designed for experts in the field of climatology and meteorology to assess the impact on key sectors such as water and agriculture and analyze the effects on people and livelihoods. Their approach is based on several steps public in their website and four of them gather some general guidelines (or steps) would work when applied to assess climate change impacts.

1. Climate change scenario development
2. Downscaling of global models to regional and local levels
3. Assessment of impact of climate variability on hydro-metrological hazards
4. Analysis of impacts of climate variability and change on communities

C.4.1. Escalating impacts of climate extremes on critical infrastructures in Europe – Forzieria et al. (November 2017)[24]

Background: The paper aims to provide a comprehensive multi-hazard risk assessment of critical infrastructures in Europe under the effects of climate change and to identify the most affected regions. The model considers climate-related disaster records together with a set of high-resolution projections of climate hazard. It aims to provide a detailed representation of sectorial physical assets but also to include a vulnerability analysis to the hazards.

Methodology: The following figure C.1 shows in good detail the framework suggested by Forzieria et al.

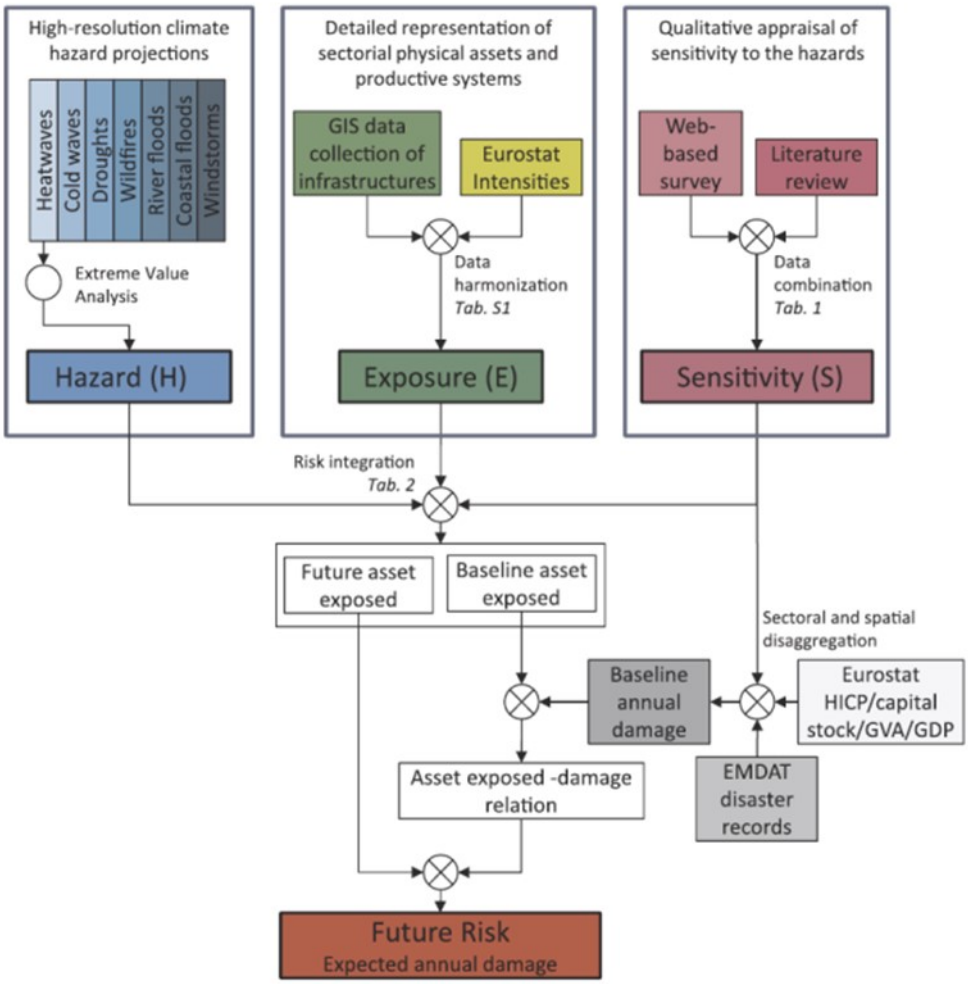


Figure C.1: Climate change impact assessment methodolgy suggested in Escalating impacts of climate extremes on critical infrastructures in Europe.

C.5. Conducting an impact assessment – Climate Change in Australia: Projection for Australian NRM regions [3]

Background: The technical report on "Projection for Australia NRM regions" aims to outline the fundamental climate change projections for Australia across a range of variables. The report presents all information found in other products, including this website. The interest on this report within the research lies in chapter 9 which focuses on how to make use of climate change data in impact assessment and adaptation planning.

Methodology: This source identifies an impact assessment as a risk assessment. They establish the goal to identify the risks under climate variability before considering any measure. The source stresses that any methodology requires input of climatology information such as climate change projections to be able to conduct a successful climate change risk assessment. The approach consists of the following general steps:

1. Establishment of the context of the impact assessment by defining the scope, the stakeholders (and their concerns), and other issues or required decisions

2. Identification of the known risks associated with current climate variability

3. Risk analysis

4. Planning horizons

5. Data sources such as climate change projection data which are usually climate models outputs driven by various scenarios of greenhouse gas and aerosol emissions

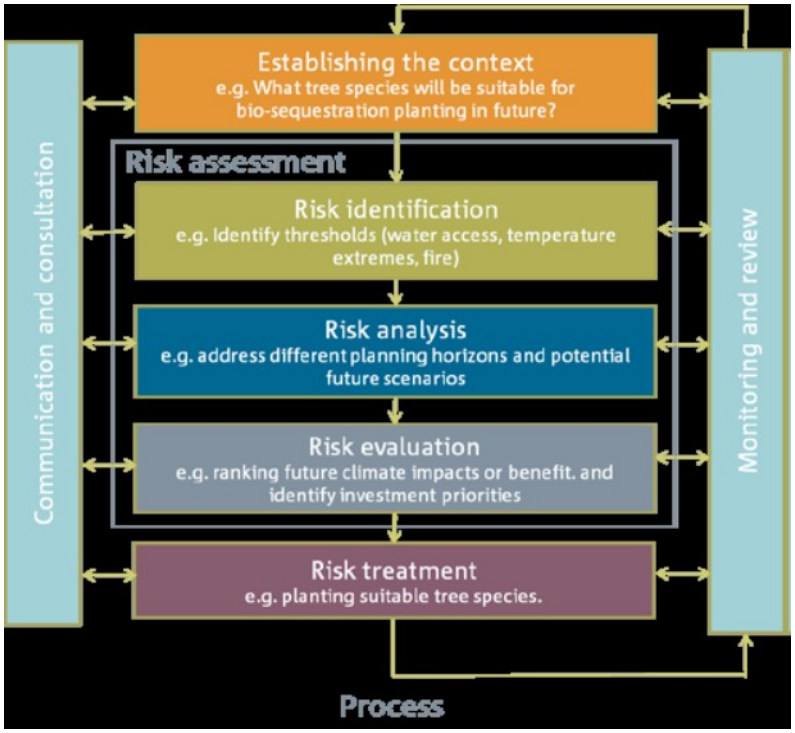


Figure C.2: Climate change impact assessment methodology suggested in Climate Change in Australia: Projection for Australian NRM regions

C.6. Development of Climate Resilient Ports – MSc. Thesis Erwanda S. Nugroho [33]

Background: Erwanda's explored during her five moths MSc thesis a mechanism for achieving viable and efficient investments in building climate resilient ports. The research is addressed to port practitioners who will need to adapt their ports to climate change so they can maintain their ports operational and sustainable.

Methodology:

Erwanda suggests as methodology an impact assessment matrix (see figure C.3) aiming to identify the following: (1) the significant climate risks and opportunities for a particular terminal and (2) the assets susceptible to the risks and hence require sufficient climate adaptation.

Chapter 3 – Assessment of Climate Risks and Opportunities for Container Terminals

Climate Risks and Opportunities Assessment Matrix for Container Terminals

Name of Assessed Terminal Terminal A

No	Weather Event and Impact of Climate Change	Main Type of Risk/Opp. for Terminal*	Main Sub-operation Affected	Relevant Asset(s)	Range/Threshold of Relevant Weather Variables		Risks and Opportunities	Risk for Terminal Assets/Operations?		Expected Impact**	Other Sub-operations Affected	Relevant Secondary or Compound Effects		Expected Impact**	Source
					Variable	Range/Threshold		Assets	Operations			Risk/Opp. Type*	Risks and Opportunities		
1	Impacts of climate change on the economies of the terminal's main trading countries	FIN	All	None	N/A	N/A	• Lower terminal demand/call due to (1) reduction in the production of main export commodities in the regions served by the terminal, such that the export volumes of the regions are lessened and/or (2) increase in the production of main import commodities in the main trading countries, such that their demands for import are reduced. • Higher terminal demand/call due to (1) increase in the production of main export commodities in the regions served by the terminal, such that the export volumes of the regions are enhanced and/or (2) reduction in the production of main import commodities in the main trading countries, such that their demands for import are enhanced.	-	√	L	All	None	None	N/A	Connell et al. (2015), Stenek et al. (2011), USCCSP (2008)
2	High salinity of seawater	ENV	None	Aquatic vegetations and species	ΔSeawater salinity	> 0 ppm	• Reduction in the habitability of the vegetations and species due to salt stress.	√	-	L	None	FIN	• Higher expenditure for compensating the loss of the vegetations and species. • Higher premium to insure the vegetations and species.	N/A	Connell et al. (2015), Stenek et al. (2011)

Figure C.3: Climate change risk assessment methodology suggested in Development of Climate Resilient Ports – MSc. Thesis Erwanda S. Nugroho

The potential impacts of climate change and extreme weather events are categorized as follows: (1) operational, (2) financial, (3) environmental and (4) social risks and opportunities for the terminal. As a plus, the known thresholds of weather variables (such as wind, wave heights…) are included for the climate change impacts. The impacts are separated to identify more easily which impacts are directly caused by adverse weather events and climate change (i.e. primary impacts) and which ones are the consequences of occurrence of the primary impacts (i.e. secondary impacts).

C.7. IPPC Report 2007 [36]: Chapter 6, National Systems for Managing the Risks from Climate Extremes and Disasters

Background: The aim of Chapter 6 from the IPPC report is to assess national management of current and projected disaster risks and ability to assess vulnerability and exposure to the known climate change impacts. The focus is on the design of national systems for managing such risks and the roles and functions of all participants involved in the system.

Methodology: The IPPC report suggests several options which range from climate vulnerability or resilience approaches referred to 'bottom-up' (i.e. vulnerability, tipping point,

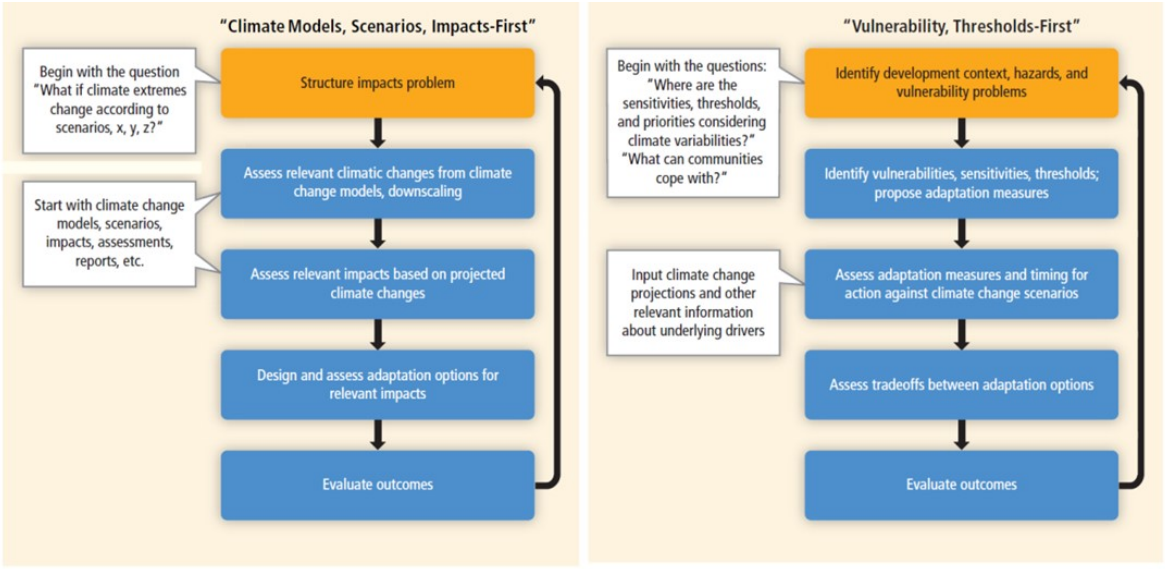


Figure 6-2 | Top-down scenario, impacts-first approach (left panel) and bottom-up vulnerability, thresholds-first approach (right panel) – comparison of stages involved in identifying and evaluating adaptation options under changing climate conditions. Adapted from Kwadijk et al. (2010) and Ranger et al. (2010).

Figure C.4: Climate change assessment methodology suggested in IPPC Report 2007: Chapter 6, National Systems for Managing the Risks from Climate Extremes and Disasters

critical threshold, or policy-first approaches) to climate modeling or impact-based methodologies also named 'top-down' (i.e. model or impacts-first, science-first or classical approaches).

On the one hand, vulnerability assessments can be performed independently of any set future climate change condition. This kind of approaches start by considering stakeholders and decision makers to identify the resilience and robustness a system is to changes in climate under future climate change scenarios.

On the other hand, scenarios-impact-first assessments usually start with several climate change modeling and socioeconomic scenarios. Their focus is on evaluating the impacts and identifying the potential adaptation measures. The aim of such approach is to raise awareness of the problem.

The steps for both approaches are shown in the figure below C.4:

C.8. Exploring Potential Climate Change Impacts and Adaptation Strategies for Seaport Operability– JUDITH K. MOL [28]

Background: The aim of the study is to provide a conceptual framework for quantifying risks for port operability and to explore strategies for adaptation. The paper was presented at the PIANC Panama conference and is based on the MSc Thesis from Judith K. Mol.

Methodology:
The methodology presented in the paper suggests a combination of the theoretical top-down and bottom-up approach of IPCC (See method 8). The starting level includes an analysis of the vulnerable port assets and climate change related variable thresholds are identified according to the bottom-up approach. Step 2 focuses on assessing climate change impacts by means of downscaling in line with to the top-down approach until local scale impacts are identified. Further quantification of the risks and eventual exploration of adaptation options is following as final steps. The framework can be shown graphically as C.5:

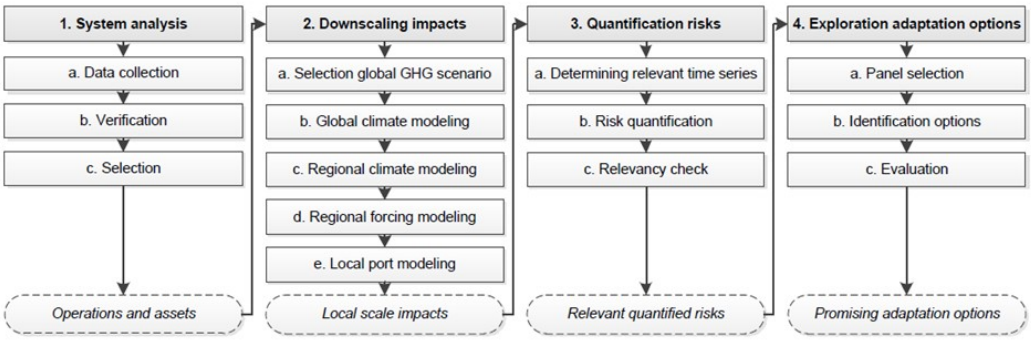


Figure C.5: Climate change risk assessment methodology suggested in Exploring Potential Climate Change Impacts and Adaptation Strategies for Seaport Operability – JUDITH K. MOL

Bibliography

[1] Brigaid european project. *https://brigaid.eu/*.

[2] Rain european project. *http://rain-project.eu/about/*.

[3] Chapter 9. Exploring potential climate change impacts and adaptation strategies for seaport operability. *Projection for Australia NRM regions*, 2007.

[4] UK's leading ports group ABP KEEP BRITAIN TRADING. Climate change adaptation report. *2016 Update*, 2016.

[5] World Economic Forum & Accenture. Industry agenda: Building resilience in supply chains. *https://www.forbes.com/sites/steveculp/2013/02/15/supply-chain-disruption-a-major-threat-to-business/66e94773b659*, 2013.

[6] Dr. Monica Altamirano. Handling disruptions in supply chains: An integrated framework and an agent-based model. *ter verkrijging van de graad van doctor aan de Technische Universiteit Delft*, 2013.

[7] MSc Thesis Pham Lan Anh. Impacts of waves and sea level rise on ports due to global climate changes - viet nam sea ports case study. *Delft University of Technology*, 2012.

[8] H. Carvalho A.P. Barroso, V.H. Machado and V. Cruz Machado. Quantifying the supply chain resilience. *Applications of Contemporary Management Approaches in Supply Chains, Chapter 2*, 2014. doi: http://dx.doi.org/10.5772/59580.

[9] Mohos-Naray. V Asatoris. R, Benamara . H. Port industry survey on climate change impacts and adaptation. *UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT*, UNCTAD Research Paper No.18, 2017. doi: UNCTAD/SER.RP/2017/18.

[10] The World Bank. The economics of adaptation to climate change (eacc) synthesis report. 2010.

[11] Inoue S. Becker, A. and B. Schwegler. Considering climate change: A survey of global seaport administrators. *Stanford University*, 2011.

[12] Hodges K. I. Bengtsson, L. and E. Roeckner. Storm tracks and climate change. *Journal of Climate Change*, 2006.

[13] R. J. Swart T. R. Carter C. Cowan T. Henrichs H. Mela-M. D. Morecroft D. Rey Biesbroek, G.R. Europe adapts to climate change: Comparing national adaptation strategies. *Global Environmental Change*, 2010.

[14] J. P. Sierra M. Casas-Prat. Analysis of potential impacts on coastal areas due to changes in wave conditions. *Climatic Change 124*, 2014. doi: 10.1007/s10584-014-1120-5.

[15] CCOHS. https://www.ccohs.ca/oshanswers/hsprograms/hazard$_r$*isk.html*.2018.

[16] PIANC: EnviCom Task Group 3 Climate Change and Navigation. Waterborne transport, ports and waterways: A review of climate change drivers,impacts, responses and mitigation. *IPCC SR1.5*.

[17] Susan Hanson · Robert Nicholls · N. Ranger · S. Hallegatte · J. Corfee-Morlot · C. Herweijer · J. Chateau. A global ranking of port cities with high exposure to climate extremes. *Climatic Change (2011)*, 104, 2011. doi: 10.1007/s10584-010-9977-4.

[18] RMSI consultants. Climate change impact assessment and adaptation strategies for sustainable development of societies. *https://www.rmsi.com/solutions/government-funding-agencies/climate-change/*, 2018.

[19] OXFORD DICTIONARIES. https://en.oxforddictionaries.com/definition/impact. 2018.

[20] Oswaldo Morales-Nápoles Bas Jonkman Dominik Paprotny, Michalis Vousdoukas and Luc Feyen. Compound flood potential in europe. 20.

[21] Wbcsd Climate Change & Energy. Building resilience in global supply chains. *http://wbcsdpublications.org/wp-content/uploads/2015/12/building-resilience-in-global-supply-chains.pdf*.

[22] A.R.M. Wolfert G. Leontaris, O. Morales-Nápoles. Planning cable installation activities for offshore wind farms including risk of supply delays. *ESREL conference*, 2016.

[23] A.R.M (Rogier) Wolfert Georgios Leontaris, Oswaldo Morales-Nápoles. Probabilistic scheduling of offshore operations using copula based environmental time series - an application for cable installation management for offshore wind farms -. *Ocean Engineering Journal*, 2016.

[24] Filipe Batista e Silvac Mario A. Marin Herrerad Antoine Lebloise-Carlo Lavallec Jeroen C.J.H. Aertsf Luc Feyenh Giovanni Forzieri, Alessandra Bianchi. Escalating impacts of climate extremes on critical infrastructures in europe. *Global Environmental Change*, 2018.

[25] ACT Government. Climate change impact assessment - discussion paper. *Triple Bottom Line Assessment for the ACT Government*, November 2011.

[26] Kwakkel J. H. Walker W. E. Haasnoot, M. and J. ter Maat. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environ. Change*, 23(2), 2013. doi: https://doi.org/10.1016/j.gloenvcha.2012.12.006.

[27] ICF International. Planning for climate change impacts at u.s. ports - white paper. *U.S. Environmental Protection Agency*, July 2008.

[28] Tiedo Vellinga2 Jill H. Slinger Victor Beumer Judith K. Mol, Wiebe P. de Boer. Using climate change data in impact assessment and adaptation planning. *PIANC-World Congress Panama City, Panama 2018*, 2018.

[29] Environmental Management Marc Eisma. Climate change adaptation in the port of rotterdam. *http://edepot.wur.nl/381429*.

[30] P. Wright MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP. Impacts of climate change on ports and shipping. *MCCIP Science Review*, pages 263–270, 2013. doi: 10.14465/2013.arc28.263-270.

[31] DeWitt W. Keebler J.S. Min S. Nix N.W. Smith C.D. Mentzer, J.T. and Z.G. Zacharia. Defining supply chain management. *Journal of Business Logistics*, 22, 2001.

[32] NASA. https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-climate-change-k4.html. 2018.

[33] Erwanda S. Nugroho. Development of climate resilient ports achieving viable and efficient investments in landlord container terminals. *Delft University of Technology*, 2016.

[34] Port of Rotterdam-Botlek pilot project. https://www.portofrotterdam.com/en/our-port/our-themes/a-safe-port/water-safety.

[35] The Committee on Approaches to Climate Change Adaptation. Approaches to climate change adaptation. 2010.

[36] IPCC Organization. Ipcc fourth assessment report: Climate change - ar4. *http://www.ipcc.ch/*, 2007.

[37] Michael Taylor (Jamaica) Ove Hoegh-Guldberg (Australia), Daniela Jacob (Germany). Chapter 3: Impacts of 1.5°c global warming on natural and human systems. *IPCC SR1.5*, 2018.

[38] Turkey A. Ravi Ravindran Penn State University-USA Ragip Ufuk Bilsel, The Boston Consulting Group. Modeling disruption risk in supply chain risk management. *International Journal of Operations Research and Information Systems*, 2012.

[39] Louis L.H.J. Goossens Roger M. Cooke. Tu delft expert judgment data base. *Reliability Engineering and System Safety*, 93, 2008.

[40] E. Rusu and C. Guedes Soares. Wave modelling at the entrance of ports. *Ocean Engineering*, 2011.

[41] Kash Barker Seyedmohsen Hosseini. Modeling infrastructure resilience using bayesian networks: A case study of inland waterway ports. *Computers Industrial Engineering*, 93, 2016.

[42] Dr. Poonam Taneja. The flexible port. *ter verkrijging van de graad van doctor aan de Technische Universiteit Delft*, 2013. doi: doi:10.4233/uuid:a9f0c128-d4c3-41a2-8790-13aec89dca63.

[43] Jan F. Feenstra Ian Burton Joel B. Smith Richard S.J. Tol. Handbook on methods for climate change impact assessment and adaptation strategies. *United Nations Environment Programme & Institute for Environmental Studies*, 1998.

[44] UNITED NATIONS CONFERENCE ON TRADE and DEVELOPMENT. Ad hoc expert meeting on climate change impacts and adaptation: A challenge for global ports. *Information note by the UNCTAD secretariat*, 2011.

[45] wbcsd Climate Change & Energy. Building resilience in global supply chains. *http://wbcsdpublications.org/wp-content/uploads/2015/12/building-resilience-in-global-supply-chains.pdf*.