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Strategic Modeling of Global Container Transport Networks

Exploring the future of port-hinterland and maritime container transport networks

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Strategic Modelling of Global Container Transport Networks

Exploring the future of Port-hinterland and Maritime container transport networks

Proefschrift

ter verkrijging van de graad van doctor

aan de Technische Universiteit Delft,

op gezag van de Rector Magnificus Prof. ir. K.C.A.M. Luyben,

voorzitter van het College voor Promoties,

in het openbaar te verdedigen op maandag 13 maart 2017 om 10 uur

door

Ronald Apriliyanto HALIM

Master of Science in Systems Engineering, Policy Analysis and Management

born in Surakarta, Indonesia

to
my Lord and Saviour, Jesus Christ,
dad, mom, Erwin,
and Indonesia.

Preface

Every dissertation has a story, not just the one that is formally and systematically laid out within the dissertation itself but also that which reflects the story of its author. This dissertation is an embodiment of the response that I have made towards the calling I received in 2011. A young man who was born and raised in Indonesia received a call to contribute to the development of his beloved country. He decided to embark on a journey to pursue his calling which required him to leave his family and friends for an extended period of time.

When I saw a PhD vacancy on the TU Delft website about modeling the global freight logistics system, I was mesmerized and strangely brought to a a time of reflection. The inner voice in me said: "This is the time for me to contribute to Indonesia, to do my part to help social justice be administered in the country, and this is the research project that would enable me to do that". At that time, I had little knowledge on the research topic, on my promotor-to-be (Lori), and I did not have a clear idea how I could contribute to Indonesia concretely.

Two and half years into my research period, I met Mrs. Elly Sinaga who was the head of the research and development department of the Indonesian ministry of transport (MoT). I believe this was God's work in leading her to come to TU Delft. Not long after that, a memorandum of understanding (MoU) for a joint research program between TU Delft and MoT was established. Because of this MoU, I was able to conduct my research for Indonesia of which the results constitute chapter 5 of this thesis. I sincerely thank Mrs. Sinaga and MoT for supporting and facilitating my work with MoT. I hope that the research done in this thesis could open more possibilities for other researchers to contribute to the Indonesian logistics systems. I believe our freight logistics system is an important instrument to help reduce the gap between the poor and the rich in Indonesia.

Along the journey of this PhD research I have received so many helping hands for which I am genuinely grateful. I would like to express my sincere gratitude to Lori as my

promotor who supervised, trained, advised, and worked along with me throughout my PhD. Lori, I deeply appreciate all the valuable lessons you taught me, all the knowledge and help you have given, your valuable ideas and contributions for my thesis, and most importantly your support, and understanding that went beyond your formal responsibility as my promotor. It has helped me to survive difficult and unexpected circumstances throughout my PhD journey.

I would like to also thank my daily supervisor Jan Kwakkel, without whom this thesis would not able to realize the ambitious scope of the project. Jan, I enjoyed every moment we worked together. Thank you for your generosity, patience, and countless contributions to my thesis. Your bright ideas and technical assistances have definitely strengthened and enriched the work of this thesis substantially. Thank you for, particularly, introducing me to exploratory modeling and analysis, and the scenario discovery approach. They are valuable research methods which will be useful for my future work.

I would like to acknowledge the Port Authority of Rotterdam for funding my PhD research. Special thanks to Frank as my port supervisor who has been very supportive and patient in supervising my research project, and also to Karin who gave useful feedbacks and contributed in valuable discussions throughout my project. The time I spent at the Port was always pleasant and stimulating.

I would like to express my appreciation to my committee members who have helped me to improve the quality of my thesis further: Alexander who helped me to improve the clarity of the thesis and who reminded me on the importance of a good documentation; Prof. Zuidwijk who helped me to sharpen the positioning of this thesis; Prof. de Jong who kindly suggested many valuable editorial improvements in this thesis.

I would also like to thank my colleagues in the transport and logistics group of TPM whose companies have made my long journey more enjoyable: Karimah, Yashar, Nilesh, Igor, Mo, Zack, Chao, Nicole, Ozgul, Nick, Sander, Maarten, Diana and Sander. Thank you for all the moments that we shared together, the stimulating, and stress-relieving discussions, and nice lunches at TPM canteen. I sincerely wish you all success in your career.

To my colleagues from other sections: Sriram, thank you for your hospitality, advice, and friendship throughout my stay at the big room. I sincerely hope you will also successfully finish your thesis soon; Cherelle: thank you for your support and friendship throughout my stay at TU Delft; Prad, Binod, Joao, Jorge, Ben, Andrew, and Zoë Robbë: thank you for your companionship and countless little help; and to many other colleagues at TU Delft who I cannot mention individually.

To my friends from church: Valerie, Verra, Johan, Gerrit, Christiaan, Marije, Jeremy, Taylor, Matthijs, Rasheeda, Samuel, and the Redeemer's student life group, I am very blessed to have met you all and I can say that the Netherlands felt like my second home only because of your friendship.

To my friends with whom I also shared my daily life in Delft: Karina, Maralus, Muryani -who also designed the cover of this thesis, Richard, Ronald A. Indra, Ramanda, Kukuh, and Yang Sun. To My friends from UPH who have supported me through their prayers: Adithia, Rahmadi, Velli, Michelle and the rest of covenant generation.

To my family: My dad, mom, and Erwin, thank you for your unconditional love, prayers, and support throughout my time away from home. You are the reason that enabled

me to contribute to our country. Words are not enough to describe how grateful I am to you and I dedicate this thesis to you. To Anna: you are definitely one of the greatest blessings in my life, thank you for walking together with me in my journey. Your understanding, prayers, and encouragements are what have given me the motivation and strength to overcome the difficulties in finishing this thesis.

Finally, I am glad to have come across the story of Jim Elliot whose writing in his journal has always been the source of my motivation throughout the most difficult and challenging moments of my PhD journey:

"He is no fool who gives what he cannot keep to gain that which he cannot lose"

I have surely had to give up certain things which are precious to me along the journey to pursue my calling which made the process challenging at times. However, I do know that these things that I gave up are not lost; I dedicated them to my master, and Lord, Jesus Christ who gives me joy, purpose, and ultimately Himself as the biggest reward in my life. To Him let all the glory be.

Ronald Apriliyanto Halim,

Paris, February 2017

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Globalization has created this interlocking fragility.
At no time in the history of the universe
has the cancellation of a Christmas order in New York
meant layoffs in China.
-Nassim Nicholas Taleb-

1 Introduction

1.1 Problem statement and objective

Over the past centuries, the growth of the world's economy and welfare has been made possible through global trade. Global trade has helped many countries worldwide in increasing their gross domestic product and, to a great extent, reducing their poverty level. Undoubtedly, global freight transport has played an indispensable role to support globalization. Mankind has managed to increase the efficiency of the global transportation system such that the cost of international shipments has been reduced substantially, to the level where it constitutes only a small fraction of the total production cost. This development has also been made possible due to the impact that global trade has had on global transport and vice versa. The rise in global trade volume has, in turn, enabled the use of economies of scale in shipping and of more efficient shipping service networks. Unsurprisingly, all these phenomena have caused transportation, together with international standardization, trade liberations and communication, to be considered as the cornerstones of globalization (Kumar and Hoffmann, 2006)

Despite the numerous positive impacts of globalization, our world today also faces new challenges. The formation of long chained supply processes in global production and consumption activities has made the economy between countries to be more dependent of one another. When one element in the supply chain fails to function, this can impact other elements in the system and eventually cause the economy of countries to suffer. Moreover, advances in one element of the chain (e.g. improvement in efficiency) do not always result in improvement for the whole system. Globalization and high degree of interdependencies have, therefore, made the world's economy, and consequently, global freight transport system a complex system.

In the past couple of years, there have been many examples of how recent developments in the global economy bring about changes in global trade patterns. A salient example is seen in China's economic slowdown and how it has caused the decline of trade and economic growth in Asia Pacific and many countries (Inoue et al., 2015). Another example of important development is the emergence of many trade agreements such as AANZFTA (ASAN-Australia-New Zealand Free Trade Area), AFTA (Asean Free Trade Area), and RCEP (Regional Comprehensive Economic Partnership) (CNBC, 2015b). These Free Trade Agreements are likely to change global trade patterns significantly and consequently also impact the spatial pattern of global freight transport. While it is difficult to predict how these trends emerge, it is possible to assess the impact of these developments on global trade and global freight transport.

Responding to trends in global trade, rapid technological and organizational changes also happen in freight transportation service systems. In maritime container transport, the rise of global trade volume has stimulated liner shipping companies to invest in mega ships to pursue economies of scale and further reduce the unit cost of transport. However, since the demand of global cargo movement does not grow at the same speed as ship size development, many liner shipping companies struggle with overcapacity and plunging rates (Drewry, 2016). These developments have forced liner shipping companies to improve the efficiency of their operations by merging with and acquiring other shipping companies to form shipping alliances. This has resulted in new shared shipping networks being created by these alliances to optimize their market coverage and the utilization of their ship's capacity. Consequently, this trend also impacts the structure of global shipping networks and the roles of ports worldwide.

On the hinterland side, increases in vessel size and cargo volume have brought new efficiency challenges to gateway ports worldwide. A striking example can be observed in the huge congestion problem faced by major ports in the U.S (CNBC, 2015c). In the beginning of 2015, the surge in cargo load and the work slowdown caused by disputes between port operators and labour unions caused west coast ports to be severely congested. This condition eventually lead to a cargo diversion to East, Gulf Coast and Canadian ports (CNBC, 2015a). Unfortunately, these ports also suffer from congestion due to limited capacity. In addition, port-hinterland connectivity faces efficiency and congestion problems as the volume of transported cargo increases. A noticeable example of this problem can be seen in Asia-Europe or Asia-North America trade connections, where hinterland transport remains the most expensive link within the global intermodal transport chain (Rodrigue and Notteboom, 2012). When this trend of rising hinterland transport cost is not mitigated properly, this will impact the global trade and, in turn, the global economy negatively. Responding to these challenges, a major reorganization of hinterland transport system needs to take place. To reduce hinterland transport cost, new policy measures that foster cooperation and coordination between regions are being proposed (see e.g. Trans-European transport policy package (TEN-T)), along with the development of logistics facilities such as distribution centers and inland terminals. However, since such measures have not been implemented or extensively studied, the outcomes of these policies on port-hinterland transport cost are highly uncertain.

Given such unpredictable global changes and their complex chained effects, it is clear that we need a systematic approach and appropriate tools to treat these deep uncertainties and be prepared to deal with their negative consequences. This is especially important for strategic planning and policies of vital freight infrastructures which support global transport chains, such as ports, intermodal terminals, logistics hubs, transhipment facilities, and road and railway networks. Robust policies are key to retain the performance of the logistics system of a country or region. Next to minimizing negative consequences caused by uncertainties, such policies can also avoid overinvestment and misallocation of national resources to less critical freight infrastructure projects (Acciaro and McKinnon, 2015).

1.2   Strategic policy questions in port networks

One of the main objectives of freight transport policy is to ensure that freight transport can be done in a cost efficient manner. Since the global freight transport system consists of multiple subsystems, different policy measures for these subsystems are required to address the threats to the efficiency of global freight transport. For instance, policy on port-hinterland connectivity is required to address the threats that emerge due to congestions between port and hinterland destinations. Different policies are also needed in the other subsytems (e.g. in the maritime shipping network) to address the threats to port that may emerge due to changing global trade patterns.

In this section we list the policy questions in global freight transport systems that outline the practical context of our research. These questions represent practical policy problems related to long term decisions such as infrastructure investments, regulations for green house gases emissions. Specifically, we consider the port authority as the central actor in this thesis and we focus our scope of analysis on three major subsystems: ports, hinterlands, and maritime transport systems. We discuss the policy questions that we take as a starting point in this thesis below.

1. Port subsystem

Ports play a central role as interfaces between hinterland and maritime subsystems. They function as the facilitator of intercontinental trade, and they sustain economic growth of country and regions (OECD/ITF, 2015b). Port development policies need to be carefully planned by taking into account future uncertain developments in hinterland and maritime subsystems, and also among ports themselves. This implies that, in light of the changes and ucertainties in global transport demand and global shipping services, ports need to identify the relevant scenarios such that anticipative measures can be taken to combat or mitigate any negative impacts such as port over or undercapacity, rise in CO_2 emission and congestions in port area. Therefore, an important policy question that needs to be addressed is:

Given the uncertain developments in future global freight transport patterns, what are the key vulnerabilities of ports that affect their competitive position within global container transport networks?

2. Hinterland transport subsystem

As the demand for transport between port and hinterland destination grows, hinterland distribution networks may undergo reorganization. For example, inland logistics service providers will restructure service networks to maintain cost-efficient transport operations. This reorganization will impact the connectivity between the port and the hinterland origins and destinations. Changes in hinterland distribution structures may affect the routing of freight flows through ports. Since port-hinterland distribution networks are structures that are established as responses to the international trade, the uncertainties in the international trade will also impact hinterland distribution networks and their flows. Therefore, a policy question that needs to be addressed for hinterland transport is:

What are the impacts of uncertain changes in port-hinterland distribution structures on port-hinterland flows?

3. Maritime transport subsystem

It is equally important to address port policies directed at anticipating the changes in the maritime transport system, to take opportunities for growth or to help combatting any trends that are potentially harmful for public and private actors. A clear example can be seen in the impacts of the imminent changes in the maritime shipping networks on the way the ports are connected with each other. New shipping networks that are operated by major shipping alliances will result in growth in some ports and decline in others. It may also change the costs of global freight transport. When this change is not carefully studied, policy measures that are useful to combat negative outcomes, such as decline in port throughput or higher total logistics costs, can not be prepared. Hence it is important to address the following policy question:

How will changes in global maritime shipping networks affect ports?

In the attempt to answer complex policy questions in freight transport systems, model based analysis can offer a systematic approach and useful insights for developing flexible and robust policies. Using computer models, the impact of different policy measures on the performance of port and its connected infrastructures can be assessed. Moreover, we can systematically explore different scenarios that represent plausible future states of the system and obtain insights on the characteristics of effective policies for these scenarios. However, modelling the global freight transport system is not without challenges. Conventional micro models that focus with great detail on specific regions or elements of the system, without looking at the way these elements interact with one another, will fail to deliver insights on the performance of the system as a whole. New models are needed that take into account the bigger picture of logistic nodes such as ports as an element of global transport systems. This implies that the models should be able to describe behavior of logistic actors in networks under different scenarios. Although this may cause the models to be inevitably large, it is also important that they are designed to be as simple as possible. In this way, the models can be validated and their outcomes can be communicated to policy makers.

The challenge undertaken in this thesis is to develop simplified, global scale network models that can contribute to answering policy questions for port-hinterland systems amidst various uncertain developments in the global freight transport system. We describe the scientific gaps that need to be addressed in developing such models in the section below.

1.3   Model-based analysis for Global Freight Transportation Policies

Along with the emergence of new policy problems in the global freight transport system, there is also a need for novel models that are specifically designed to help policy analysts in answering these problems. In this thesis, we take the perspective of port policy makers as the central actors who face policy problems and whose decision-making processes can be supported by model-based analysis. In order to develop models that are grounded in the freight transport modelling literature, attention should be devoted to current state-of-the-art modelling approaches and relevant gaps within this literature should be identified. In this section we list the gaps in the literature of global freight modelling, concerning the 3 subsystems, that are addressed in this research.

1. Gap in the systematic exploration of the impact of uncertainties

There is a crucial gap in the way the impacts of uncertainties in global freight transport are now identified. Many port policy makers and government institutions make use of models to help them in designing appropriate policies and strategies for ports and related infrastructures. In the effort to answer important policy questions, most modelling exercises in freight transport are aimed at predicting the impact of certain scenarios on the performance of the transport systems. However, the results of modelling exercises can be misleading when the models are used to predict the states of complex system with many uncertainties (Kwakkel and Pruyt, 2013a). Specifically, this can happen when a wide array of uncertainties, which exist in the factors that drive changes in the system, is not properly taken into account when calculating plausible outcomes of different scenarios. When using models to support decision making under uncertainty, models have to be used in an exploratory manner rather than in a predictive manner (Bankes, 1993, Bankes, 2002, Bankes et al., 2013). A promising method to explore the impact of uncertainties is exploratory modelling. Exploratory modelling is an analysis method that takes into account a range of uncertain parameter values and model designs to estimate the plausible behavior of the system under study (Kwakkel and Pruyt, 2013a). Here, fully parameterized models are used based on the limited but available information to produce insights in the behavior of the system. These models together represent the plausible variations in model structures and input values. In contrast, in predictive modelling, models are used to predict system behavior and developed by consolidating known facts into a single package (Bankes, 1993). When experimentally validated, a predictive model can be used for analysis as a surrogate for the actual system. In the presence of deep uncertainty and complex systems, the construction of a model that may be validly used as a surrogate is simply not possible. Despite this shortcoming, most of the freight models are used in predictive manner rather than in exploratory manner, for identifying policies for ports and infrastructure development.

2.   Gap in port-hinterland distribution network modelling

There is also a gap in freight transport modelling literature for analysing port development policies that take the broader interconnected system elements into account such as port-hinterland distribution networks. This is a policy area that is important for port authority and also national government who make strategic long-term decisions to ensure that ports and hinterland regions have a good connectivity. The gap can be seen from the scarcity of supranational/regional and global models in freight transport for port-hinterland subsystem. The available models are still unable to address important policy issues concerning port-hinterland connectivity, especially those that cover large regions comprised of multiple countries. So far, only few models have been developed to describe port-hinterland distribution networks. The majority of the port-hinterland literature contributed mainly to the taxonomy and conceptualization of port-hinterland distribution systems (see e.g. Notteboom, 2008, Notteboom, 2010, Notteboom and Rodrigue, 2005, Rodrigue and Notteboom, 2010, Van den Berg and De Langen, 2015). Structures of port-hinterland logistic systems are only rarely assessed through the application of a quantitative modeling approach. More specifically, there have not been any mathematical models that can explain the structures of port-hinterland distribution networks based on the observed patterns of the networks. Moreover, those researchers that do apply quantitative modelling approaches typically aim to optimize the performance of individual companies (Goetschalckx et al., 2002), rather than focusing on describing the aggregate port-hinterland distribution system. There are a few models that explicitly address the design of port-hinterland intermodal connections, such as in Wan et al. (2014) and Lam and Gu (2013). However, these models suggest normative designs of intermodal connections in the port-hinterland network, without recognizing behavior and preferences of different actors or accounting for distribution centers in these logistics networks.

3.   Gap in global maritime shipping network modelling

A major modelling gap within the port-maritime literature can also be identified. There has not been any study that explores the impact of changes in global shipping service networks on the connectivity and competitiveness of ports worldwide. Although there have been studies indicating that global shipping networks evolve dynamically due to changes in the global trade patterns (Davidson, 2014, Ducruet and Notteboom, 2012), the relationship with port connectivity and competitiveness has never been formalized in a working descriptive transport model. Most of the studies in shipping service networks take the perspective of liner shipping companies as the central actors and are aimed at optimizing the cost or profit of a single liner shipping company (Christiansen et al., 2007, Liu et al., 2014, Wang and Liu, 2015, Wang et al., 2013). They do not analyze the aggregate global shipping service network as a superposition of many individual liner shipping networks and how changes in this network impact port competitiveness. We propose an aggregate model for analyzing the plausible impacts of the growing transport demand globally along with the uncertainties that exist therein. This model should take into account the cost-minimizing rationality of liner shipping companies at aggregate level. However, the main focus of the model is to analyze how port competitiveness is affected by the changes in the structure of the global maritime shipping networks.

To summarize, this thesis addresses 3 gaps in the literature concerning the exploration of maritime-port-hinterland systems:

1. There is a knowledge gap as to how the uncertainties in global container transport can be explored systematically, such that the key vulnerabilities of ports can be identified.
2. There are no predictive models for port-hinterland distribution networks, with which the impact of different policy measures can be assessed.
3. There are no predictive aggregate models for global maritime shipping networks to investigate how changes in global transport demand affect maritime network structures and, indirectly, global port flows.

In summary: the goal of this thesis is to develop and test models that can fill these gaps, particularly in the context of global container transport networks. We draw upon the fields of operational research and freight demand modelling to model, respectively, future logistics supply networks and the aggregate behavior of users of the global container transport system. Special attention is given to the relation between maritime shipping or hinterland distribution networks on the one hand, and global container transport demand on the other. Furthermore, we also study how the ports are impacted by the changes in both the hinterland and the maritime networks. The next section lists the research objective and questions in more detail.

1.4   Research Objective and Questions

The main objective of this research is formulated as follows:

To design empirically grounded models that can support policy analysis for ports and their intermodal transport networks, taking into account uncertain developments in future global container transport demand and services.

The main research question addressed in this thesis is:

What are designs of freight logistics network models that are suited to explore the impact of long-term changes in global container transport chains on the competitive position of the ports?

In order to answer the main research question, the following sub-research questions are formulated:

1. *How can we systematically identify the key vulnerabilities of ports that affect their competitive position?*

Given the intrinsic complexity of the container transport system and the presence of a wide range of deeply uncertain factors affecting the system, identifying plausible scenarios for the global container network poses various challenges. This is partly because a vast amount of scenarios can be built on the various uncertain factors in the system. Additionally, it is also challenging to asses the impacts of these uncertain factors on the competitive position of the ports, and to discover the key factors that can lead to negative impacts on the port. Therefore, this research question addresses the need to develop an approach to identify the key vulnerabilities of the ports systematically.

2.   *How can we design a freight logistics model that can explore the effects of port-hinterland distribution networks on port-hinterland flows?*

Globalization and international trade have given rise to global supply networks. These networks, and in particular the distribution networks between ports and hinterland regions, have shaped freight flows on many continents. Currently, there is no descriptive freight transport model that explicitly takes into account how changes in the location of continental distribution centers affect the routing of freight flows from ports to hinterland destinations. Most of the models available are aimed at optimizing the supply chain costs and the profitability of a single company. Policy analytical models generally require the strategies of different companies to be taken into account while focusing on the performance of the system as a whole under certain policy measures. In this research, we specifically focus on the gap in descriptive models that allow the testing of transport policy measures on port-hinterland systems.

3.   *How can we model plausible future structures of global maritime shipping networks to gain insight into the impact of these structures on port competitiveness?*

A clear trend in maritime network development during the past decades has been the formation of alliances between carriers to create new network structures. While the rate at which very large network alliances will be realized is uncertain due to market regulatory barriers, their effect on maritime shipping networks could be significant, affecting also the competitive position of ports and hinterland networks. Consequently, it is in the interest of ports worldwide to gain insight in how new maritime network structures could affect their throughput volumes. In order to gain this insight, a model-based analysis of the global shipping networks is needed. This research question aims at investigating the design of a model that can be used to analyze the way global trade patterns affect global shipping network structure and port choice.

1.5   Research approach

This research project makes use of modelling approaches that require both theoretical and empirical supports in its approach to deliver valid answers for the research questions stated above. As such, theoretical foundations from freight transport modelling and empirical experimentation will be used to design the components of the models. Alternative designs for the model are proposed whenever limitations are encountered in previous design efforts to model the system.

Figure 1.1 provides an overview of the connection between, policy questions addressed in this research, the identified gaps, the research questions, and how they result in the chapters of this thesis. Each of the gaps identified represents the area where this thesis makes its contribution to answer the policy questions addressed in this thesis. The thesis is structured such that each of the research steps corresponds to a chapter in this thesis.
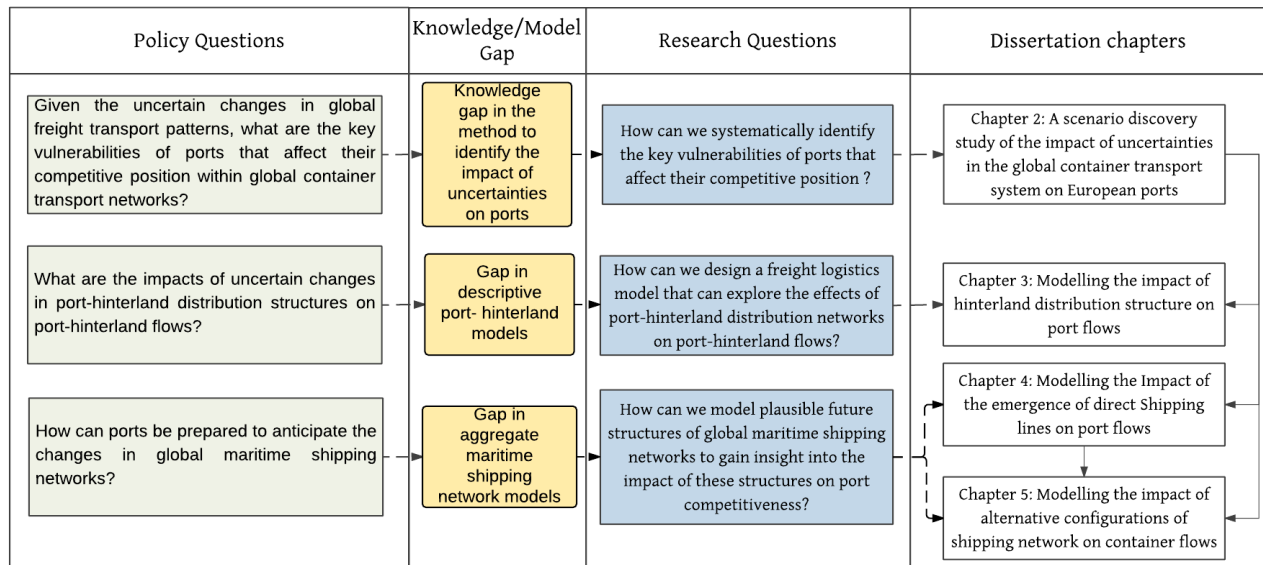
Figure 1.1 Research framework and its corresponding dissertation chapters

First of all, given the importance of the function of ports, we position the identification of the key vulnerabilities for the competitive of the ports as a foundational first step that sets the direction of the ensuing research in this thesis. We develop a methodology to analyze plausible future scenarios for global freight transport and identify the key factors that pose threats for the competitive position of ports. This methodology is applied to European ports to compute the expected impacts of changes in the global freight transport system on the ports. The analysis in chapter 2 forms a foundation for the research presented in chapter 3,4 and 5 as it also gives input to the specification of the models needed to further investigate the impact of changes in global trade patterns on the hinterland distribution networks and the maritime shipping networks.

In chapter 3, we develop a model for port-hinterland distribution structures where different alternative structures can be estimated. Using this model the impact of these distribution structures on port-hinterland flows can be studied in greater detail. Next, chapter 4 and 5 address the policy question on the impact of the future global shipping networks on port flows. Both describe alternative modelling approaches that can complement one another in describing the behavior of the global shipping networks under foreseen global trade scenarios. In chapter 4, a model is developed specifically for investigating the impact of the emergence of direct shipping lines on port flows. In chapter 5, a modelling approach is developed to investigate the impact of changes in future global trade patterns on the structure of global shipping networks and also on port choice. In order to build the models, we adopt the modelling cycle from the systems engineering field that is presented in Figure 1.2 (Daalen et al., 2009), where for each of the models developed in chapter 3,4, and 5 we complete one cycle. In model assessment step, a special attention is given to model validation process in which the calibration of model parameters is required. This is because a descriptive transport model can only be considered to have a good validity when the output values of the model have a good-fit with the observed values of the system under study (Ortúzar and Willumsen, 2011). Hence, in validating the models we perform calibration to optimize the goodness-of-fit measures that are defined in each chapter.
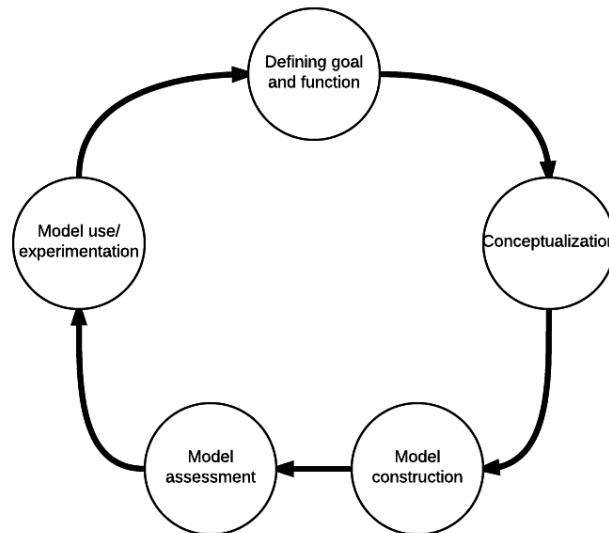
Figure 1.2 Modeling cycle used for developing the freight transport models (Daalen et al., 2009)

1.6   Contribution of this thesis

The research in this thesis is designed to have both scientific and real-world contributions. The following sub-sections describe these contributions respectively.

1.6.1   *Scientific contribution*

Scientifically, this thesis has two main contributions. First, it contributes to the body of literature in the field of modelling freight transport systems. The models developed in this thesis contribute to fill the gaps identified in the research area of modelling global freight transport. Second, this thesis also contributes to the policy analysis literature, by presenting analyses on the impact of scenarios on future global container transport systems. We summarize the specific contributions of this thesis by chapter below:

Chapter 2: A scenario discovery study of the impact of uncertainties in the global container transport system on European ports[1].

Chapter 2 proposes an approach to study the impact of uncertainties in the global container network on European ports. Specifically, it contributes to (*i*) the way in which a large amount of uncertain factors can be explored in an effective way, (*ii*) methods to assess the impacts of various uncertain factors on the competitive position of the ports, (*iii*) the discovery of key factors that can harm the competitiveness of ports. The research adds to the literature of exploratory modelling analysis (Bankes, 1993) and of applications of the scenario discovery approach (Dalal et al., 2013).

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[1] This chapter has been published in Futures (Halim et al., 2016a)

Chapter 3: Modeling the impact of hinterland distribution structure on port flows.[2]

Chapter 3 presents a model that attempts to fill a gap in research on port-hinterland freight transport models. Specifically, we propose a strategic model that integrates hinterland distribution structures into an existing global freight transport network model (Tavasszy et al., 2011). We describe the specification of the model and its estimation, and demonstrate the application of the model for future container flows in Europe. The resulting model contributes to the literature in port-hinterland modelling methods (Wan et al., 2014) and its applications to port connecitivity and global freight transportation analysis.

Chapter 4: Modeling the impact of the emergence of direct shipping lines on port flows.[3]

Chapter 4 proposes a modelling approach that can give a preliminary picture of the aggregated responses of shipping lines to foreseen trends of growth. Specifically, we investigate the mechanisms on how direct shipping lines emerge between ports worldwide and analyze the impacts of these direct services on the port flows. As a case, we investigate the influence of the emergence of these direct lines on European ports, in terms of port throughput. Furthermore, we analyze how the direct lines affect container flow patterns worldwide and how port choice is affected, particularly for big ports in the US and East Asia. The approach presented contributes to the literature in global freight transport modelling and in maritime networks analysis (Ducruet and Notteboom, 2012).

Chapter 5: Modeling the impact of alternative configurations of shipping network on container flows[4].

Chapter 5 proposes a strategic global maritime network model that combines models for freight demand and maritime network design. The model addresses a knowledge gap in approaches to explore plausible future global shipping networks. In our approach we avoid having to model individual carriers and their clients, which reduces data needs and decreases run times to an extent that strategic applications, such as exploratory modelling, become possible. In two applications we study the consequence of maritime network development in Indonesia and globally, focusing on the impacts on ports within the North-Western European port range. This chapter contributes to literature of global maritime shipping network modelling (Gao et al., 2005, Song et al., 2005)

1.6.2   Policy contribution

The models and results produced by this research are intended to support policy-making processes of organizations that deal with problems related to global container transport.We have identified several organizations that may utilize the products of this research and the way they can benefit from this research. Each of these organizations might

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[2] The chapter is an extended version of a paper that has been published in Transportation Research part E: Logistics and Transportation Review (Halim et al., 2016b)
[3] This chapter has been published in Maritime Networks: Spatial Structures and Time Dynamics. Oxford: Routledge (Halim et al., 2015b)
[4] This chapter is an adapted version of a paper presented at the GPRA conference 2015

act as an actor who can test their policy measures and strategies using the models and also by taking into account the possible changes in the system as well as policies of other relevant actors.

1. Port Authorities

Port authorities, especially the port of Rotterdam, have been one of the main target groups in this research due to their important role as a logistic hub in global container transport networks. The models that have been developed in this research are useful in formulating strategic measures to retain and increase port competitiveness. Particularly, the models can be used to estimate the long-term infrastructure and service capacity that is needed, such that under or over-investments can be minimized. Furthermore, port authorities can make use of the study as an input in their coordination strategy with the Ministry of transport, in planning the development of infrastructures such as road/rail networks throughout the country and the European Union.

2. National and supranational government institutions

Government institutions, particularly those that are directly involved in making policies for transport and infrastructure, are important potential users of models that are developed in this research. These institutions can make use of the models to analyze how different policy measures impact different elements of transport systems and eventually the economy of the nation. Furthermore, the models, due to their scale and strategic nature, also allow identification of infrastructure investment projects that need to be prioritized to support economic growth of the region. This is especially important for supranational government institutions (such as the European Union) that coordinate transport policies and infrastructure budgets across different countries.Last but not least, the models can also be used to analyze the impact of cross-port coordination measures on the performance of their shared transport system.

3. Non-governmental organizations

Non-governmental organizations can make use of the models and methods developed in this research to analyze and estimate the impact of planned regional freight transportation systems for specific interests such as industry sectors or the living environment. For instance, the models can be further developed to analyze the effectiveness of different mitigation strategies for reducing the emission of greenhouse gasses on global freight transport networks.

"All truths are easy to understand once they are discovered;
the point is to discover them."
-Galileo Galilei-

2 A scenario discovery study of the impact of uncertainties in the global container transport system on European ports

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Abstract

The global container transport system is changing quickly. Ports can be severely affected by these changes; therefore ports need insight into how the system might change and what the impact of this would be on their competitive position. Given the intrinsic complexity of the container transport system and the presence of a wide range of deeply uncertain factors affecting the system, we use an exploratory modeling approach to study future scenarios for the global container network.

The main question that we address in this chapter is 'How can we systematically identify key vulnerabilities that can affect the competitive position of ports in the face of deep uncertainties?' In order to answer this question, we use scenario discovery, and worst-case discovery, to identify the key vulnerabilities of ports. As a proof of concept, we apply these approaches to Port of Rotterdam. It is found that the overall, the competitive position of Rotterdam is quite robust with respect to the various uncertain factors. The main vulnerability is the quality of the hinterland connections. A modest deterioration of the quality of the hinterland connections, resulting in increased travel time, will result in a loss of throughput for Rotterdam.

This chapter is structured as follows. Chapter 3.1 provides an introduction on the complexity and deep uncertainties within global container transport system. Chapter 3.2

elaborates on the scenario discovery approach proposed in this chapter. In Chapter 3.3, we present a case study illustrating the application of scenario discovery approach to deal with uncertainties faced by European ports. Furthermore, this chapter also provides the specification of the worldwide container transport model used together with this approach. Chapter 3.4 elaborates on the implementation of the computational method used in this study. Chapter 3.5 discusses the results of the case study together with the analysis done using scenario discovery approach. Finally, Chapter 3.6 provides the conclusions of the study.

2.1   Introduction

In the past couple of decades, changes in global container transport system have happened very rapidly. These changes have affected virtually all actors in the system, but the biggest impact has been on the ports. Ports have to be adaptive and resilient in responding to the changes in the global container shipping system. In today's globalized economy, ports need to ensure that they can function robustly both as a transshipment node and as a gateway node for global trade flows. A failure to respond to changes in timely manner often result in a huge negative consequences for the port itself, as well as the economy of the region or country to which the port belongs. For example, the recent congestion of ports on the west coast of the US has estimated damages for the economy of roughly 7 billion US dollar (CNBC, 2015c).

Preparing a port for a wide range of possible future developments is a profound challenge. The global container shipping system is composed of many elements, with strong interdependencies. Often, small changes somewhere in the system cascade quickly through the system, potentially resulting in substantial changes somewhere quite far removed from the initial small change. For example, recently Ultra Large Carrier Vessels (UCLVs) have entered the market. In response, Liner shipping companies have started to form alliances to pursue economy of scale. This in turn affects the frequency of port calls, the port rotation schedule, and the container volumes loaded and unloaded at each port. Changes not only take place on the seaside. Developments in the hinterland, such as the construction of new infrastructures such as road, railways, and intermodal facilities affect transport cost. This in turn influences the spatial flow of containers through different ports from the origin site to the destination site. The operation of Transiberian railways is an example of the importance of hinterland infrastructure on global container flows through ports (Rastogi and Arvis, 2014). A similar chained effect also takes place when global policies are imposed on ports. An example of this is the recent International Maritime Organization (IMO) regulation that limits the use of sulfur in ship's fuel in many ports in the world (IMO, 2014). All of these components in the system, both physical and institutional, and the potential chained changes therein demonstrate that ports are part of a complex system. In such systems, observation on the components, and their interaction mechanisms can only be done partially, leading to a limited predictability on the behavior of the system when certain changes occur.

A second reason why preparing a port for possible future developments is that the future is deeply uncertain (Kwakkel et al., 2010, Lempert et al., 2003). Since there are many actors with different objectives involved in the global logistic system, it is virtually impossible to predict how changes in any given component of the system will affect the

system as a whole. An example of a disruptive change can be seen in labor strike case in the western coast of the US in early 2015. The strike caused the port of Long Beach to be shut down for several days, causing a loss to the GDP of the Unites States of America of roughly 150 M dollar per (Durden, 2015). Another example is the recent drop in the global oil price, which in turn, has reduced transport cost significantly. When this low oil price is sustained for a long period (>5 years), it will likely influence trade flows between countries positively. Consequently, this results in an increase in the volume of containers loaded/unloaded at the ports associated with both countries. Predicting when oil price will return to the level where it was in 2013 is highly challenging. Other changes might also include the opening and closing of certain maritime routes such as Suez canal and the Northern passage (i.e. the artic route), changes in competition strategies of other ports, emergence of political tensions that hamper trade agreements between countries, etc. In short, there is a massive number of scenarios that can be generated to account the uncertainties within the global logistic system. It is highly implausible that all these changes can be explored using a single model. In fact, there are different modeling formalisms that can be used to model the whole system and its sub-systems. Examples of those modeling approaches include discrete choice model (Tavasszy et al., 2011), computable general equilibrium (Hertel, 1999), discrete even simulation models (Sinha-Ray et al., 2003) and optimization models (Bell et al., 2013). Experts in each of these modeling approaches might argue that their modeling approach is best suited to represent the system. To complicate matters, different plausible scenarios can be specified using these models. Consequently, different alternative outcomes might emerge from these different modeling exercises.

Because of the intrinsic complexity of the global container shipping system, many port authorities and government institutions make use of models to help them in designing appropriate policies and strategies for ports and related infrastructure. However, relying on models to perform predictions on such a complex system with many uncertainties might seriously be misleading (Kwakkel and Pruyt, 2013a). Specifically, this can happen when the irreducible uncertainties, which exist in the factors that drive changes, are not properly taken into account when calculating the plausible outcomes. Therefore, there is a need for a systematic approach to deal with the uncertainties in the complex container shipping system.

In this chapter, we use scenario discovery (Bryant and Lempert, 2010) in order to assess the consequences of various uncertain factors on future global container flows. Scenario discovery is an innovative model-based approach to scenario development. It is inspired by the scenario logic approach to scenario development. Scenario discovery uses series of computational experiments to explore the consequences of various unresolved uncertainties. These series of computational experiments are subsequently analyses using statistical machine learning algorithms in order to identify the combinations of uncertain developments that produces characteristic types of results. The computational experiments are designed such that they are consistent with the available information on the system and the associated uncertainties (Bankes, 2002, Bankes et al., 2013).

The objective of this chapter is to apply scenario discovery in order to provide insight into the main vulnerabilities for the port of Rotterdam. The results reported on in this chapter are an updated of the results of an earlier study conducted for the port authority. The main question that we address in this chapter is 'what are the key vulnerabilities for the

competitive position of Rotterdam in the Bremen – Le Havre range?' In order to answer this question we use a world container-shipping model (Tavasszy et al., 2011).The main uncertain factors that we will be analyzing have been derived from both literature as well as from discussions with various experts at the Port of Rotterdam. Methodologically, we apply both scenario discovery as well as a worst-case discovery technique.

2.2   Scenario discovery: a model based approach to scenario development

Scenario discovery is a relatively novel approach for addressing the challenges of characterizing and communicating deep uncertainty associated with simulation models (Dalal et al., 2013).The basic idea is that the consequences of the various deep uncertainties associated with a simulation model are systematically explored through conducting series of computational experiments (Bankes et al., 2013) and that the resulting data set is analyzed to identify regions in the uncertainty space that are of interest (Bryant and Lempert, 2010, Kwakkel et al., 2013). These identified regions can subsequently be communicated through e.g. narratives to the decision-makers and other actors involved. In this chapter, we complement this basic idea of scenario discovery with a directed search technique that is useful for worst-case discovery.

A motivation for the use of scenario discovery is that the available literature on evaluating scenario studies has found that scenario development is difficult if the involved actors have diverging interests and worldviews (Bryant and Lempert, 2010, van 't Klooster and van Asselt, 2006). Another shortcoming identified in this literature is that scenario development processes have a tendency to overlook surprising developments and discontinuities (Derbyshire and Wright, 2013, Postma and Liebl, 2005, van Notten et al., 2005). A third problem is that any scenario development approach that relies on the mental models of the analyst will struggle when faced with complex systems. Since mental models are typically event based, have an open loop view of causality, ignore feedback, fail to account for time delays, and are insensitive to non-linearity (Sterman, 1994), essential elements of dynamics in complex systems, namely feedback, time delays and non-linearity, cannot be appropriately dealt with. Consequently, mental simulations of complex systems are highly defective, something that has also been demonstrated empirically (Atkins et al., 2002, Brehmer, 1992, Diehl and Sterman, 1995, Dörner, 1996, Kleinmuntz, 1992, Sastry and Boyd, 1998, Sterman, 1989).

Scenario discovery is a model-based approach that offers support for decision-making under deep uncertainty. Deep uncertainty is encountered when the different parties to a decision do not know or cannot agree on the system model that relates consequences to actions and uncertain model inputs (Lempert et al., 2003), or when decisions are adapted over time (Hallegatte et al., 2012). In these cases, it is possible to enumerate the possibilities (e.g. sets of model inputs, alternative relationships inside a model, etc.), without ranking these possibilities in terms of perceived likelihood or assigning probabilities to the different possibilities (Kwakkel et al., 2010).

When using models to support decision making under uncertainty, models have to be used in an exploratory manner rather than in a predictive manner (Bankes, 1993, Bankes, 2002, Bankes et al., 2013). In predictive modeling, models are used to predict system

behavior and developed by consolidating known facts into a single package (Bankes, 1993). When experimentally validated, this single model can be used for analysis as a surrogate for the actual system. In the presence of deep uncertainty and complex systems, the construction of a model that may be validly used as a surrogate is simply not possible. The complexity of, and deep uncertainty pertaining the system together imply non linearity of system behavior, dynamic complexity, and rival representations of the system which are underdetermined given the available data (Campbell et al., 1985, Oreskes et al., 1994, Sterman, 2000). Exploratory modeling starts from this fact of not knowing enough to make predictions, while acknowledging that there is still a wealth of information and knowledge available that could be used to support decision making (Bankes, 1993)

When developing and using models for exploratory purposes, the available information is insufficient to specify a single model that accurately describes system behavior. Instead, the information can be used to construct a variety of models, which, taken together, are consistent with the available information. This ensemble of models typically captures more of the available information than any of the individual models (Bankes, 2002). Each of these individual models will have different implications for potential decisions. A single model drawn from this potentially infinite set of plausible models is not a prediction. Rather, this model is a computational experiment that reveals how the world would behave if the various hypotheses encapsulated in this single model about the various unresolvable uncertainties were correct.

A key challenge is to develop effective strategies for searching through the implications of the ensemble of plausible models for the decision problem at hand. Two families of search strategies can be identified: open exploration and directed search. Open exploration can be used to systematically explore the set of plausible models. That is, open exploration aims at generating a set of computational experiments that covers the space of plausible models, or uncertainty space for short. This exploration relies on the careful design of experiments and can use techniques such as Monte Carlo sampling, Latin Hypercube sampling, or factorial methods. An open exploration can be used to answer questions such as "under what circumstances would this policy do well?", "under what circumstances would it likely fail?", and "what kinds of dynamics can this system exhibit?".Open exploration provides insight into the full richness of behaviors of the ensemble of models.

Open exploration uses series of computational experiments. In order to reason on this ensemble, the results from these computational experiments have to be analyzed. The main algorithm that is used for this is the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999). PRIM tries to find combinations of values for input variables that result in similar characteristic values for one or more outcome variables. Specifically, the algorithm seeks a set of hyper rectangular subspaces of the uncertainty space within which the values of a single output variable are considerably different from its average values over the entire model input space. PRIM describes these subspaces in the form of boxes of the model input space. This results in a very concise representation, for typically only a limited set of dimensions of the model input space. That is, a subspace is characterized by upper and/or lower limits on only a few input dimensions. In other words, PRIM seeks to identify the ranges within the uncertainty space under which conditions, undesired or desired outcomes of the model are likely to occur. In searching the uncertainty space, PRIM also seeks the

minimum number of uncertain factors that would capture the maximum number of outcomes that are of interest. Hence, PRIM does not provide any information on the sensitivity of other uncertain input variables to the outcome when these variables are deemed to be not influential. This is different from multivariate sensitivity analysis where the influence of each uncertain factors on the outcome variable is quantitatively measured. That is, multivariate sensitivity analysis allows the full ranking of the sensitivity of each uncertain factor based on its variance contribution to the model outcome.

In contrast to open exploration, directed search is a search strategy for finding particular cases that are of interest. Directed search can be used to answer questions such as "what is the worst that could happen?" "What is the best that could happen?" "How big is the difference in performance between rival policies?" A directed search provides detailed insights into the dynamics of specific locations in the full space of plausible models. Directed search relies on the use of optimization techniques, such as genetic algorithms and conjugant gradient methods. Open exploration and directed search can complement each other. For example, if the open exploration reveals that there are distinct regions of model behavior, directed search can be employed to identify more precisely where the boundary is located between these distinct regions.

Although scenario discovery can be applied on its own (Gerst et al., 2013, Kwakkel et al., 2013, Rozenberg et al., 2013), it is also the analytical core of Robust Decision Making (Dalal et al., 2013, Hamarat et al., 2013, Lempert and Collins, 2007, Lempert et al., 2006). Robust decision-making is a model-based decision support approach for the development of robust policies. That is, policies that perform satisfactory across a very large ensemble of future worlds. In this context, scenario discovery is used to identify the combination of uncertainties under which a candidate policy performs poorly, the vulnerabilities of a candidate policy, allowing for the iterative improvement of this policy. The use of scenario discovery for Robust Decision Making suggests that it could also be used in other planning approaches that design plans based on an analysis of the conditions under which a plan fails to meet its goals (Walker et al., 2013).

2.3 A global container shipping model

In this section, we introduce the global container model and the associated uncertain factors that will be explored.

2.3.1 A strategic global container network choice model

The World Container Model (WCM) is an existing strategic network choice model for global container flows (Tavasszy et al., 2011). The model considers more than 400 major ports, 237 countries, and more than 800 shipping lines. It is built on multinomial logit theory for explaining the mode and route choice behaviour of the shippers across alternative routes for each origin and destination. Transport cost is used as a key variable that determines the probability of a certain route is chosen by the shippers. The input data for the model mainly consists of transport costs data, network data, and a demand matrix for container movements between countries worldwide. The origin and destination demand matrix data is obtained based on international trade statistics (COMTRADE) and two European statistics database

(EUROSTAT). Since the model uses TEU (in 20 foot Equivalent Units -TEU) as the unit of analysis, trade flows data between countries in tonnages are converted into containers in TEU. We use this model as an experiment tool together with exploratory modeling analysis and scenario discovery approach to analyze the impact of uncertain factors on port flows.

Given a country-to-country origin destination demand matrix, the model calculates how container flows are distributed over the global network of shipping lines and through the various ports. Transport costs in the model are based on transport time (which is calculated based on speed of the transport mode), distance, unit cost of transport per kilometer per TEU, toll, value of time of the goods transported, and cost of handling the containers at the ports. The data used to estimate value of time and unit cost of transport are obtained from earlier studies done in (Tavasszy et al., 2011). Table 2.1 summarizes data for maritime and hinterland unit transport. provides the value of time for different commodities. The model uses an average value of time for container which is 73 US$/day.

Table 2.1 Cost and speed parameters of transport service

	Maritime	Hinterland
Cost (US$/km/TEU)	0.025	0.57[a]
Speed (km/day)	Calculated[b]	1000

[a]
  average, actual cost dpends on continent

[b]
  calculated separately for each service with default value of 1000km/day

Table 2.2 Estimated value of time for different commodities

ID	Commodity	Value of time (US$/ Day)
0	Agricultural Products and Live Animals	38
1	Foodstuffs and Animal Fodder	50
2	Solid Mineral Fuels	11
3	Crude Oil and Petroleum Products	34
4	Ores and Metal Waste	27
5	Metal Products	69
6	Crude and Manufactured Minerals, Building Materials	13
7	Fertilizers	9
8	Chemicals	70
9	Machinery, Transport Equipment, Manufactured Articles, and Miscelaneous Articles	411
10	Empties	1

The formal definition of the cost model is delineated below:

$$C_r = \sum_{p \in r} A_p + \sum_{l \in r} c_l + \alpha \left(\sum_{p \in r} T_p + \sum_{l \in r} t_l \right) \qquad (2.1)$$

where:

C_r unit cost of route r from origin country to destination country (US$/TEU)

p	ports used by the route
l	links used by the route
A_p	unit cost of transhipment at port p (US\$/TEU)
c_l	unit cost of transportation over link l (US\$/TEU)
T_p	time spent during transhipment at port p (days/TEU)
t_l	time spent during transportation over link l (days/TEU)
α	value of transport time (US\$/day)

The mode of transport (sea or land modes) is embedded in the network attributes and does not appear in the cost formula. This mode-abstract formulation enables the use of a more detailed underlying multimodal network; the aggregate result is a level of service expressed in time and cost. The value of the transhipment cost A_p represents port attractiveness parameter and it needs to be estimated for each port. The scaling parameter l captures the phenomenon that, although individual shippers and carriers may decide to use one port or another, their aggregate behavior results in the use of more than one alternative route and that their joint response to policies is a smooth one.

The model enumerates the majority of plausible route alternatives for major countries in the world using the publicly available service tables of shipping lines worldwide and a shortest path algorithm. A route from port of origin to port of destination is determined by first looking at the port-call order of container shipping lines worldwide and then, based on this order, using a shortest path algorithm to identify the sub-segments of the complete shortest route for each port-to-port segment of a shipping line. Hence choice sets are generated for every country O/D pair using both the physical network between port and hinterland and the network of service lines defined on top of this physical network.

For instance, a route between an origin country O and destination country D, starting at an origin port S and a destination port E is defined by one or more maritime services between S and E, with intermediate transshipment at ports where a change of service can be carried out. For each (outgoing) port S to the (incoming) port E the shortest path is added to the choice set of this combination O–S–E–D.
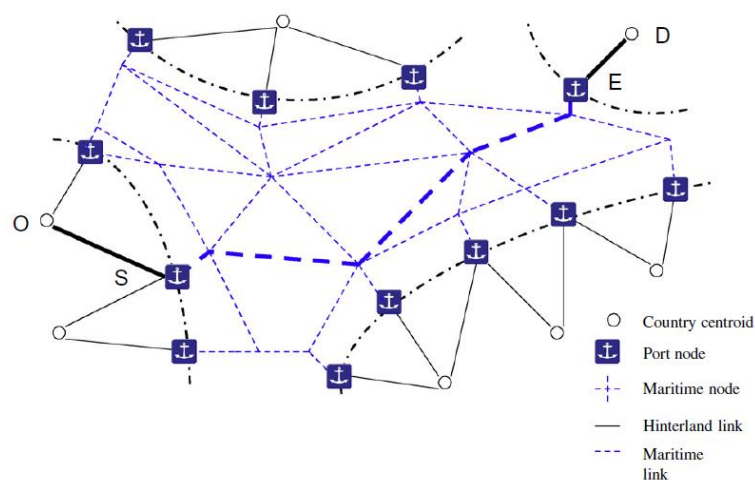
Figure 2.1 Example of a route between OD-country pair (adapted from Tavasszy et al., 2011).

The model accounts for both maritime connections between two countries as well as overland connections between these countries. The route and port choice algorithms uses a path-sized logit model which takes overlaps between the alternative routes into account and distinguish the transport costs associated with these alternatives properly. The basis of this model can be found in (Ben-Akiva and Bierlaire, 1999). The following is the formal definition of the route choice model. The route probabilities are given by:

$$P_r = \frac{e^{-\mu(C_r + \ln S_r)}}{\sum\limits_{h \in CS} e^{-\mu(C_h + \ln S_h)}} \tag{2.2}$$

With the path size overlap variable S defined as

$$S_r = \sum\limits_{a \in \Gamma_r} \left(\frac{z_a}{z_r} \right) \frac{1}{N_{ah}} \tag{2.3}$$

where:

P_r the choice probability of route r
C_r generalized costs of route r
C_h generalized costs of route h within the choice set
CS the choice set with multiple routes
h   path indicator/index
μ logit scale parameter
a link in route r
S_r degree of path overlap
Γ_r set of links in route r
z_a length of link a
z_r length of route r
N_{ah} number of times link a is found in alternative routes

2.3.2 Model verification, calibration, and validation

Before the model is validated, as part of model assessment step, we verify the model components such that they accurately represent the characteristics of the global container transport system and are built on solid theoretical foundation from literature. The network schematization, the cost function, and the procedures used in the model were assessed by the experts throughout the model construction phase. To validate the model, we use the predictive validation technique as defined in Balci (1998). In this technique past system input data is used and output data of the model is compared with the corresponding past system output. Specifically, the following steps are performed:

1. calibration of the model parameters
2. comparison of model outputs with available statistics

We adopt the definition of calibration in Balci (1998) as :" iterative process in which a probabilistic characterization for an input variable or a fixed value for a parameter is tried until the model is found to be sufficiently valid". In the calibration process, we estimate the values of port attractiveness parameter (A_p) for each port and logit scale parameter (μ) such

that differences between modeled and observed port throughput volumes are minimized. We use container throughput data that is available for 295 ports worldwide based on the UN COMTRADE data in 2006, and for these ports the model is able to explain over 90% of the amount of variation between ports'throughput volumes. The R^2 value between the observed and modeled throughput volumes was 0.9 (with R^2 value of 1 indicating a perfect fit), indicating a good fit between model output and observed data. The sum of the absolute differences for all ports' throughput volumes divided by the total observed port throughput volumes is less than 10%.

Next, we compare the sum of the modeled throughput and transshipment volumes for all ports with the observed total number of containers handled at ports using data from the European Sea Ports organization (ESPO). Table 2.3 provides the detailed comparison between the model output and the observed data. We can observe that the model produces similar value for the total volume of containers (measured in TEUs) handled at ports to the two observation data. The model produces slightly higher total transshipped TEU, which means that an improvement can be made to better account for transshipment volumes. This will be subject to further research.

Table 2.3 Comparison between modeled and observed container handled at ports (in million TEU)

	Total Handling	Port to port full containers	Port to port Empty containers	Transhipment
ESPO	399	231	59	108
Model output	390			124

As an additional step of model assessment, we visualize the spatial patterns of global container flows using a tool specifically developed for this research project and we assess the face validity of the global flow patterns produced by the model. Here visualization is used as a verification, validation, and testing technique to assess the credibility, and accuracy of the model results (Balci, 1998). The resulting global flows of containers are shown in Figure 2.2. The network allows hinterland transportation routes with different modes of transport such as truck, rail, waterways or short sea but is omitted here for visual convenience. The thickness of the lines indicates the magnitude of the flows on each links. Each port is visualized as a pie chart, which shows the magnitude of throughput (in dark grey) and transshipment (in light grey). A comparison with a visualization made in (Kiln, 2016) using satellite-based Automatic Identification System (AIS) data confirms a good similarity between the WCM output and the observed global container flow patterns.
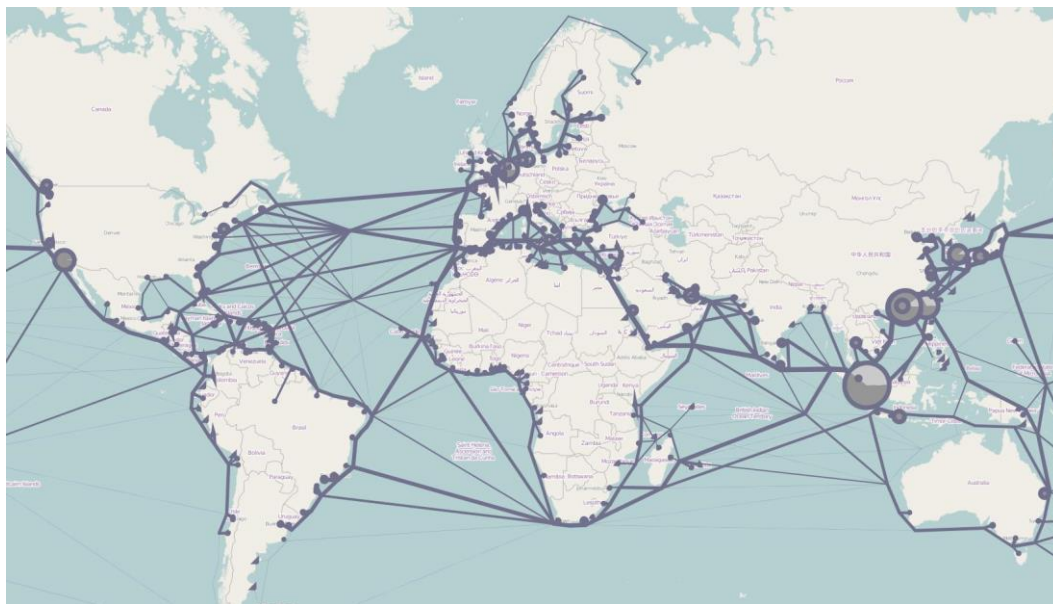
Figure 2.2 the global maritime shipping network in the WCM

2.3.3   Identification of relevant uncertainties

In this chapter, we use the world container model to assess the impact of several key uncertain factors on the global flow of containers. The following key uncertainties are identified relative to the baseline data and treated in the exploratory modeling analysis:

Table 2.4 Key Uncertainties that will impact the performance of ports in the Hamburg - Le Havre range

Name	Range
Cost of hinterland connections in Europe	0%– 25%
Hinterland cost for Rotterdam	-25% – +25%
Travel time of the hinterland connections of Rotterdam	-2 days —+2 days
Costs of the hinterland connection of Mediterranean ports	-25% – 0%
Handling costs of the Mediterranean ports	-25% – 0%
Handling costs of ports in the Hamburg - Le Havre range	-25% – 0%
Trade volume with Asia that is affected by availability of overland connection or shift of production to Eastern Europe	-25% – 0%
Northern passage	(present, absent)
Suez Channel	(present, absent)

The key uncertainties are identified by means of brainstorming and discussions between the experts from various organizations, including the Port authority, Delft University of Technology, and TNO (a national lab). These brainstorm and discussion sessions are conducted as part of a larger project called Masterplan + (Ankersmit et al., 2013, NGI, 2014) which was carried out under the Next Generation Infrastructure knowledge institute. The primary aim of Masterplan + project is defined as: "to provide insight into the impact of structural uncertainties on the Maasvlakte 2 by means of the implementation of the Adaptive Port Policy Planning" (NGI, 2014). In this research, we use the key uncertainties that are

produced by these brainstorming and discussions as input to our analysis. The complete documentation of the brainstorming and discussions activities together with the data used to analyze the key uncertainties are available in (Ankersmit et al., 2013).

These brainstorm sessions and in depth discussions where fed by a meta-analysis of transport scenarios and forecasts across the globe, from a heterogeneous set of actors including port authorizes, national governments, international think tanks, and other knowledge institutes.Visions on possible future developments, forecast studies, vision documents from various institutions, and historical data pertaining each of these uncertainties have been used as input for the discussion. Since we are interested to study the impacts of uncertainties on European ports in general and Rotterdam in particular, the key uncertainties that are identified are limited to those that will potentially impact these ports.

One of the most plausible uncertain factors that could make the ports in Hamburg - Le Havre range to experience a decline in container flows is the increase of hinterland transport cost. This increase in cost can be caused by congestion at the terminals, environmental tax, bottlenecks in the inland waterways, etc. A related factor is that is subject to change is the hinterland cost of Rotterdam. This change can be caused by congestion or improvement in efficiency of the transport networks that connect Rotterdam to the hinterland destinations. In line with the scenario discovery approach, we took a broad bandwidth into account for this factor. We assumed that the change in cost can vary from 25% increase to 25% decrease respectively. Next, the same presumption is also applied to the travel time of Rotterdam's hinterland connections. Improvement in logistics services at the terminal and throughout forwarding process can bring reduction to the total time needed to transport the containers. We specify a range of plausible change for this variable between -2 to 2 days, representing an increase and a decrease in travel time respectively. For the ports in the Bremen – Le Havre range, a change of two days amounts to a significant change on virtually all hinterland connections.

Furthermore, we also identify the developments in Mediterranean ports that can potentially present threats and opportunities for Rotterdam. The Mediterranean ports are closer to the main sources of products shipped to Europe in South East Asia and China. From a logistical point of view, this makes these ports quite attractive. A plausible development is the improvement of hinterland connections of these ports. The improvements can take form of better connectivity due to availability of better infrastructure such as rail and road, and the availability of better freight forwarding services. Eventually, this development can be foreseen to reduce the cost of the hinterland connections of these ports. Furthermore, in the face of competition with ports in the Hamburg -Le Havre range, Mediterranean ports might reduce their tariff so that they can increase their attractiveness for the freight forwarders, especially for containers that can be directly shipped from and to Southern Europe. The plausible range for the reduction of hinterland cost due to this development is assumed to reach a maximum of 25% of the current cost.

The ports in the Bremen – Le Havre range are quite competitive and part of their strategy can be a reduction in tariffs. This reduction in tariff would also increase their attractiveness for liner shipping alliances that use Ultra Large Container Vessels (ULCV) so that they would call hub ports in the Hamburg - Le Havre range. Again, we use a range of up to 25% reduction in tariffs.

At the trade level, we also identify that there can be a reduction in overseas trade volume with Asia due to the presence of overland connections or the possible shift of production to Eastern European countries. As the plausible range of the reduction we used 25% of the current trade volume. Last but not least, we also include uncertainties in the availability of maritime routes such as those via northern passage and Suez Canal. Due to political instability in the Middle East, and the presence of pirates in the Gulf of Aden, the Suez channel might become too dangerous to use of shipping. Due to climate change, slowly but steadily, a new possible maritime route is emerging. This northern passage offers an alternative direct route from China and Japan, via the artic to Europe.

2.3.4   Implementation and Computation

The various uncertain factors may affect the same model parameter. In this case, we handle the effects from the different uncertain factors additively. That is, say we have a scenario with an increase of costs on the hinterland connections in Europe of 20%, in combination with a change of the hinterland connection costs for Rotterdam of -10%, than the final costs will be the original costs + original costs * 0.2 + original costs * -0.1.

To explore the consequences of the various uncertain factors in an open exploration, we defined 10,000 experiments using Latin Hypercube sampling across these 9 uncertainties. This means we generate 10,000 random values for each of the uncertainties within the specified ranges and combine these values in a random order into 10,000 sets of 9 input parameters for the model. So, we sample across the 9 uncertainties simultaneously. Next, the world container model is run for each of the 10,000 scenarios. The experiments where performed of a 48 logical core Xeon E5 workstation, and 192 GB of RAM. Runtime was roughly 4 hours. To support the computational experimentation, and the subsequent analysis, we used the Exploratory Modelling Workbench (Kwakkel and Pruyt, 2013b). This is an open source python project that facilitates the entire process of scenario discovery. The World Container Model is implemented in Java and connected to the workbench using JPype, a Python-Java bridge.

2.4   Results

In this section we present the results of exploratory analysis using two different approaches: open exploration and directed search. By using the open exploration approach, we identify how the uncertain factors jointly impact the throughput of the ports in the Hamburg - Le Havre range. Subsequently, we use PRIM in order to gain a deeper insight on the meaning of the results for Port of Rotterdam. This analysis results in the identification of main factors, which jointly cause Port of Rotterdam to be both vulnerable or flourishing. They are the combination of input variables that cause the ports to experience decline and gain in their throughput respectively. Next, we also apply directed search technique to identify the worst possible scenario that could happen to Port of Rotterdam. This analysis results in the identification of the conditions under which this scenario manifests itself, and to what extend Rotterdam will be negatively impacted by the plausible uncertainties.

2.4.1   *Open exploration and scenario discovery*

Figure 2.3 shows the change of throughput for the ports in the Bremen – Le Havre range across the 10,000 scenarios. To facilitate interpretation, we divided the throughput resulting from the model by the base flow when there is no uncertainty introduced based on the data in the year 2006. This implies that a score lower than 1 means a loss of flow, while a score above one means an increase in flow. In order to allow a comparison across the different ports in the Hamburg – Le Havre range, we have visualized the results across the 10,000 scenarios using a Gaussian Kernel Density Estimate (KDE). The colloquial interpretation of a KDE is that it is a continuous alternative to a histogram. Higher probability density value (y-axis) for a certain port's throughput change value (x-axis) corresponds to higher occurrences of model outcomes with the respective change in the port's throughput value.

So, the figure suggests that Hamburg, Antwerp and Dunkirk are most vulnerable to losing flows. Most of the mass of the KDE of each of these ports is below 1. In contrast, Le Havre and Bremen have most of their mass above 1, suggesting that they benefit from the various uncertain factors. The ports of Rotterdam and Zeebrugge occupy a middle position. The figure also suggests that there is substantial downside risk, and a smaller percentage wise upside opportunity: ports can lose close to 50% of their flow, but only gain a max of almost 20%.
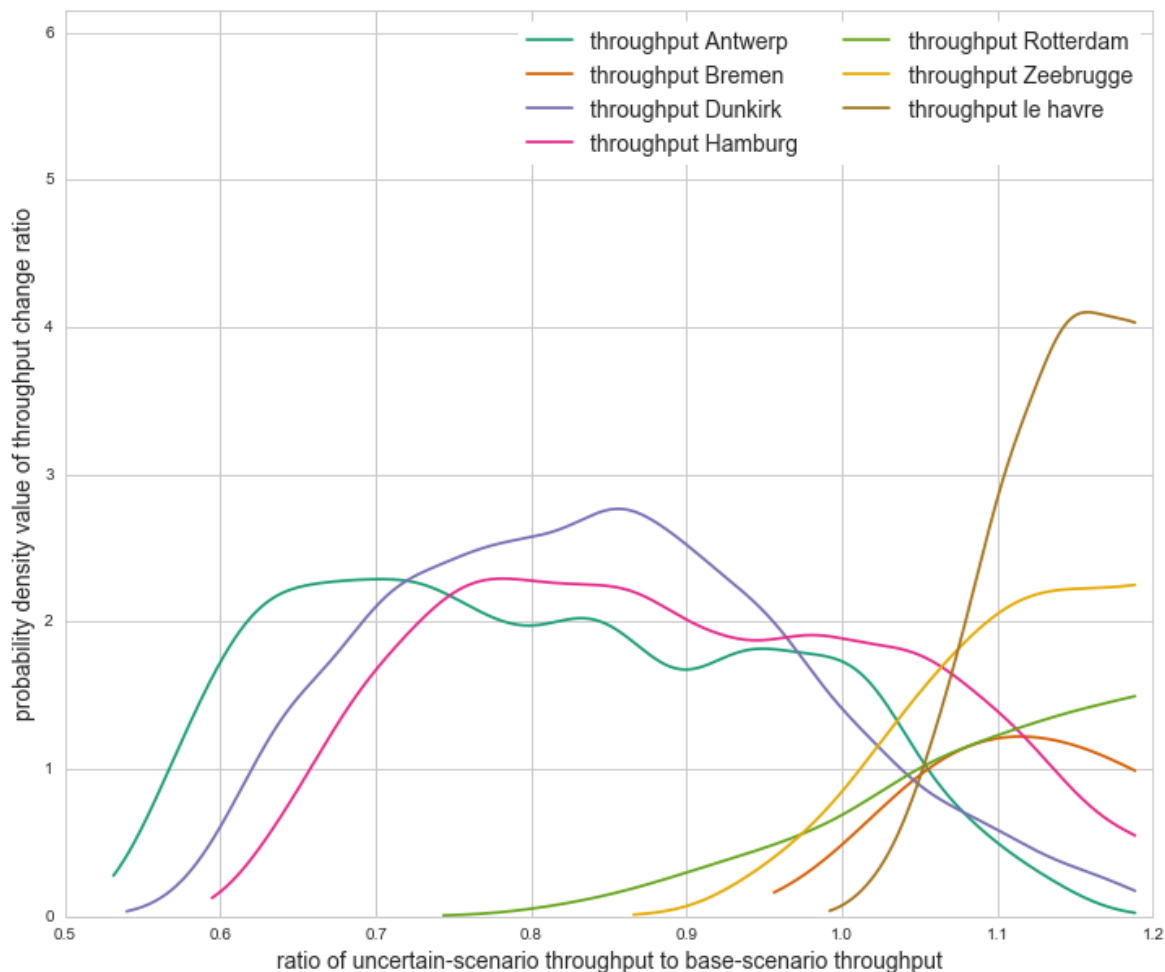

Figure 2.3 Probability density value across port throughputs changes over 10,000 runs

Looking closer at the result for Port of Rotterdam, we observe that there is a small but substantial amount of mass below 1. This suggests that there are quite a number of scenarios where Rotterdam loses throughput as a result of the various uncertain factors. This is indicated by the relatively large area covered by the graph between roughly 0.75 and 1. This suggests that the consequence of the uncertainties can be very significant, where Rotterdam suffer a 25% reduction in their throughput. Based on these findings, it is valuable to get a deeper insight into the combination of uncertain factors that jointly cause Rotterdam to be vulnerable and potentially lose their throughput.

First, we specify when a scenario is of interest or not by establishing a classification rule. To this end, we classify all cases where Rotterdam witnesses any decline in throughout compared to the reference case as being a case of interest. Specifically the following equation is used to classify all the results:

$$f(x) = \begin{cases} 1, if\ x < 1 \\ 0, otherwise \end{cases} \quad\quad\quad (2.4)$$

where x is the factor change in throughput as compared to the base flow for Rotterdam as also used in Figure 2.3. Next, we use PRIM to identify the combinations of uncertainties that jointly produce undesirable results. PRIM returns multiple explanations for the undesirable results. The analyst can select the explanation that covers most of the undesirable result - this is known as coverage in scenario discovery - while also being mainly valid for the undesirable results – this is known as density in scenario discovery (Bryant and Lempert, 2010). To assess whether the inclusion of a given uncertain factor in a given explanation is statistically significant, one can use a one-sided binomial test - this is sometimes also called the quasi-p value in scenario discovery (Bryant and Lempert, 2010).

Figure 2.4 shows the results from the PRIM analysis. The coverage value of 0.75 shows that 75% of the cases with a loss of throughput can be explained by the combination of three uncertain factors: the Hamburg – Le Havre cost factor, the Rotterdam hinterland travel time factor, and the Rotterdam hinterland cost factor. We use critical value of 0.05 and the p-value for all factors were below the critical value indicating that all the three factors play a significant role in Rotterdam's throughput loss. The shaded light grey background specifies the full range for each of these uncertain factors, while the blue lines specify the ranges of values for each factor under which the model output indicates a loss in Rotterdam's throughput.

So, what does this result from PRIM imply? In essence, if Rotterdam experiences an increase of travel time on the hinterland of 0.8 days or more (until the predefined upper bound of 2 days), in combination with a small reduction in costs for the ports in the Bremen – Le Havre range (1.3E-05% until 5.9%), and not an extreme reduction in costs on the hinterland of Rotterdam (20% reduction until 25% increase), Rotterdam will lose throughput. This suggests, that the quality of the hinterland connections of Rotterdam determine the competitive position of Rotterdam in the Bremen – Le Havre range.
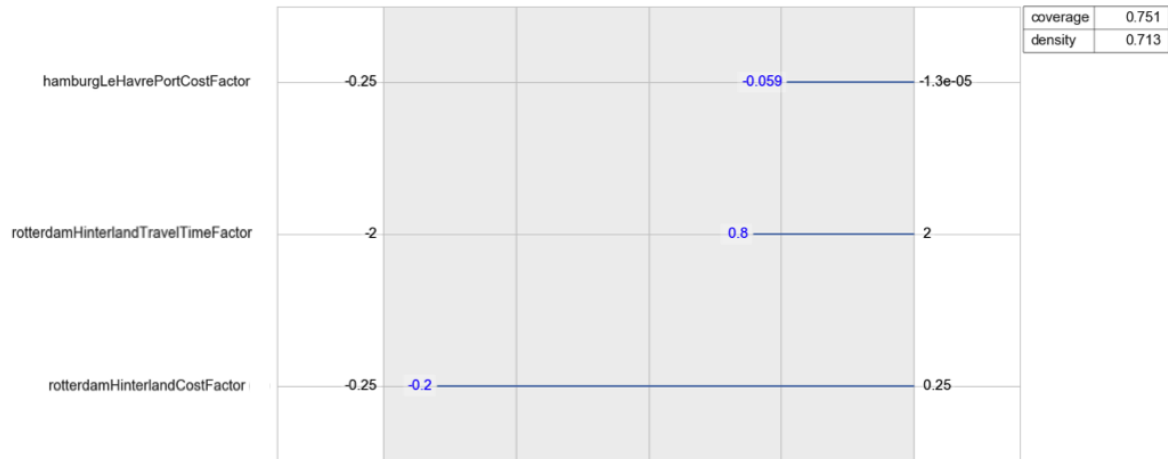
Figure 2.4 Key uncertainties that play a significant role in explaining major cases with negative impact for Rotterdam

Interestingly, an increased efficiency on the hinterland connections of the Mediterranean ports in combination with a reduction in costs for these ports does not cause a significant decline in the throughput of Rotterdam. Furthermore, it is also remarkable that the reduction in trade with Asia does not give a significant effect on the changes in the throughput of Rotterdam.

2.4.2   Directed search for worst case discovery

In search of a perfect storm

In light of the results of the open exploration, a follow up question was formulated by the Port Authority: is there a scenario possible where the combination of small changes in the individual uncertain factor can substantially affect the throughput and transshipment of the Port negatively? Here small changes are defined as changes in uncertain variable values between 5-10%. This question is interesting for the Port Authority to assess the impact of a scenario where the possible known factors jointly cause significant decline in port throughput and port transhipment as well as to gain insight into the conditions that jointly produce this scenario. To answer this question, we formulate a two objective optimization problem as follows :

Decision variables:

l_{rc} : a vector of the values of uncertain variables in the reference case without any introduction of changes

l_p : a vector of the values of uncertain variables with introduction of changes

P_{eucost} : fraction of changes in hinterland cost in Hamburg- Le Havre range

$P_{rothintercost}$: fraction of changes in hinterland cost of Rotterdam

$P_{rothintertravel}$: fraction of changes in hinterland travel time of Rotterdam

$P_{medportcost}$: fraction of changes in mediterannean ports' handling cost

$P_{medhintercost}$: fraction of changes in mediterannean ports' hinterland cost

$P_{hlehcosts}$: fraction of changes in handling cost of ports in Hamburg – Le Havre range

$P_{nothern}$: presence of northern arctic route

P_{suez} : presence of suez canal

Objectives:
- to minimize the ratio between the throughput of Rotterdam in the scenario searched ($Tp_{rotterdam}(l_p)$) and in the reference case ($Tp_{rotterdam}(l_{rc})$).
- to minimize the ratio between transhipment of Rotterdam in the scenario searched ($Ts_{rotterdam}(l_p)$) and in the reference case ($Ts_{rotterdam}(l_{rc})$).

$$\textbf{Minimize } F(l_p) = \left(\frac{Tp_{rotterdam}(l_p)}{Tp_{rotterdam}(l_{rc})}, \frac{Ts_{rotterdam}(l_p)}{Ts_{rotterdam}(l_{rc})} \right) \tag{2.5}$$

$$\text{Where } l_p = \begin{bmatrix} P_{eucosts} \\ P_{rothintercosts} \\ P_{rothintertravel} \\ p_{medportcost} \\ p_{medhintercost} \\ P_{hlehcosts} \\ p_{northern} \\ p_{suez} \\ P_{tradechange} \end{bmatrix}$$

$p_{northern} \in \{true, false\}$
$p_{suez} \in \{true, false\}$

subject to:

$$c1: 0 \leq P_{eucosts} \leq 0.05 \tag{2.6}$$
$$c2: -0.05 \leq P_{rothintercosts} \leq 0 \tag{2.7}$$
$$c3: -0.1 \leq P_{rothintertravel} \leq 0.1 \tag{2.8}$$
$$c4: -0.05 \leq p_{medportcost} \leq 0 \tag{2.9}$$
$$c5: -0.05 \leq p_{medhintercost} \leq 0 \tag{2.10}$$
$$c6: -0.05 \leq P_{hlehcosts} \leq 0 \tag{2.11}$$
$$c7: -0.05 \leq P_{tradechange} \leq 0 \tag{2.12}$$

To solve this multi objective optimization problem, we used ε-NSGA2, a state of the art genetic algorithm for solving multi-objective optimization problems (Reed et al., 2007). We ran the algorithm for 150 generations, and as can be seen in Figure 2.5, the algorithm converged over the course of this simulation. A detailed inspection of the results reveals that all solutions are at the edges specified by the constraints. That is, the maximum negative deviations that are possible specify the worst-case scenarios for Rotterdam. These worst-case scenarios all point to a little bit less than 5% reduction in throughput and transshipment for Rotterdam, given a maximum of 5% change on the uncertain factors. Follow up analysis where we change these boundaries to 10% and 15% respectively, yielded essentially the same results. The loss in transshipment and throughput is about equal to the maximum percentage change allowed on the various uncertain factors.
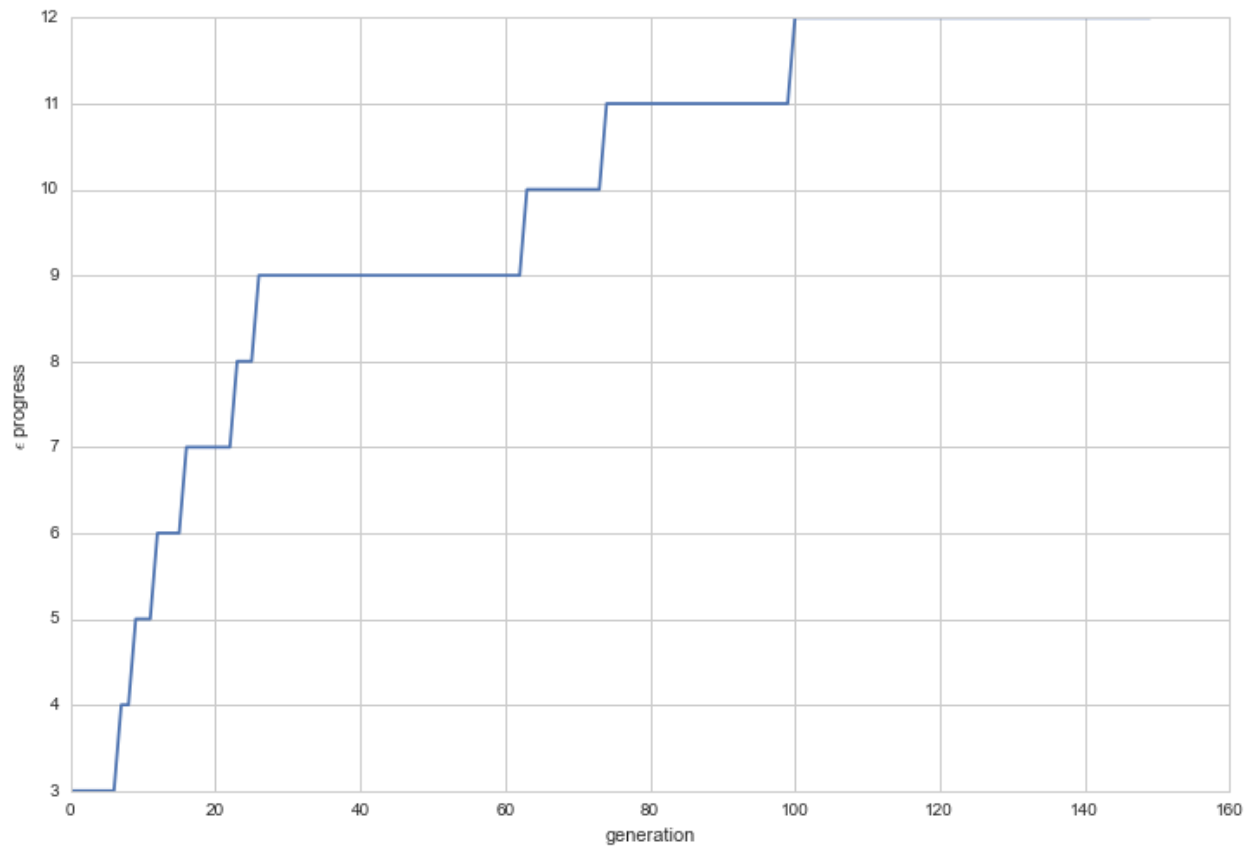
Figure 2.5 Cumulative ε-progress over the course of running ε-NSGA2

Impact of the competition from Mediterranean ports

The analyses so far, aimed at investigating situations where Rotterdam experiences changes in their throughput or where its competitiveness changes in regards to changes in ports in the Hamburg - Le Havre range. Based on the previous analysis, we have discovered that a decrease in the cost factor in Mediterranean ports is not able to increase the competitiveness of these ports relative to Rotterdam. Specifically, the container flows to Rotterdam is not affected significantly when port cost factors of these ports are reduced.

Since there have not been many studies concerning competition between Rotterdam and Mediterranean ports, a more thorough investigation on how increased competitiveness of Mediterranean ports will impact container flows in Rotterdam can give valuable insight to the port of Rotterdam. Hence, in this analysis, we address the question: under which change in the hinterland costs of the Mediterranean ports will Rotterdam be impacted negatively? Thus, instead of defining a plausible range of variable values in which uncertainties might be present and looking at the outcomes caused by one or more major variables, we look at the how big the change in input variables needs to be in order to cause the system to behave in a very specific manner. Specifically we are interested to find combination of factors, which will minimize the throughput difference between Rotterdam and each of the Mediterranean ports simultaneously. This problem can be modeled as a multi-objective optimization problem as follows:

Decision variables:

l_p : a vector of the values of uncertain variables with introduction of changes

P_{eucost} : fraction of changes in hinterland cost in Hamburg- Le Havre range

$P_{medportcost}$: fraction of changes in mediterannean ports' handling cost

$P_{medhintercost}$: fraction of changes in mediterannean ports' hinterland cost

$P_{nothern}$: presence of northern arctic route

P_{suez} : presence of suez canal

Objectives:

f_{genoi} : throughput difference between port of Genoa and port of Rotterdam

f_{barce} : throughput difference between port of Barcelona and port of Rotterdam

f_{marsf} : throughput difference between port of Marseille and port of Rotterdam

f_{laspii} : throughput difference between port of La Spezia and port of Rotterdam

f_{venii} : throughput difference between port of Venice and port of Rotterdam

$$\text{Minimize } F(l_p) = \left(f_{genoi}, f_{barce}, f_{marsf}, f_{laspii}, f_{venii} \right) \tag{2.13}$$

$$\text{Where } l_p = \begin{bmatrix} p_{eucosts} \\ p_{medportcost} \\ p_{medhintercost} \\ p_{northern} \\ p_{suez} \end{bmatrix}$$

$$f_i = |T_{rotterdam} - T_i|$$
$$i \in \{Genoi, Barce, Marsf, Laspii, Venii\}$$
$$p_{northern} \in \{true, false\}$$
$$p_{suez} \in \{true, false\}$$

subject to:
$$c1: 0 \leq p_{eucosts} \leq 0.25 \tag{2.14}$$
$$c2: -1.0 \leq p_{medportcosts} \leq 0 \tag{2.15}$$
$$c3: -1.0 \leq p_{medhintercosts} \leq 0 \tag{2.16}$$

Again, ε-NSGA2 is used for solving this multi-objective optimization problem. As can be seen in Figure 2.6, the algorithm converged quickly. Figure 2.7 shows the results found by the optimization algorithm. In the two sub figures, we use parallel coordinate plots. These plots can be used to visualize data with more than three dimensions. Defining each of the dimensions parallel to one another does this. A dimension is depicted as a vertical line, while a data point in the multi-dimensional solution space is depicted as a line that is connected between different dimensions. The left hand side figure presents the values of each decision variable for each solution, while the right hand side figure present the values of the objective functions of the problem.
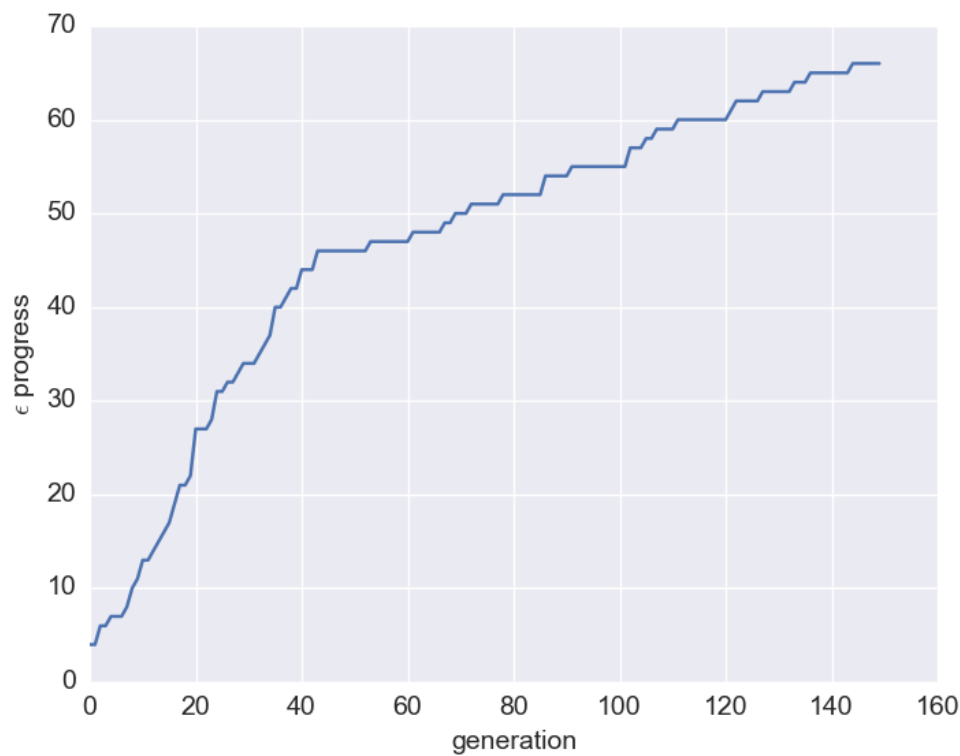
Figure 2.6 ε-progress
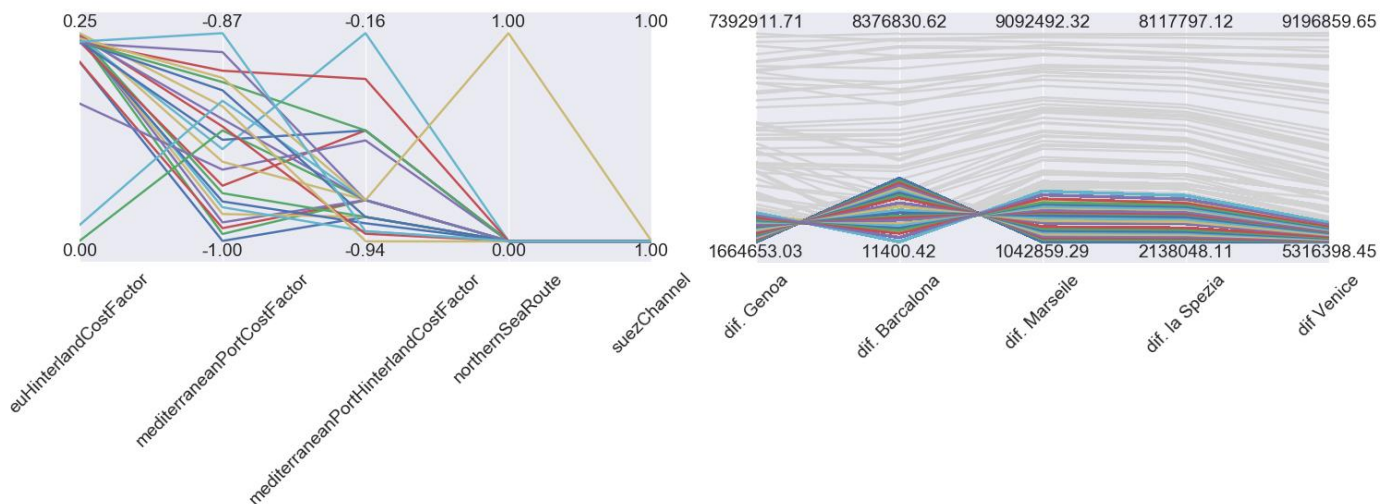
Figure 2.7 Optimization results

As can be seen from the right hand side of Figure 2.7, when the throughput difference between Rotterdam and each of the Mediterranean ports is minimized simultaneously, each of the solutions presents a trade-off across the objective functions. This means all of these solutions are non-dominated which means that there is not a solution with superior performance in comparison with other solutions. For example, the blue line performs well in minimizing throughput difference between Genoa and Rotterdam and between la Spezia and Rotterdam while it performs relatively poor in minimizing throughput difference between Barcelona and Rotterdam.

From the result, it can be concluded that both port and hinterland costs of the Mediterranean ports need to decline significantly in order for them to be competitive against Rotterdam. Surprisingly, the closing of Suez Canal and the opening of arctic route also contribute to the increase of Mediterranean port's competitiveness. This can only happen when liner-shipping companies that call Mediterranean ports before calling Rotterdam do not change their port rotation schedule in the event of such disruptions. In this case, the shortest path from many countries in the Far East to Rotterdam is through the northern passage. As a result, transport cost from these countries to Rotterdam will increase significantly due to the increase in distance that has to be travelled by these shipping companies. In a more realistic scenario, an adaption of the shipping routing is expected to take place. We return to this point below.

2.5 Closing remarks

The global container transport network is constantly changing in response to a wide range of developments. It is virtually impossible to correctly anticipate the future dynamics of how global flows of containers can change due to the intrinsic complexity of the network and the wide range of uncertain factors affecting the network. For ports, this poses a profound challenge in their long term planning of their strategy and investments.

To address the combined challenge of complexity and uncertainty, we used a novel model-based approach to scenario development. Rather than predicting future container flows for a limited set of alternative assumptions, we systematically explored what the container flows could be across 10,000 scenarios, covering 9 uncertain factors. The analysis focused on the consequences of uncertainty for the competitive position of the port of Rotterdam in the Bremen – Le Havre range. Uncertainties that were taken into account included changes in global trade flows, changes in the physical network available to ships, and various factors related to transportation costs of ports in Europe and costs on the hinterland connections within Europe. It was found that the key vulnerability factor affecting the competitive position of Rotterdam is the quality of their hinterland connection. A modest increase in travel time on the hinterland connections from Rotterdam will shift flows away to other ports in the Bremen – Le Havre range.

In two follow up analyses, we used an optimization based search strategy in pursuit of two worst-case scenarios. First, we search for the presence of a perfect storm where a set of small changes jointly substantially deteriorated the competitive position of the port of Rotterdam. We were not able to find such a perfect storm, which suggests that the competitive position is quite robust with respect to small changes.

In a second analysis, we tried to find a scenario where the Mediterranean ports become serious competitors with Rotterdam. We were able to find such a scenario, which includes the use of the northern passage and the closure of the Suez channel. This counterintuitive result suggests two things. First, it points again to the robust position of Rotterdam in the current global container shipping network.

Second, the results of the second directed search point to one of the main limitations of the presented study. The uncertain factors we explored focus on different aspects of global container transport, but they were mainly focused on the ports and the hinterland connections.

We have not explored the impact of changes in the shipping line network itself and how these could affect global trade flows. The analyses that have been performed assumed the global shipping service networks to remain the same across different scenarios. This is a gap that needs to be addressed as this change in the networks certainly poses uncertainty to the ports in the Hamburg - Le Havre range and it can make the position of the ports to be vulnerable. This is not a trivial challenge, because at present to the best of our knowledge no model exists that represents the dynamics of shipping line companies changing their network structure over time. The available literature, instead, focuses on optimizing the routing and frequency for individual shipping lines, or occasionally for an individual shipping company.

Modeling how shipping companies change their network is not simple as there are many factors, both observable (such as cost of transport, market share coverage, and international competition policy) and unobservable (internal agreement between shipping companies to form alliances, political agendas of relevant governments, strategic behavior on part of the shipping companies, etc.), that contribute to the actual structure of their network at any given point in time. Hence, in order to systematically deal with this uncertainty, a separate model needs to be developed with which changes in the global shipping networks can be estimated and its impact on the ports can be assessed. Combining such a model with exploratory modeling analysis and scenario discovery would give a valuable insight in how uncertainties in global shipping network will impact the performance of the ports.

To conclude, the results in this chapter demonstrate the value of using scenario discovery as a method that utilizes simulation models to explore a wide range of plausible futures and summarize the results into concise and clear insights. Scenario discovery, both through open exploration and directed search provides a solid approach for answering strategic questions that come up in the long-term planning of ports.

2.6 Acknowledgements

"Every kingdom divided against itself is brought to desolation;
and every city or house divided against itself shall not stand."
-the gospel of Matthew 12:25, the Bible-

3 Modelling the impact of hinterland distribution structure on port-hinterland flows

Abstract

An important insight obtained from scenario discovery study presented in chapter 2 is that the hinterland connectivity of the port of Rotterdam plays a crucial role in determining its competitive position in the Hamburg - Le Havre range. An increase in cost in the hinterland connection of Rotterdam may significantly reduce the container flows transported through the port. This finding calls for a deeper study on the factors that influence transport cost in the hinterland link of the port and how they will, in turn, affect the volume of containers transported through the port. Apart from operational cost factors such as congestion, and availability of mode of transport, a strategic factor that significantly determines hinterland transport routes and its associated costs is the structure of the distribution network. The way the ports, distribution centers and destination regions are connected, determines the routing of the goods, shipment size, and eventually the cost associated with each of the routes.

The main question that is addressed in this chapter is "How does port-hinterland distribution structure affect the flows of containers that are transported through ports?". In order to answer this question, a strategic freight modeling approach which takes the location of distribution centers into account needs to be developed. As such, this chapter focuses on the development and application of a set of models that can be used to estimate the impact of hinterland distribution structure on port related flows. The model presented here is designed to support policy making exercises by providing the decision makers with insights on the

impact of different trade scenarios on port hinterland distribution structure and consequently, also on the competitiveness of the ports.

This chapter is structured as follows: in section 3.1, we present an introduction that provides a background on the need and challenges to develop a freight demand model, which take logistics considerations into account. Furthermore a modelling approach and framework designed to answer this need is presented. The framework provides an overview of computational steps that need to be performed by different models to estimate how port-hinterland distribution structure affect port flows. Section 3.2 presents the specification, validation, and application of the port-hinterland model, while section 3.3 elaborates on the method to build the integrated models. Specifically, the models that we highlight in this chapter are the port-hinterland logistics network model, and the integrated maritime-hinterland network choice model. Lastly, we present conclusions obtained from the development and application of these models on a case study in Europe.

3.1   Introduction

In the past decades, international trade has grown substantially due to flourishing interregional economic cooperation and international economic competition. Established and emerging economic blocks such as ASEAN (Association of South East Asian Nations), AANZFTA (ASEAN, Australia, and New Zealand Free Trade Area), EFTA (European Free Trade Association) the EU (European Union), RCEP (Regional Comprehensive Economic Partnership), BRICS (Brazil, India, China, Russia and South Africa) and IBSA (India, Brazil, South Africa) are increasingly aware of the need to stimulate and facilitate trade between their member states.

Advances in the efficiency of global freight logistics systems play a key role in supporting the growth of international trade, specifically trade taking place between major economic blocks and continents. Major developments such as containerization and the emergence of global maritime shipping networks have reduced maritime transport cost to an unprecedented level. Logistics services in the maritime component of the global freight transportation system have become very efficient. However, inland freight distribution systems, which connect the maritime network to production and consumption sites, still face profound efficiency challenges.

Hinterland transport costs, on average, constitute 80% of the total transport cost of intermodal shipment, while hinterland transport covers only 10% of the total transport distance (Rodrigue and Notteboom, 2012). Port-hinterland transport costs are both a strong measure of port connectivity, as well as the highest cost component in global freight transport chains. Improvements in port-hinterland distribution systems will positively impact the connectivity of ports to hinterland destinations, while simultaneously substantially reducing costs in global shipping networks. In fact, as concluded in the previous chapter, port-hinterland connectivity plays a very important role in the port choice of the shippers and hence the routing and volumes of transported goods.

Unlike maritime freight transport, hinterland transport is much more resistant to changes due to the involvements of many actors, and the strong path dependency in infrastructure developments. A salient example is the tension between the slowly developing

port-hinterland infrastructure, and the rapidly growing demand for hinterland freight transport (Notteboom, 2008). Over the past couple of decades, there has been a steady increase of port related flows. This has caused traditional direct shipments using trucks to face problems such as congestion, negative environmental impacts, and economic losses due to prolonged transport time.

Logistic service providers respond to the tension between transport demand and transport supply by dynamically adapting their services and strategies, ensuring that producer, product, and customer service level requirements are met. Strategic logistics decisions related to the selection of the right modes of transport, the location of distribution centers and the connection between these, in search for the lowest generalized logistics cost. Regular updates of these decisions by shippers and logistics service providers will follow the fast paced changes in trade flows and will determine the way seaports are connected to hinterland destinations.

So far, only few aggregate predictive models have been developed to test policy measures in port-hinterland distribution systems. The majority of port-hinterland literature contributed to the taxonomy and conceptualization of port-hinterland distribution systems (see e.g. Notteboom, 2008, Notteboom, 2010, Notteboom and Rodrigue, 2005, Rodrigue and Notteboom, 2010, Van den Berg and De Langen, 2015). Moreover, those researchers that do apply quantitative modeling approaches typically aim to optimize the cost or profit of individual companies (Goetschalckx et al., 2002), rather than focusing on the aggregate port-hinterland distribution system with multiple different companies/operators. Models that explicitly address the design of port-hinterland intermodal connections are among others Wan et al. (2014) and Lam and Gu (2013) and Ypsilantis (2016). However, these models suggest normative designs of intermodal connections in the port-hinterland network, do not take government perspective for policy making, or account for distribution centers in these logistics networks. We intend to fill these gaps.

The main subject of this chapter is the quantitative modelling of port-hinterland distribution systems, aimed at providing support to strategic decisions to improve the efficiency of hinterland infrastructures and services. Firstly, we present a novel approach to descriptively model complex port-hinterland distribution networks. The approach utilizes an integrated multi-stage logistics network model for aggregate agents, recognizing heterogeneous service preferences and including locations of distribution centers[5] that serve port-hinterland flows. We use the model to analyse how locations of distribution centers and their connectivity to the ports impact the routing of global container flows. Our approach also allows for calculating port-hinterland connectivity using advanced measures of port-hinterland transport costs and transport time, which account for these complex port-hinterland distribution networks. Since strategic changes in hinterland networks normally affect large regions (such as the European Union), the geographic scope of the model is therefore, that of a continent, which covers the hinterland of a major maritime port. This is a scale at which port competition and port-hinterland connectivity will typically be studied. To demonstrate the feasibility of the model, we present an application to the European port-hinterland

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[5] There exist many definitions of what a DC is. In this research, we consider a DC to be either a warehouse where containers are stripped and the contents are stored or cross-docked, or a container depot where goods wait inside the container to be called by a factory nearby

distribution network, for which data are readily available. We consider 1445 regions at the NUTS-3 (The European nomenclature of territorial units for statistics) level as demand regions, 309 regions as potential DC locations, and 121 seaports in Europe, as the origins and destinations of the port related flows. Secondly, we develop an integrated global maritime-hinterland network choice model as a tool to analyse port-hinterland transport flows comprehensively. The model allows to investigate the impact of various changes including demand growth, infrastructure supply and transport pricing.

3.1.1 Challenges in integrating logistics into freight demand modeling

The need to integrate logistic considerations into freight modeling has long been acknowledged and discussed (see e.g. Tavasszy et al. (2012) for a recent review). These considerations may vary from the operational level such as the effect of economy of scale on shipment size, to the tactical level such as vehicle routing between production and distribution facilities, or the transport mode being used, to the strategic level, which include the location of the DCs and the supply chain structure.

We see the basic architecture for an integrated model that has a solid theoretical foundation as one that complements the classical 4-step modelling approach, such as the 5-step modeling approach proposed in (Tavasszy and de Jong, 2014). In this architecture, the integrated model has a separate logistics module which explains the choice for the location of DCs and the routing of goods from origin to destinations using these DCs (Figure 3.1). A functionally consistent network choice model should be able to produce such supply chain structures to be included as choice alternatives for the shippers. The advantage of using this approach is that when trade flow or other relevant cost variables (such as distances between the logistic nodes) change, the projected spatial pattern of the flows would take the changes in distribution structure into account.
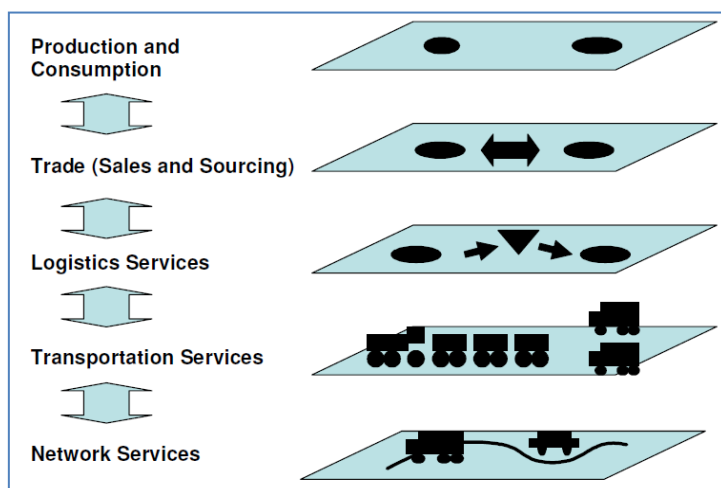
Figure 3.1 5-Step modeling approach

However, there are not many logistics model which comply with this architecture. This is because the developments of such models are often hindered by the unavailability of data regarding trips and flows generated by the DCs (Huber et al., 2014). Among many freight models that incorporate logistics considerations, only few models incorporate the effect of the DCs on freight flows comprehensively such as the SYNTRADE (Friedrich, 2009), Logistics

Chain Model (LCM) (Davydenko et al., 2014), LAMBTOP (Mommens and Macharis, 2014) and the integrated model presented in the Maurer (2008). LCM is an aggregate logit choice model for European distribution structure developed by Davydenko. This model uses a discrete choice approach, similar to the principle used in estimating the throughput of the distribution centers in the Netherlands in (Davydenko and Tavasszy, 2013). However, all of these models are developed to analyze inland trade and there is no freight transport model that has been developed to address issues for port-hinterland transport.

A plausible way to incorporate logistics considerations into freight demand models is to use a hypernetwork approach. Tavasszy et.al (2010) proposed modelling inventory decisions such as the location of distribution centres as part of a hypernetworks choice problem. In this approach, different layers of the network represent segments of the chain upstream and downstream from distribution centres. Hypernetworks are a generalization of the transport network concept into choice alternatives that go beyond transport activities (Friedrich et al., 2013). Though important, most of the hypernetwork methods that have been developed do not provide a framework for a descriptive, or empirical model. Nagurney et al. (2002), and Yamada et al. (2009) present normative frameworks to model distribution centers within a supernetwork setting.

Hypernetwork approach can be used to integrate logistic network structures into infrastructure networks used in freight demand models. Specifically, we can generate choice sets of alternative routes that takes into account distribution structure between each origin and destination. Subsequently, a route choice model can be implemented using deterministic or probabilistic network choice methods. Note that this approach differs from the supernetwork approaches for transport mode choice. In supernetwork, the choice for inventory location is not included or the alternative routes constitute only transport service related network choices and not, like in this case, the choice of supply chain configuration.

The aim of this research is to develop a descriptive model that reproduces observed distribution activities. There exist some examples of such models, however not within the setting of port-hinterland networks. Other freight supernetwork modelling approaches (Friesz et al., 1986, Guélat et al., 1990) focus on the question of network equilibrium, assuming congestion costs in the network which makes transport costs dependent upon flows. A more difficult problem that is typical for freight and where flows cannot be solved for a global network flow optimum concerns the economies of scale in a network (Zhang et al., 2013). We ignore these economies and diseconomies of scale, in order to develop and test a simplified (yet sufficiently complex) empirical model of the combined problem of port choice, DC choice and hinterland mode/route choice.

3.1.2   *Modeling global intermodal transport system using hypernetwork approach*

Intermodal freight transport is an important area of application of hypernetwork modelling approaches. Ports, together with networks of shipping lines, and inland intermodal transport form a global intermodal freight transport network. At the global level, there are few freight models that describe world trade flows; examples of those are the World Container Model (WCM) (Tavasszy et al., 2011), Container World (Sinha-Ray et al., 2003), and GloTram-2 (Smith et al., 2011). In the context of investigating how changes in global trade flows affect the performance of ports, the WCM is suited to analyze the port choice of

the shippers at the global maritime scale. In comparison to other global scale freight models, the WCM has the most comprehensive specification of global shipping service networks and ports.

There are only a few examples of port-hinterland oriented freight network models. Jeong et al. (2007) and Limbourg and Jourquin (2009) optimize the locations of container terminals in Europe. However, they do not explicitly address the issue of port-hinterland connectivity. Among the few aggregate models available, only the Interport model (Wan et al., 2014) and the models described by Lam and Gu (2013) and Zhang (2013) address the optimization of the intermodal port-hinterland system. The Interport model has been further extended and used to design a multimodal inland transport solutions in Italy that can increase the efficiency of private and social cost of the freight system (Davydenko et al., 2014). Lam and Gu (2013) focuses on the optimization of both the total generalized logistics costs, and the door-to-door transport time as new indicator for competitiveness. Zhang (2013) includes the expected usage of transshipment terminals in the optimization. Unfortunately, none of these models address the emergence of port-hinterland distribution networks resulting from the establishment of hinterland distribution centers.

Using a hypernetwork approach, we can extend a global maritime network choice model such as WCM with a port-hinterland network choice model. The figure below shows how the distribution structures in the hinterland will form new origin/destination pairs for transport, for which decisions on mode choice and routing will be made. Among the available models, the CLONE model (Halim et al., 2015a) has a distinct feature of being designed as an aggregate model of port's hinterland logistic network. Therefore using this model as a part of the integrated model proposed would fit into the modelling objective of this research.
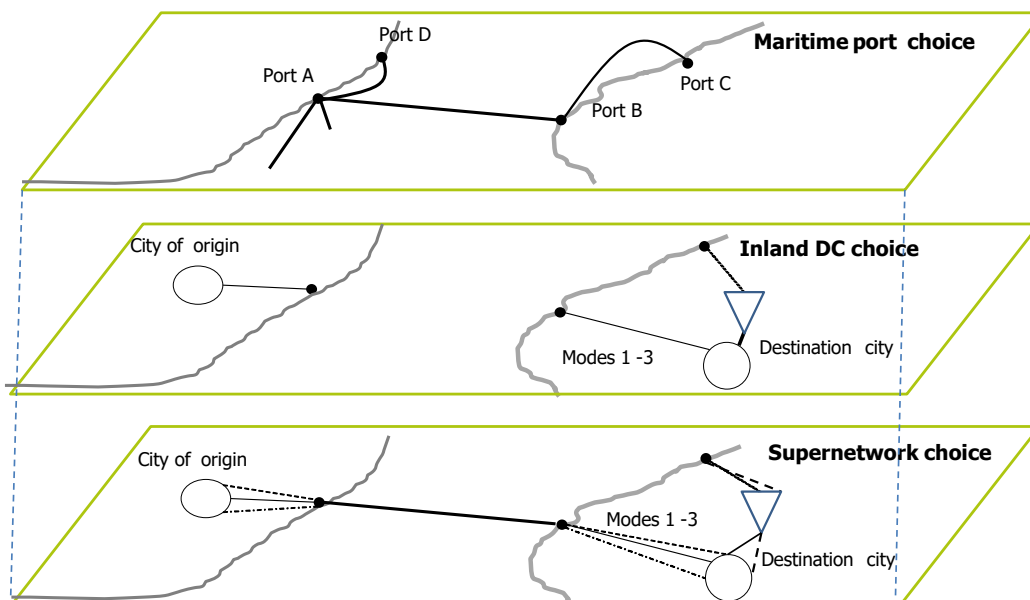
Figure 3.2 Sketch of the combined port/hinterland model

3.1.3   A multi-level modeling approach for an integrated transport model

In this section, we present the modeling framework used to combine the port-hinterland model (CLONE) and the World Container Model (WCM). The sub models which are part of this framework were developed independently but together allow analysis of an intermodal transport system both from the supply side (in this case the maritime services, DC regions and hinterland transport networks) and the freight demand side (global trade and door-to-door transport flows). Below we describe the components and the operation of the combined model (Figure 3.3).
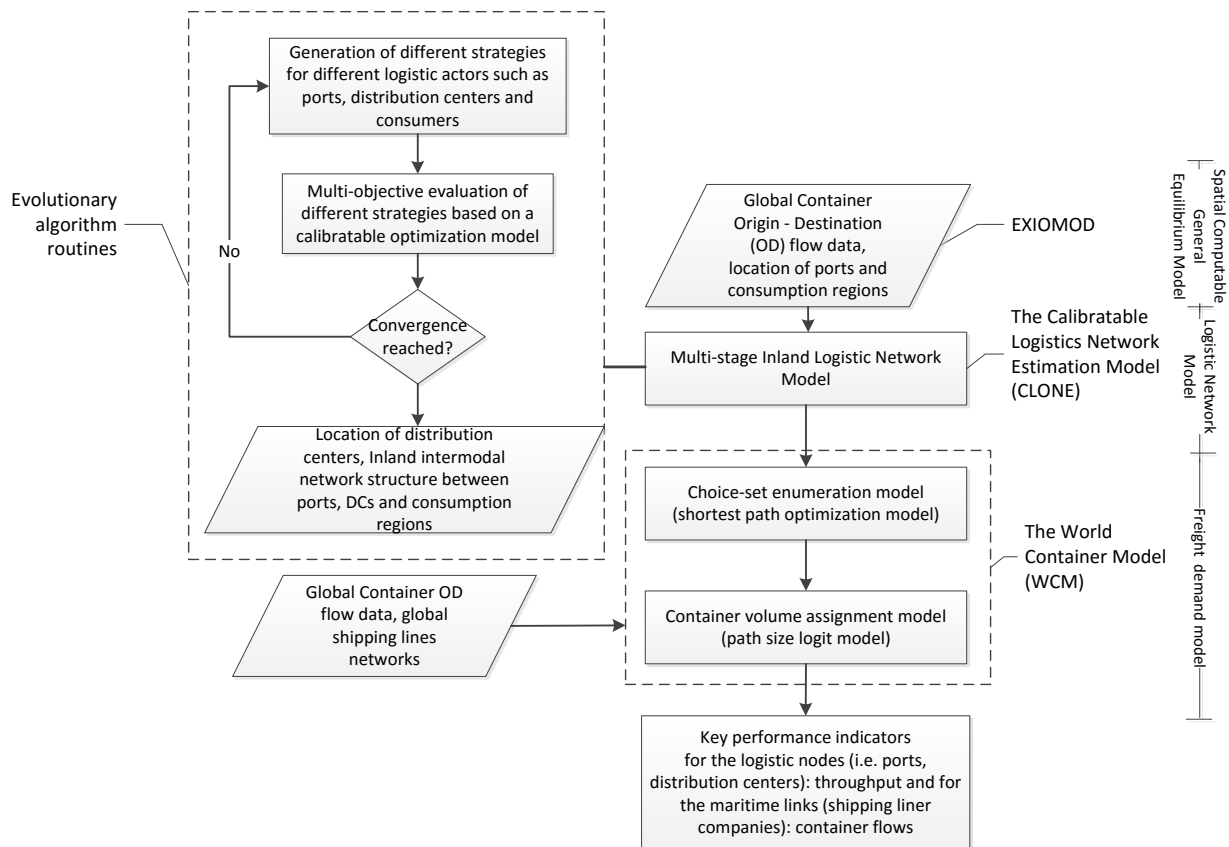
Figure 3.3 Multi-level computational framework

The main input data used in this framework are the flows of container trade (Origin - Destination flow) for 237 countries in the world, the geo-locations of the ports, consumption regions, and the shipping networks. We obtained the OD data as an output of a Spatial Computable General Equilibrium (SCGE) Model EXIOMOD (Ivanova, 2013), which produces global production, consumption and trade flows.

We use the CLONE model to estimate the distribution structure on the hinterland based on the magnitude of container flows going into economic regions in the hinterland. Thus, we can estimate how changes in container flow distributions defined at OD level would affect the inland distribution structure.

After the distribution structure is estimated by the CLONE model, the WCM uses that together with the global OD flow, and global shipping lines network in order to assign container flows. By using this distribution structure, a special choice set is made for each destination, taking into account the DCs as well as the ports to which a destination/

consumption region is connected to. A path size logit model is then used to assign the container flows to all OD pairs over the global intermodal network. We elaborate on this approach in the remainder of this section.

First, the CLONE model produces a hinterland distribution structure which consists of DC nodes, linkages between DCs and the ports, and linkages between the ports and destinations/ consumption regions. For each of the origin-destination pairs, a unique choice set containing alternative routes is created. A route may consist of a hinterland link connecting the origin to the nearest outgoing port, the shortest path from this port to the incoming port, a hinterland link from the port to the distribution center, another hinterland link from the DC to the destination or a direct link from the port to the destination. The shortest path between the outgoing port and incoming port depends on the available service networks of different liner shipping companies which call at these two ports with a certain order and possible transshipment in between these two ports. We obtained the data of these networks from the publicly available shipping tables of container shipping companies worldwide.

3.2 A strategic model of European port-hinterland freight distribution networks

Model-based analyses can provide insights and results for decision-making process such that effective and robust policies can be made. Davydenko et al. (2014) provide examples of how a logistic model can be used to assess the impact of integrated policy measures on the port-hinterland system. The authors use an optimization model to evaluate the impact of different policy instruments such as infrastructure developments and changes in regulatory framework on the total costs and CO_2 emissions of the port-hinterland multimodal transport system in Italy. Another example is Van den Berg and De Langen (2015), where policy questions related to the development of port infrastructure are addressed using regression analysis. Qualitative studies aimed at supporting policy making in port hinterland systems include Dooms et al. (2015), Van den Berg and De Langen (2015). Most of these studies argue also that there is a need for developing a toolkit for measuring the societal and economic impacts of policy measures on the port-hinterland system. Three studies in which port-hinterland connectivity has been studied quantitatively are Ferrari et al. (2011) Thill and Lim (2010) and Wang et al. (2016). These studies use models of hinterland transport networks to calculate port connectivity measures. The main independent variable in the connectivity indicator is transport distance or cost. Importantly, however, these studies still ignore the possibility of using DC's in a logistic network, and they disregard the trade-off with service levels in terms of transport time. The model presented here provides such insights and thus allows for calculating extended measures of port connectivity.

The model is designed according to the principles discussed in Friedrich et al. (2013), with parameters which can be calibrated to enable the use of the model to describe the observed transportation flows of the system under study. Specifically, the model presented in this research is developed to: (1) calculate locations of distribution centers/hubs based on economic activities in different regions; and (2) calculate routings of freight from ports to distribution centers and to consumption sites and from consumption sites to distribution

centers to ports. We formulate the model based on a multi-objective, multi-actor optimization approach to take into account the rationality of different stakeholders such as shippers and logistics service providers. Using this optimization approach, the distribution of preferences in the trade-off between total logistics costs and demand coverage is used to derive the aggregated port-hinterland distribution network.

One of the challenges in modeling the port-hinterland logistics network is that there are different types of distribution network configurations that emerge in response to client service level requirements. If we take Europe as an example, depending on the type of product or service, distribution networks can take extreme forms such as a continental, central DC or multiple Regional DC's. (Davydenko and Tavasszy, 2013, Rodrigue and Notteboom, 2010) – see Figure 3.4 with examples for Europe. In between these structures there are other intermediate structures with varying degrees of centralization. The layout of distribution structures depends on the service requirements and cost structures associated with different types of commodities.
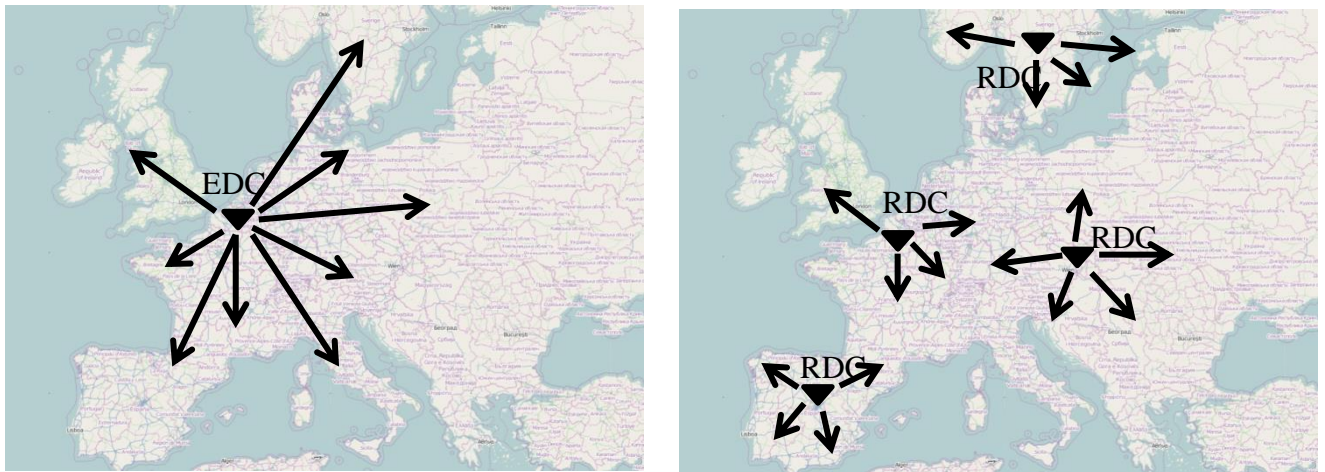
Figure 3.4 Centralized European DC (left) vs Regional (right) DC structure (HIDC, 2014).

In a network with a European DC, products are shipped directly from the production facility or ports to the European DC (usually in full containers), and then further distributed to clients in different places. This configuration is cost-efficient as it produces economies of scale from consolidating the inbound transport and the fact that it only uses a single DC. With the development of consumer markets, the need has risen to shorten the delivery-lead times of goods. This has resulted in higher shipping frequencies, decentralization and a rise in total logistics costs. For some companies, supplying all the demand in Europe from a single centralized DC has become inefficient. To reduce lead time, they have switched their distribution network configuration from having a single centralized European DC to multiple regional DCs (RDCs). They typically have 3 or 4 RDCs spread out over Europe, where each RDC serves a particular region or market. The RDC's are supplied either through a single centralized DC, or directly from the production facilities. Networks with a central DC and RDC's are used by companies that want to maintain a short delivery lead time to the clients while at the same time keeping economies of scale effects on the inbound transport to the central DC.

The approach that we take in this model is as follows. By means of an optimization model we generate alternative distribution structures that represent optimal trade-offs between service levels and total logistics costs. The choice between these alternative distribution network structures is determined by the preferences of individual companies concerning service level versus costs. Next, the throughput volumes for each DC region are determined by assigning the port-to-DC flows to the distribution structures. We estimate the distribution of service/cost preferences across the population of companies using statistics of the usage of distribution centers. In this way, we obtain useful performance metrics for policy-related analyses on the port-hinterland distribution system under study. In the research we present here, metrics include the total gateway throughput market coverage of each port, and the average distance between ports and DCs, total transport cost and time from port to client regions, and transport lead time from DC to client regions (see section 5 for the detailed results on these metrics). Figure 3.5 describes the computational steps employed. Below, we describe each of these steps in more detail.

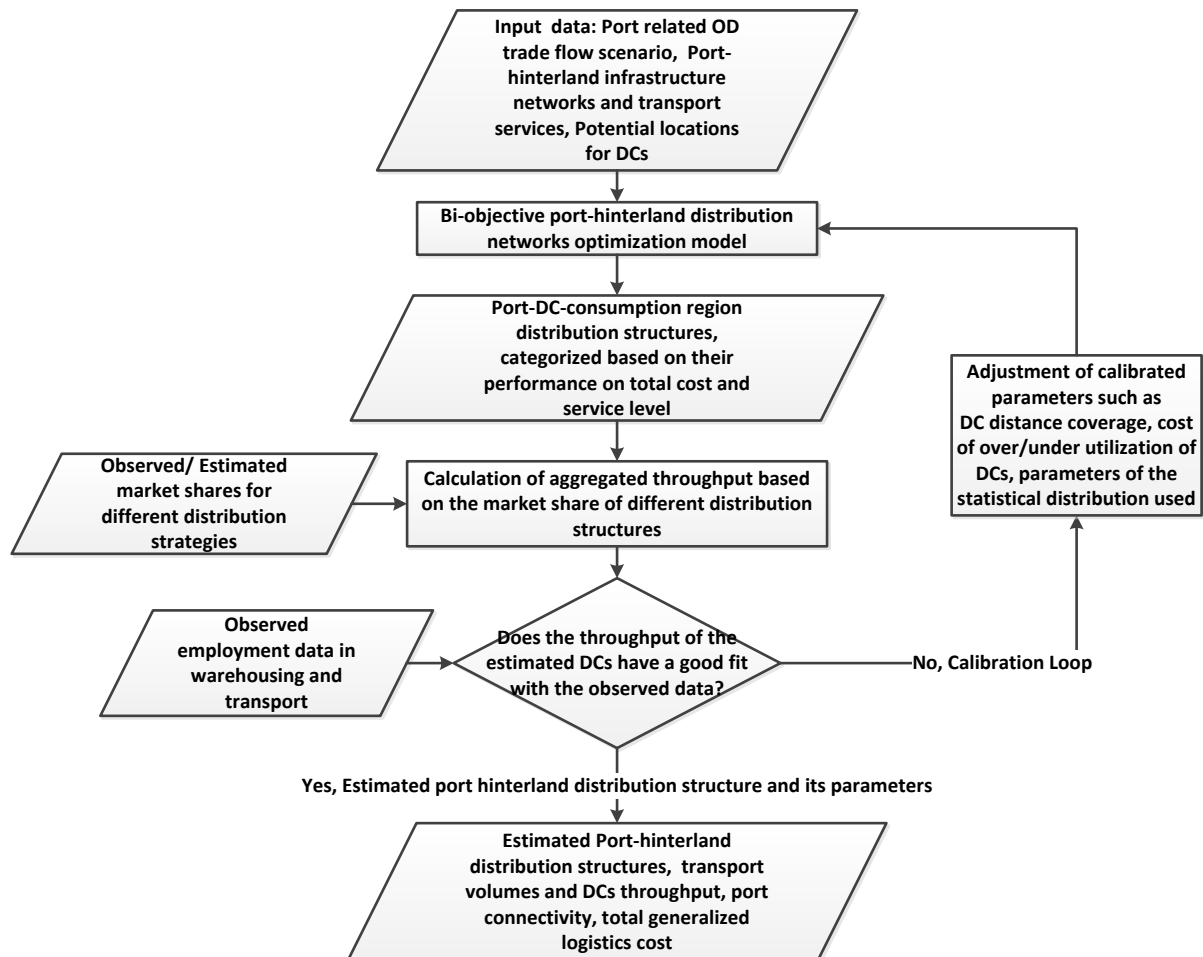**Figure 3.5 Computational framework for the logistics network estimation model**

3.2.1   Bi-objective Logistics Network Optimization Model

In order to model the locations of DC's including the supply network that serves these centers, we approach the modeling problem as a Network Design Problem (NDP). This class of problems can be applied to determine the locations of distribution centers and the routing

of the flows of the transported materials or the supply network in such a way that the total logistics cost can be minimized (Gen et al., 2008). In many applications, models for solving the NDP have been used to optimize key performance indicators of individual organizations. Turnquist (2006) and Nozick and Turnquist (1998) provide generic examples of modeling the trade-off between costs and service levels for distribution centers at the scale of the North American continent. The design of a global distribution network for a chemical company is presented in Baumgartner et al. (2012). Another example is given by Roni et al. (2014) where a biomass co-firing distribution network is designed for the United States. In our approach we use the NDP as a basis for modeling the logistic networks of multiple companies simultaneously.

The formulation of the objective functions and the constraints of the optimization problem are based on a multi-stage capacitated facility location model (Klose and Drexl, 2005, Nozick and Turnquist, 1998). Since the model considers two distribution stages (i.e. from ports to DCs and from DCs to client/demand regions) and each client region is served by one DC, the model is a Two Stage Capacitated Facility Location Problem with Single Sourcing or a TSCFLPS (Klose and Drexl, 2005). In this model, a distribution system is comprised of two distinct hierarchical layers where location of facilities on a higher level is determined independently of the facilities that are chosen on a lower level. Although our model is based on a traditional TSCFLPS formulation, its formulation has been adapted to take the context of port-hinterland distribution networks into account. Traditionally, facility location models have been used to optimize the distribution networks of manufacturing companies where decisions for locating production facilities, and distribution centers along with their client regions are optimized (Ding et al., 2009, Nozick and Turnquist, 2001). The model we propose is based on this rationality, yet it is specifically designed to estimate port-DC-client regions distribution networks. Furthermore, the main objective of traditional TSCFLPSs has been to minimize total system cost, or to maximize profit while fulfilling a certain service level. That is, the traditional model is mono-objective, where other potential objectives such as service level or environmental impacts are included as constraints (Harris et al., 2014). In contrast, our model is explicitly multi-objective, given the heterogeneity among different companies regarding service level requirements. Our model uses two objectives: the minimization of overall transportation costs, and the maximization of the coverage of the client regions by the whole distribution network. The coverage of client regions here is defined as the percentage of the demand total regions that can be served within a certain predefined service radius or time. This metric can be used as a way to measure the service level or service-responsiveness of a distribution network (Nozick and Turnquist, 2001, Turnquist, 2006). The model will identify different port-hinterland distributions structures reflecting different tradeoffs between total logistics costs and client regions coverage. The model is specified as follows:

Input parameters:
I: total number of ports
J: total number of DCs
K: total number of client/demand regions
a_i: throughput of port i, (TEU, Twenty-Foot Equivalent Unit)

r_k: demand of client k, measured by the flows of freight going into this region, (TEU)

f_{ij}: unit cost of transportation from port i to distribution center j, (US\$/TEU.km)

d_{ij}: distance from port i to distribution center j (km)

f_{jk}: unit cost of transportation from distribution center j to demand region k (US\$/TEU.km)

d_{jk}: distance from distribution center j to demand region k (km)

q_j: amount of supply flow to distribution center j (TEU)

w_j: cost for establishing and operating distribution center j (US\$/TEU)

α: uncertainty factor describing the fluctuation of stocks in distribution center j (0.1-0.25)

u: average fraction of capacity utilization of the distribution center (0.8-0.9)

b: average fraction of capacity which is subjected to the fluctuation of demand (0.1-0.2)

γ: penalty cost per percentage of capacity shortage of the distribution network (US\$/percent)

Decision variables:

x_{ij}: binary variable for the decision of supplying distribution center j from port i

y_{jk}: binary variable for the decision of supplying demand region k from distribution center j

z_j: binary variable for the decision of establishing a distribution center at location j

s_j: capacity of distribution center j

Objectives of the model:

to minimize z_1:

- total transportation costs from the ports to the distribution centers and from the distribution centers to the ports
- total costs of operating distribution centers, which consist of inventory holding costs based on the capacity of the DC
- total transportation costs from the distribution centers to the demand regions and from demand regions to the distribution centers
- total penalty costs incurred from shortage of capacity of the distribution centers

$$
\begin{aligned}
min\ o_1: &\sum_{i=1}^{I}\sum_{j=1}^{J} f_{ij}d_{ij}q_j\,x_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K} f_{jk}d_{jk}r_k y_{jk} + \sum_{j=1}^{J}\left(w_j\sqrt{s_j}\,(u+b\alpha)\right)z_j \\
&+ \gamma\,\frac{\sum_{j=1}^{J} max(0,\sum_{k=1}^{K} r_k y_{jk} - z_j s_j)}{\sum_{j=1}^{J}\sum_{k=1}^{K} r_k y_{jk}}
\end{aligned}
\tag{3.1}
$$

to maximize o_2:

- the coverage of the client/demand regions served by these distribution centers within a certain service distance radius.

$$
max\ o_2: \sum_{k=1}^{K} r_k \sum_{j\in Q_k}^{J} y_{jk}
\tag{3.2}
$$

Subject to:

$$\sum_{j=1}^{J} y_{jk} = 1; \; k\epsilon K \tag{3.3}$$

Constraint (3.3) ensures that each of the customers is attended by 1 DC facility.

$$\sum_{j=1}^{J} s_j x_{ij} \leq a_i; \; i\epsilon I \tag{3.4}$$

Constraint (3.4) ensures that the sum of the flows from the ports to the DCs is equal or less than port throughput.

$$\sum_{i=1}^{I} x_{ij} \geq 1; \; j\epsilon J \tag{3.5}$$

Constraint (3.5) ensures that there is at least 1 port connected to the DC

$$\sum_{k=1}^{K} r_k y_{jk} \leq z_j s_j; \; j\epsilon Q_k \tag{3.6}$$

Constraint (3.6) describes a capacity constraint for depots and it also ensures that flows of goods only occur from the set of opened facilities Q_k. We use a function as described in the last element of the first objective function (z_1) to penalize any assignment that produces total flow above the DC capacity.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} q_j x_{ij} \geq \sum_{j=1}^{J}\sum_{k=1}^{K} r_k y_{jk} \; ; \; j\epsilon Q_k \tag{3.7}$$

Constraint (3.7) ensures that there is adequate supply from the port to the demand points.

$$s_j \geq 0, \qquad j\epsilon J \tag{3.8}$$
$$x_{ij} \epsilon \{0, 1\}, \quad i\epsilon I, j\epsilon J \tag{3.9}$$
$$y_{jk} \epsilon \{0, 1\}, \quad j\epsilon J, k\epsilon K \tag{3.10}$$
$$z_j \epsilon \{0, 1\}, \quad j\epsilon J \tag{3.11}$$

Constraint (3.8) is a non-negativity constraint for each of the DC. Constraints (3.9), (3.10) and (3.11) form binary property of the decisions of serving distribution center j from port i, opening distribution center- j (z_j), serving demand region-k from distribution center-j (Y_{jk}).

3.2.2 Solution Algorithm

Network design problems are typically NP-hard and are therefore virtually impossible to solve using exact methods (Gen et al., 2008) To solve the problem presented in the previous section, we use a well-known multi-objective evolutionary algorithm: the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002) together with local search procedures. NSGA-II is an Evolutionary Algorithms and is rooted in evolutionary

theory. The algorithm is built on top of a classic Genetic Algorithm. Despite many improvements and additional features, the fundamental theory regarding the adaptive capabilities that underlies NSGA-II is the same as that used in standard Genetic Algorithm (Goldberg, 1989). Like any other EA, NSGA-II is a population-based approach where multiple solution points are used to explore the solution space and find the best solutions for the (conflicting) objectives. In searching the solution space, NSGA-II uses crossover and mutation operators that mimic evolutionary processes. Together with a solution selection routine, the algorithm explores and exploits the solution space efficiently (Črepinšek et al., 2013).

The representation of a candidate solution is a crucial aspect in Geneti Algortihm as it significantly affects the efficacy of the algorithm in finding the best solutions (Rothlauf, 2006). To reduce the search space and preserve the use of the original NSGA-II operators such as simulated binary crossover and polynomial mutation, both binary and real coding have been used. The first part of the chromosome defines the open/close decisions for the locations and the second section defines the capacities assigned at each of the opened distribution centers. This representation scheme is similar to what has been used by Villegas et al. (2006). Figure 3.6 below illustrates the solution representation of the algorithm.
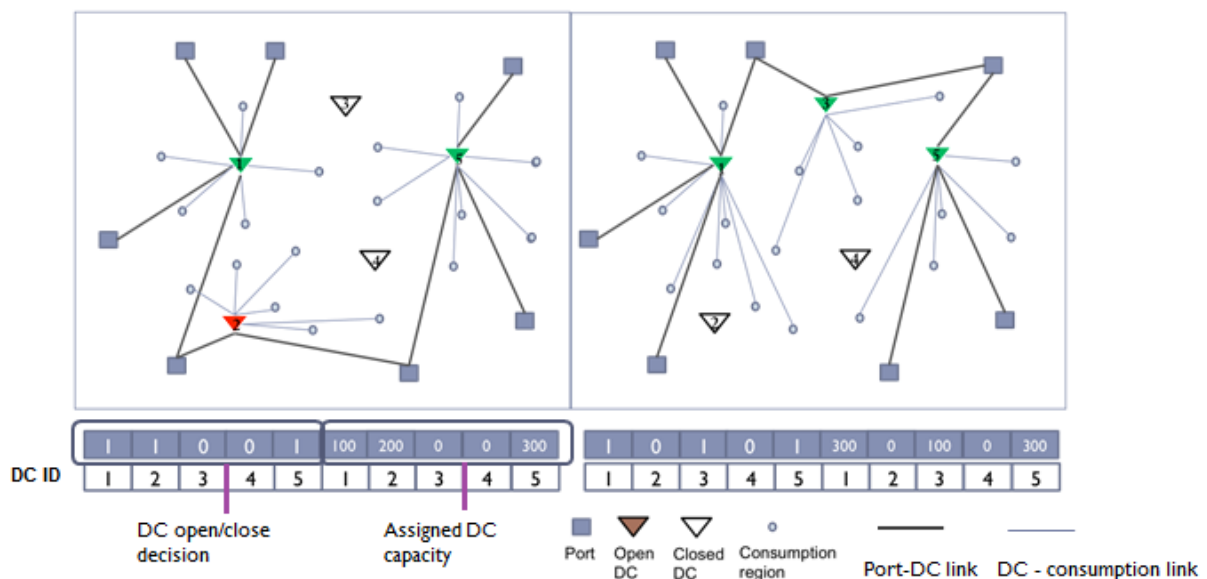
Figure 3.6 Design of solution representation in NSGAII, the first row of numbers indicates the open/close and capacity decisions, the second string indicates the DC ID relevant to the decisions.

After the locations and capacities of the DCs are determined, a neighborhood search heuristic is used to find the linkages/distribution structures between the ports, DCs, and consumption regions. This heuristic is based on a greedy approach where each of the surrounding potential nodes in the network that falls within a certain cost boundary is searched to find the most cost-efficient connections. The algorithm first performs a search on the most cost efficient dc-consumption region networks by taking into account the distance, available infrastructure, and modes. Second, the most probable port-DC supply network is

estimated using a second heuristics analogous to the first. This neighborhood search algorithm is similar to the approaches used by Villegas et al. (2006).The pseudo-code for both heuristics can be found below.

- Pseudo code for client-dc assignment

Input:	I: set of clients-i; J: set of DCs- j;

d_{ij}: distance from client i to distribution center j

dmax: max. distance coverage

c_{ij}: cost to transport goods from client i to distribution center j

j_{inside}*: DC within the max distance coverage with the minimum cost to connect to

$j_{outside}$*: DC outside the max distance coverage with the minimum cost to connect to

$c_{ij\text{-}inside}$*: minimum cost to connect to a DC inside the max. distance coverage

$c_{ij\text{-}outside}$*: minimum cost to connect to a DC outside the max. distance coverage

Output: assignment structure between clients and DCs

//initialization of variables

Step 0: $c_{ij\text{-}inside}$*: very big number

$c_{ij\text{-}outside}$*: very big number

//assignment algorithm

Step 1: For i =1 to I

For j = 1 to J

//determining the cheapest dc inside covered distance

If (d_{ij} <= *dmax*)

If (c_{ij} <= $c_{ij\text{-}inside}$*)

$c_{ij\text{-}inside}$* = c_{ij}

j_{inside}* = j

//determining the cheapest dc outside the covered distance

Else

If (c_{ij} <= $c_{ij\text{-}outside}$*)

$c_{ij\text{-}outside}$* = c_{ij}

$j_{outside}$* = j;

// making the assignment for clients

If (j_{inside}*! = null)

assign client i to j_{inside}*

Else

assign client i to $j_{outside}$*

Exit

- Pseudo code for port-dc assignment

Input:	I: set of Ports-i; J: set of DCs- j;

K_j: Boolean variable for DC-j

d_{ij}: distance from port i to distribution center j

dmax: max. distance coverage

c_{ij}: cost to transport goods from port i to distribution center j

i*: port with the minimum cost to connect a DC to

j_{inside}*: DC within the max distance coverage with the minimum cost to connect to

$j_{outside}$*: DC outside the max distance coverage with the minimum cost to connect to

$c_{ij\text{-}inside}$*: minimum cost to connect to a DC inside the max. distance coverage

$c_{ij\text{-}outside}$*: minimum cost to connect to a DC outside the max. distance coverage

$c_{ij\text{-}disconnected}$*: minimum cost to connect an unconnected DC

Output: assignment structure between ports and DCs

//initialization of variables

Step 0: $c_{ij\text{-}inside}$*: very big number

$c_{ij\text{-}outside}$*: very big number

$c_{ij\text{-}disconnected}$*: very big number

//assignment algorithm

Step 1:   For j:1 to J

K$_j$ = true //set Boolean variable for all disconnected DCs

//determining the cheapest dc inside covered distance

For i :1 to I

For j: 1 to J

If ($d_{ij} <= dmax$)

j_{inside}* = j

K$_j$ = false

//determining the cheapest dc outside covered distance

Else if ($c_{ij} <= c_{ij\text{-}outside}$*)

$c_{ij\text{-}outside}$* = c_{ij}

$j_{outside}$*= j

//making the assignment for the port to the DC

If (j_{inside}*!=0)

assign port i to j_{inside}*

Else

assign port i to $j_{outside}$*

K$j_{outside}$* = false

//connecting disconnected DCs to the cheapest port

Step 2:   For j: 1 to J

//if a DC is still unconnected to any port

If (Kj =true)

// search for the cheapest port to connect with

For i :1 to I

if ($c_{ji} <= c_{ji\text{-}disconnected}$*)

$c_{ji\text{-}disconnected}$* = c_{ji}

i* =i

assign Disconnected DC-j to port i

Exit

3.2.3   Calculation of DC location throughputs

Since we are interested in the patterns of the freight flows of the entire population of firms using hinterland services, an aggregation technique has to be used to approximate the network by taking distribution structures used by different industry sectors into account. We wish to capture the heterogeneity of the users in the market in terms of their preferences towards the trade-off between service levels and costs. In order to do this, several steps are needed. First we generate a set of optimal port-dc-consumption site distribution network configurations for the service level and the total logistics cost objectives or also called Pareto

set. Each solution in the Pareto set represents an alternative network configuration, based on different trade-offs between both objectives. This means that there are companies who aim at minimizing costs rather than their demand coverage and vice versa. Figure 3.7 illustrates the non-dominated solutions, which depict the trade-off between service level and total logistics costs.
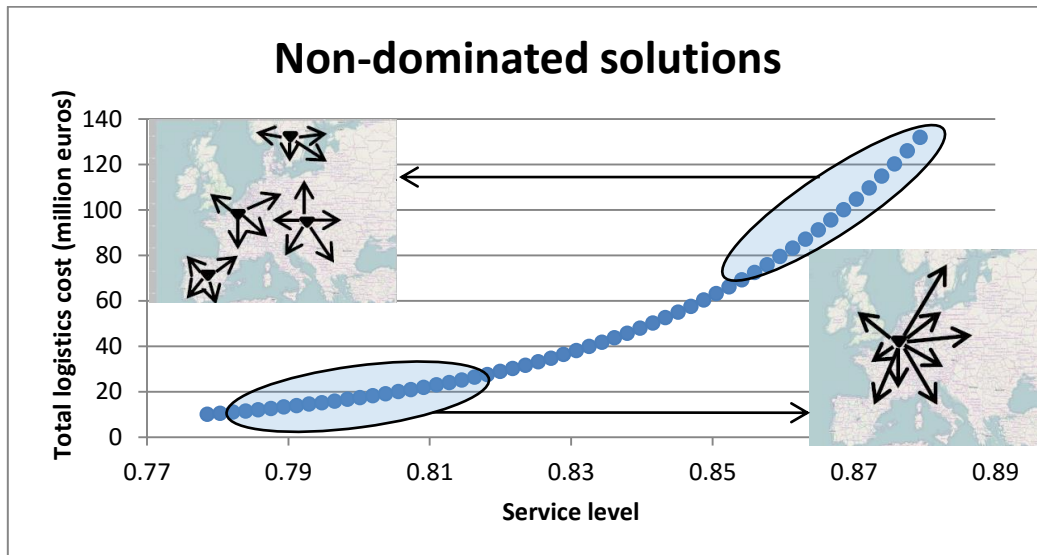
Figure 3.7 Illustrated trade-offs between logistics costs and service level

Second, the statistical distribution that represents the market share of the companies is estimated and fitted to the non-dominated solutions identified in step 1. By doing this, we assume that each distribution structure in the set of non-dominated solutions has a fraction of the total freight flows. For example, if we assume that the market share across different non-dominated solutions is distributed normally then a normal distribution $N(\mu, \sigma^2)$ is constructed using mean and standard deviation values estimated based on the non-dominated solutions. Subsequently, a certain number of bins are created to discretize the normal distribution. Figure 3.8 illustrates this approach with 9 bins.
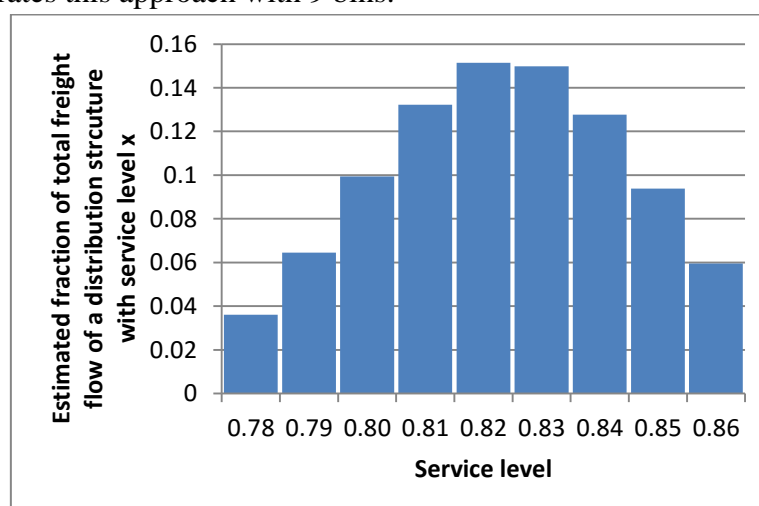
Figure 3.8 Discretized normal distribution

Third, we count the number of solutions for each service level bin. In this way, we obtain the total number of non-dominated solutions belonging to each bin (N_i). Figure 3.9 illustrates the resulting counts for all the non-dominated solutions presented above.
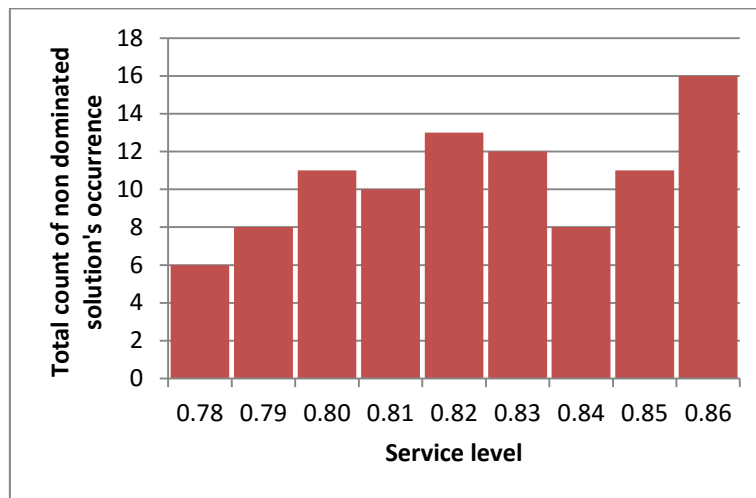
Figure 3.9 Count of non-dominated solutions for each service level bins

The value of the market share of a certain distribution structure is determined by a probability density function of the estimated statistical distribution and the tally count of the bin within which the non-dominated solution is found. The following formula defines the value of market share.

$$w_s = \frac{P(lb_i \leq SL_s \leq ub_i)}{N_i} \tag{3.12}$$

Where,
w_s = value of market share of solution-s
N_i = total number of non-dominated solution within bin-i
$P(lb_i \leq SL_s \leq ub_i)$ = probability density function of service level-s

Given the market share, the following formula defines how the aggregated throughput of the DCs is calculated using a statistical distribution.

$$T_j = \sum_{s=1}^{S} d_j^s z_j^s w_s \tag{3.13}$$

Where,
T_j = total aggregated throughput of distribution center- j
d_j^s = total throughput of distribution center – j in solution-s
z_j^s = open/close binary decision for distribution center- j in solution s

3.2.4   Model calibration

In order to estimate the model parameters, we perform a calibration based on a proxy for the observed throughput of DCs. In order to make it possible to perform a comparison between modeled throughput and observed data, a conversion factor (ρ) that converts the unit

of employment into throughput (e.g. in metric tons or containers moved per year) served by a distribution center. In addition to the conversion factor, the other calibration parameters are:

1.   Parameters of statistical distribution used (μ, σ^2)

Since a statistical distribution is used to model the distribution of the market for different distribution structures, the shape parameters of the distribution have to be calibrated.

2.   Capacity of each of the DCs (S_j)

The capacity of the DCs significantly effects the total number of DCs in the network as it defines the maximum throughput of a DC. When there are many DCs with high capacity, there will be less regional DCs but more centralized DCs, and vice versa. This is because DC capacity determines the number of demand regions that can be assigned to them. Furthermore the capacity of a DC also determines the pattern of linkages between a DC and demand regions since we are minimizing the penalty costs incurred due to capacity shortage. Unlike the hub forming coefficient and the maximum distance coverage, the capacity of each of the DCs is calibrated using NSGA-II. In case of multiple solutions with differing capacity value for the same DC, the aggregation method will use the upper bound of the DC capacities suggested by the solutions.

3.   Maximum distance coverage for both dc-client (D_{dc}) and port-dc (D_{pd}) connection assignment

Depending on the mode of transport, and infrastructure used to transport the goods, the maximum distance (in km) covered from logistical nodes such as ports and DCs can differ from one continent to the others.

To perform the calibration, we formulate a bi-objective optimization problem in which the total logistics costs and the Root Mean Squared Error (RMSE) between modeled and observed DC throughput are minimized simultaneously. In this way, the non-dominated solutions found by the calibration procedure represent distribution structures that simultaneously have the best fit with the observed data, and are the most efficient in terms of total logistics costs. Note that we consider the impact of different service levels on the network structure in calibrating the model by incorporating penalty cost as the last component of the cost function. This penalty cost will become higher when the service level is low and vice versa.

$$\min o_1 : \sum_{i=1}^{I}\sum_{j=1}^{J} f_{ij} d_{ij} q_j\, x_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K} f_{jk} d_{jk} r_k y_{jk} + \sum_{j=1}^{J} (w_j \sqrt{s_j}(u + b\alpha)) z_j$$

$$+ \gamma \frac{\sum_{j=1}^{J}\max(0, \sum_{k=1}^{K} r_k y_{jk} - z_j s_j)}{\sum_{k=1}^{K} r_k y_{jk}} \tag{3.14}$$

$$\min o_2 : \sqrt{\frac{1}{n}\sum_{j=1}^{n}(V_j^m - V_j^o)^2} \tag{3.15}$$

$$V_j^m = \frac{\sum_{k=1}^{K} r_k y_{jk}, j \in Q_k}{\rho} \tag{3.16}$$

Where,

V_j^m = modeled throughput of DC-j calculated as the sum of all freight flows that are transported from or to DC-j in a year. For calibration purpose, the volume of throughput is converted into number of employment.

V_i^O = observed throughput of DC-i, measured in number of employment

n = total number of locations

ρ = conversion factor to convert the unit of employment to the throughput (e.g. in metric tonnes or containers moved per year) served by a distribution center (130 TEU/year/employee)

3.2.5 Application to European Ports' Hinterland Distribution Structure

To illustrate the use of the model for policy analysis, we apply the model to Europe. Besides presenting a full empirical application of the model, we demonstrate how the model can be applied to generate inputs for new port-hinterland connectivity indicators. The model is generic, i.e. it can be applied to other large regions/continents besides Europe, provided that the necessary data is available.

For Europe, we approximate the flows between international seaport, DCs, and destination regions. We assume that each of the regions at the NUTS 2 level is a potential location for DCs, so there are 309 potential DC locations. Demand is modeled on the NUTS 3 level, using data on the Gross Domestic Product (GDP) of 1445 NUTS 3 regions from Eurostat (Eurostat, 2014b). We translate GDP to freight demand by assuming a linear dependency between GDP and freight demand, following best practices in freight generation modeling (Holguín-Veras et al., 2014). That is, in the model we disaggregate international container flow data between European seaports and European countries into container flows between seaports and NUTS 3 regions. Demand for both front haul and backhaul transport between the DCs and the demand regions is taken into account by combining them into a single aggregate demand between DCs and demand regions. We used 121 seaports that are part of EU member states as the origin of the international flows into Europe. These 121 ports handle the large majority of all container flows going into Europe and they are also all subjected to the port related policies issued by the European Union.

For calibration, data on DC establishments is obtained from Eurostat, within the regional structural business statistics data, as employment data under the H-52 category (warehousing and support activities for transportation)(Eurostat, 2014a). The primary reason for using this dataset is that there is no micro data available on DC throughput (e.g. in tonnage of freight transported) that encompasses all commodities being transported. Earlier work for the Netherlands has shown that employment numbers and freight generation data are strongly correlated (Davydenko et al., 2012).

In addition, pre- and post-haulage distances for DC were constrained according to typical EU practice, to keep the calculation times within practicable bounds. In case of Europe, Echenique and Partners (2002) and Limbourg and Jourquin (2009) estimate that the maximum post-haulage shipment distance from a logistical node such as a freight terminal is 50 km, while the minimum distance over which intermodal transport becomes competitive is 300 km. Therefore, the following assumption is used in our model: shipments between distribution center and client will be transported with truck within distance range $50 < D_{dc}$

<150 , and between ports and distribution center with barge, truck, or train , within distance range $300 < D_{pd} < 650$.

The model was implemented in Java using the SIMEON framework (Halim and Seck, 2011). We utilize the java geo-visualization library Unfolding (Nagel et al., 2013) to visualize the results of the model. Several experiments have been conducted to test and validate the model. For these experiments, we parameterized the NSGA-II algorithm as follows: a population size of 100 (meaning that there are 100 solutions generated for each iteration); with 10,000 evaluations as the stopping criterion; we use simulated binary crossover for both the binary and the real segment of the chromosome with a crossover rate of 0.9, polynomial mutation was used with a rate of 1/number of variables for the real segment, and 0.05 for the binary segment. The distribution index for both crossover and mutation is 2.0. We performed the computation on a desktop PC with Intel i5 processor with 3.33 GHz, and 4096 MB memory. The algorithm takes around 30 seconds to finish the evaluation and the estimation of the aggregated DC throughput.

Figure 3.10 show the resulting set of non-dominated solutions. As can be seen, the total logistics costs (the first objective function) varies by around 8% (between 2.08E09 and 2.24E09), while the service level (the second objective function) varies between 84% and 92%, which are realistic ranges. Note that costs rise sharply with service levels near the maximum.
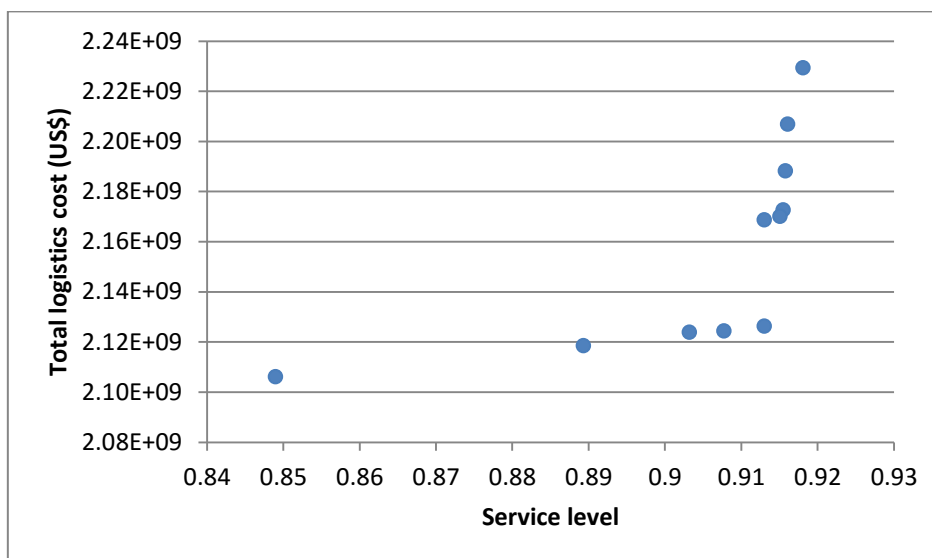
Figure 3.10 Non-dominated solutions for the network design problem with 121 ports, 309 potential DCs, 1445 demand regions.

The set of solutions demonstrates the trade-off that has to be made in typical logistic operations between total costs and service level. The different solutions in the Pareto approximate set represent different logistic structures used by different companies working in different sectors. The solutions in the bottom left corner represent distribution structures where more centralized hubs are used, while solutions in the upper right corner represent distribution structures where more decentralized local hubs are used. Patterns are as expected: more central structures have lower costs but also provide a lower service level. Relative variations in service levels (84%-92%) are higher than variations in the degree of centrality in

the alternative networks (223-235 DC's in this example). Figure 3.11 visualizes a typical distribution network structure for Europe with the main regions served.
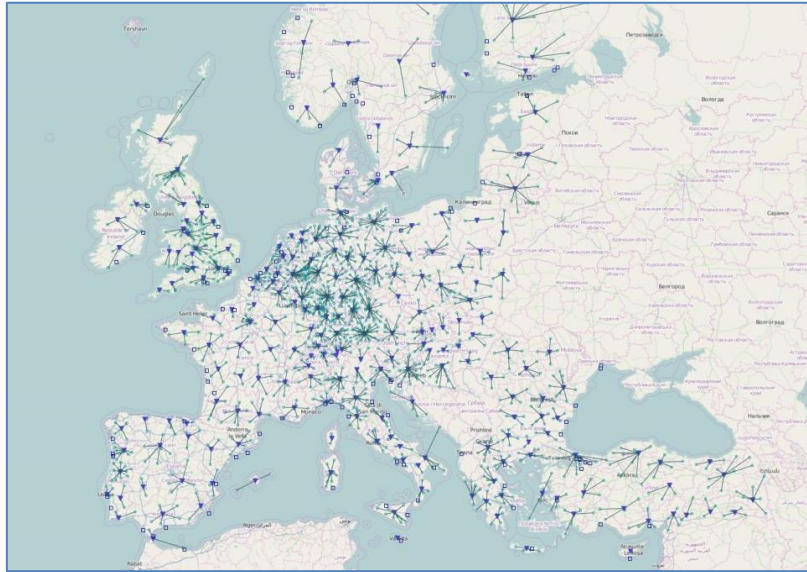
Figure 3.11 Example of a distribution structure

Given the non-dominated solutions found above, we estimated a normal distribution that represents the demand profile for different distribution structures. Subsequently, we used the service level value of the solutions and calculated the corresponding market share value of each of the solutions using eq.3.12. Finally, using eq.3.13, we computed the aggregated throughput for each of the DCs in the NUTS2 regions and compared the results with the observed DC throughputs (Figure 3.12). An R^2 value of 0.75 indicates that there is a good fit between the two datasets. This means that the model is performing satisfactorily in estimating the throughput of the DCs and therefore it also gives a degree of confidence on the estimated structure of the intermodal logistics network.
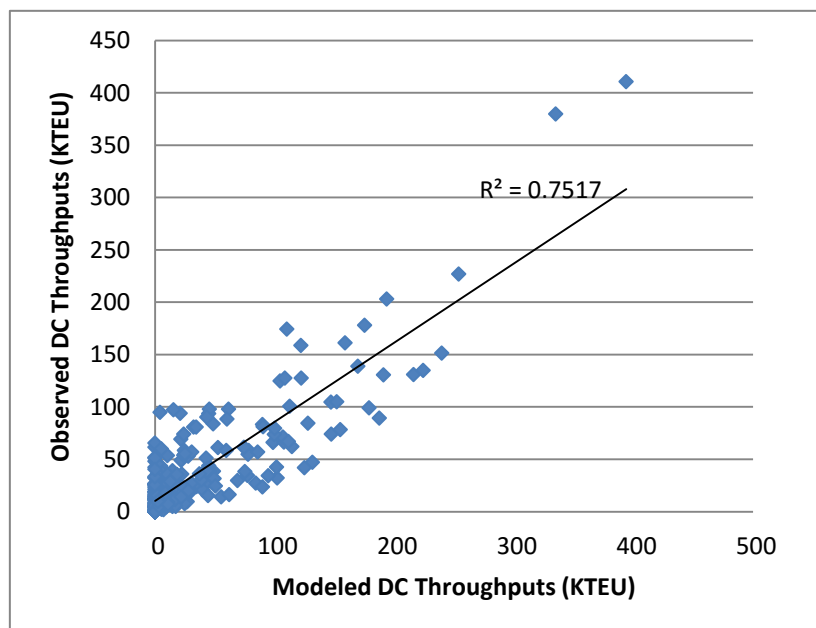
Figure 3.12 Calibration result for modeled vs observed DC throughputs

The aggregation technique also gives a set of DC locations and their associated flows. The aggregated distribution network is obtained by aggregating the non-dominated solutions found with NSGA-II. Figure 3.13 below shows the resulting European logistics network.
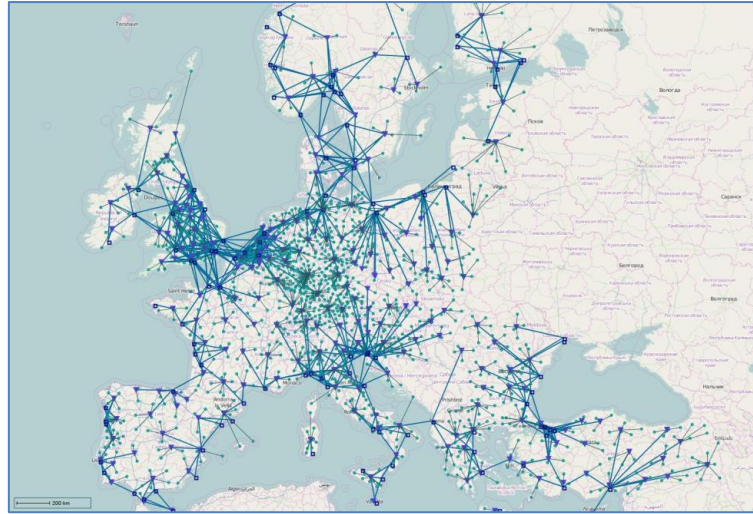
Figure 3.13 Estimated network in Europe. Ports, DCs, and consumption regions are denoted by rectangles, triangles, and circles respectively.

As the first part of the calibration steps, we experimented with different distance coverage values between DCs and clients (D_{dc}) to analyze the sensitivity of the model and to find the best D_{dc} value that matches the observed data satisfactorily.

Figure 3.14 provides a visual impression of contrasting distribution structures generated by the model throughout different DC's distance coverage values. As can be seen, the longer the distance covered by a DC, the more centralized the DCs (top left picture) are with connections to different ports. On the other hand, there are more decentralized DCs and significantly less connections to different ports when the distance covered is shorter (bottom picture).
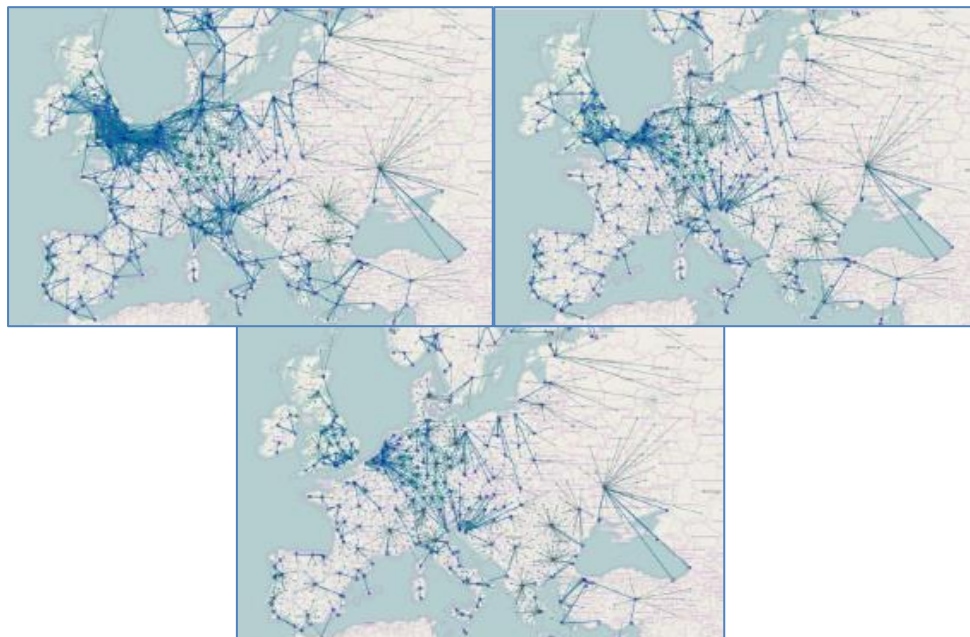
Figure 3.14 Experimentations with different maximum distance coverage values, top left picture: D_{dc}=300 km, top right picture: D_{dc}=200km, and bottom picture: D_{dc}=150 km

The next step in the calibration process is to estimate the distribution of service level preferences across optional structures that allowed the calculated flows to match best to observed flows. The best fit with statistics was found using the following parameters that have been previously calibrated in the first step (rounded numbers): conversion factor ρ =130 TEU /year/employee, client-dc   maximum distance coverage (D_{dc}) = 100 km, and port-dc maximum distance coverage (D_{pd}) = 350 km. For the conversion factor, a search step of 10 TEU/year/employee was used. The value of distance coverage was searched using a search step of 50 km. Eventually, a normal distribution with a mean of 0.87, and a variance of 0.04 appeared to be best to represent the distribution of the flow fractions of each distribution structure. The values for the mean and variance were obtained based on the service level values of the non-dominated solutions. The average value for the unit cost of transport between the DCs and the consumption regions is 0.57 US$/TEU.km. We assume that all transport between DCs and consumer regions will be done by truck. Without loss of generality, the model developed here can be expanded to include multiple modes in connection between DCs and consumption regions following the procedure used in Tavasszy et al. (1998) and de Jong and Ben-Akiva (2007). Furthermore, we use the average value for both the unit cost of transport between seaports and DCs, and the unit cost of DCs operation. They are 0.45 US$/TEU.km and 100 US$/TEU respectively. An important condition here is that the unit cost of DC operation includes both inventory costs as well as DC operating costs. We obtained these values from Davydenko et al. (2014).

Figure 3.15 shows the results of calibrating the model using NSGA-II. We can see that the observed flows force the distribution towards the range of more decentralized networks. The RMSE does not change much in the upper range of the logistics costs (at around 10% of maximum costs). This probably indicates a limit to the granularity of the model in this application.
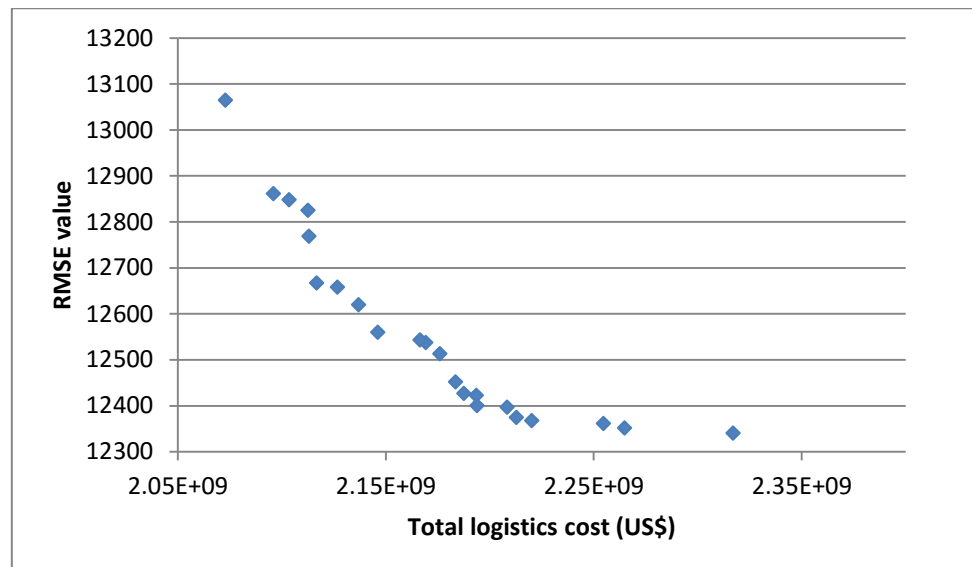
Figure 3.15 Non-dominated solutions obtained through calibrating Root-Mean-Square Error against total logistics cost

The minimum RMSE is 12340 with a total logistics cost of 2.3 E10^9 US$. It is noteworthy that the difference between the highest and the lowest total logistics costs of the

networks in the set of optimal solution is close to 12%. Since the total logistics cost increases exponentially along with the increase in the service level, the current European Seaport's Intermodal network is geared towards high service level with many local distribution centers serving regions within 50 km radius.

The above implies that total logistics cost might be reduced if more centralized distribution structures would be adopted. This would enable to take advantage of economy of scale effects through consolidation. A downside of adopting a more centralized distribution structure is that the average transport time between DCs and destination regions increases, while also reducing the average service level of the system.

Based on the estimated model, we can now obtain performance metrics that describes the connectivity of ports to hinterland destinations. Straightforward measures that can be calculated include transport costs and times between ports and hinterland regions. In addition, we can calculate lead times between DCs and hinterland regions. This measure is relevant for industries that replenish inventories from nearby port-served warehouses or who export through these warehouses. For the current illustration, we calculate aggregate measures per port using a volume-weighted average of all regions served by a port. As an additional measure of potential economies of scale, the potential gateway throughput is calculated based on the sum of the throughput of all the DCs that are connected to each port. The following equations specify the metrics described above:

$$TC_i = \frac{\sum_{j \in DC_i} \sum_{k \in R_j} (d_{ij} f_{ij} + d_{jk} f_{jk}) r_{jk}}{V_t \sum_{j \in DC_i} \sum_{k \in R_j} r_{jk}} \qquad (3.17)$$

$$PLT_i = \frac{\sum_{j \in DC_i} \sum_{k \in R_j} (d_{ij} + d_{jk}) r_{jk}}{V_t \sum_{j \in DC_i} \sum_{k \in R_j} r_{jk}} \qquad (3.18)$$

$$DLT_i = \frac{\sum_{j \in DC_i} \sum_{k \in R_j} d_{jk} r_{jk}}{V_t \sum_{j \in DC_i} \sum_{k \in R_j} r_{jk}} \qquad (3.19)$$

$$TP_i = \sum_{j \in DC_i} \sum_{k \in R_j} r_{jk} \qquad (3.20)$$

Where
DC_i = set of DCs j that are connected to port i
R_j = set of demand regions k that are connected to DC j
r_{jk} = freight volume that is transported from DC j to demand region k (TEU)
V_t = speed of mode of transport t(km/hour)
TC_i = Volume-weighted average of transport cost from port i to all demand regions served by the port (US$/TEU)
PLT_i = Volume-weighted transport lead time from port i to all demand regions served by the port (hours)
DLT_i = Volume-weighted transport lead time from DCs that are connected to port i to all demand regions served by the port (hours)
TP_i = total potential gateway throughput of port i (MTEU/year)

Table 3.1summarizes these port-hinterland connectivity metrics for the major ports in North-Western Europe.

Table 3.1 Port-hinterland connectivity through logistic networks. Weighted average for all regions per port.

Port	Potential throughput (MTEU/year)	Average Port-DC distance (km)	Port-region lead time (hours)	DC-region lead time (hours)	Port-region transport cost (US$/TEU)
Antwerp	6.36	203	5.0	0.91	142
Rotterdam	6.31	213	5.2	0.96	149
Bremerhaven	5.07	256	6.9	1.11	196
Hamburg	3.14	431	7.6	1.14	217
Le Havre	2.84	228	7.2	0.90	205
Zeebrugge	5.64	257	6.0	0.94	172

The table shows strong differences between ports. The relatively long distances for Hamburg does not result in extended lead times from DC's but are served by longer trunk haul distances between port and DC. Antwerp and Rotterdam perform best for containerized goods and have the largest potential hinterland market. Antwerp and Rotterdam are preferable for hinterland access both from the perspective of overall costs and lead time, as well as the replenishment lead time from DC's. Evidently, many of the ports in the Bremen – Le Havre range share hinterland regions in their gateway throughput market. Interestingly, Zeebrugge, despite being a relatively small port in the Hamburg - Le Havre range, has a relatively large potential gateway throughput market. This is because Zeebrugge's hinterland coverage includes DCs both in Belgium and France. The competition with other ports in the Hamburg - Le Havre range, such as Le-Havre and Antwerp, definitely impacts the actual throughput of Zeebrugge. Future studies can explore how the different parameters in the network may affect the relative position of these ports.

3.3 Integration of port-hinterland distribution network into global container network choice model

In order to integrate the CLONE model into the steps of estimating global container flows, the cost function specified within the WCM has to be adapted. Since the CLONE model estimates DC locations and how they are connected to both the ports and the hinterland destinations, this allows higher specificity in calculating the cost of a route, especially from ports to hinterland destinations. The output of the CLONE model allows the construction of a set of alternative routes (also called choice set) that contains both direct and indirect shipments (via the DC). This distinction on the routes and its associated costs are specified at the link level for any routes connecting origin and destination pair. The unit cost associated with using a certain link depends on the mode that is used. We assume trucks are used for direct shipments between ports and hinterland destinations while barges, trucks, or rail can be used to transport goods via the DCs.

3.3.1 Specification of generalized cost for global intermodal container transport

The following formula specifies the new cost function of a route:

$$C_r = \sum_{i \in r, I} Tr_i + \sum_{l \in r} c_l + \beta \cdot \left(\sum_{i \in r, I} T_i + \sum_{l \in r} t_l \right) \tag{3.21}$$

where:

c_l

$$= \begin{cases} f_{ik} d_{ik}, \text{ if } l = direct\ shipment\ from\ port\ i\ to\ destination\ k, i, k\ \in r \\ \quad f_{ij} d_{ij}\ x_{ij}, \text{ if } l = port\ to\ DC\ link, i, j\ \in r, I, J \\ \quad\quad f_{jk} d_{jk} y_{jk}\ \text{ if } l = DC\ to\ consumer\ region\ link, j, k\ \in r, J, K \\ \quad f_m d_m, \text{ if } l = maritime\ link\ from\ port\ i\ to\ port\ i+1, i \in r, I \end{cases} \tag{3.22}$$

C_r unit cost of route r (US\$/TEU)
i ports used by the route-r
j DCs used by route-r
k consumption region (destination of route-r)
l links used by the route
f_{ik} unit cost of transport from port-i to destination-k (US\$/TEU.km)
d_{ik} distance from port-i to destination-k (km)
f_{ij} unit cost of transport from port-i to distribution center-j (US\$/TEU.km)
d_{ij} distance from port-i to DC-j (km)
f_{jk} unit cost of transport from DC-j to destination-k (US\$/TEU.km)
d_{jk} distance from distribution center-j to destination-k (km)
f_m unit cost of transport of maritime route (US\$/TEU.km)
d_m maritime distance from between port of origin and destination (km)
Tr_i cost of transshipment at port-i (US\$/TEU)
c_l cost of transportation over link l (US\$/TEU)
T_i time spent during transshipment at port-i (day/TEU)
t_l time spent during transportation over link l (day/TEU)
β value of transport time (US\$/day)

To determine the choice set, the WCM enumerates all plausible route alternatives for major countries in the world. On the maritime side, we use the publicly available global shipping network data and shortest path algorithms to enumerate maritime routes between ports. Furthermore, the CLONE model enumerates the alternative routes on the hinterland sides and combine these alternatives to the maritime routes. Figure 3.16 provides an abstraction of the choice Set, a route in the choice set is defined as a set of edges which connect origin-port A – port D – DC – destination or origin – Port B – port E – destination, where the first includes the use of the DC, and the later includes direct shipment from the port to the end destination. Note that since the CLONE model is currently aimed to model how changes in the DC locations in the destination continent affect the port choice of the shippers, we assume that the distribution structure of the origin continent remains unchanged and hence it is not rigorously modeled. When the scope of the model application requires taking the distribution structure in the origin continent into account, applying the CLONE model to both origin and destination continents is possible.
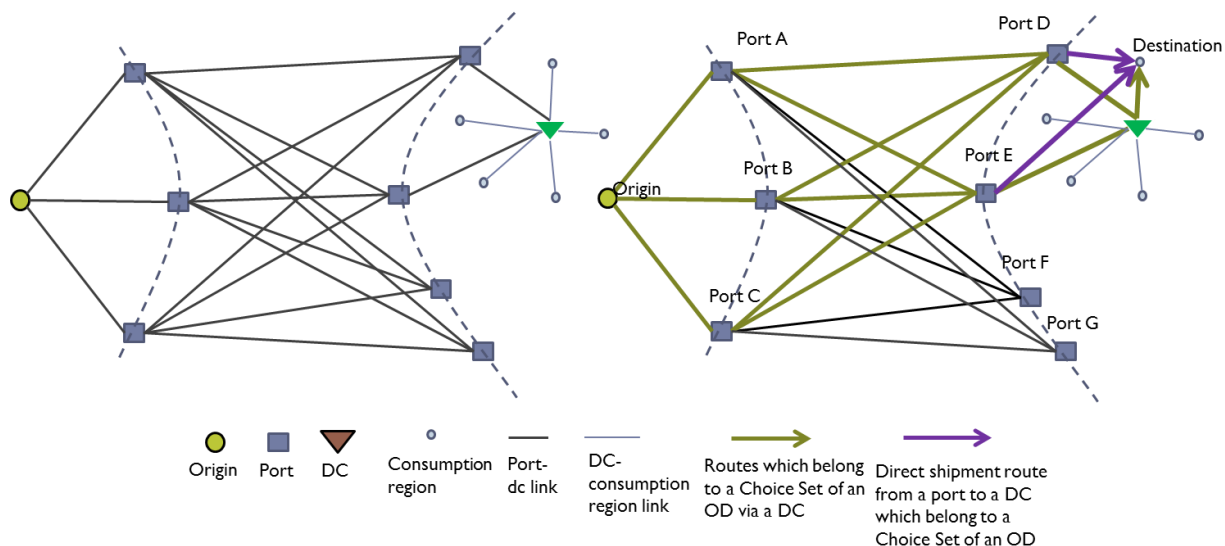
Figure 3.16 Illustration of a Choiceset for an origin - destination pair. The left picture depicts the physical intermodal network between the OD pair, the right picture denotes the Choice Set for a specific OD pair.

A distinct feature in the method used to build this choice set is that the direct shipment routes between the port and the destinations are enumerated automatically based on the locations of the DCs in a region. All destinations that are connected to the DCs will also have alternative direct routes to the ports with which these DCs are connected. In this way, there are always alternative for direct and indirect shipments (via the DC) for every destination using different modalities (i.e. truck for direct shipment and barge or rail for indirect shipment).

We use the path size logit model (Ben-Akiva and Bierlaire, 1999) as described in chapter 2 to calculate the choice probability of each alternative route in the choice set. This probability is used to calculate the distribution of the OD flows over the links and nodes in the choice set directly. Different modalities with different unit costs can be assigned on different segments of the alternative routes between the ports and the end destinations to investigate the shift in modalities and how this influence the port choice and the use of the DCs by the shippers. Figure 3.17 gives a visualization of a distribution network which involves direct and indirect shipments.
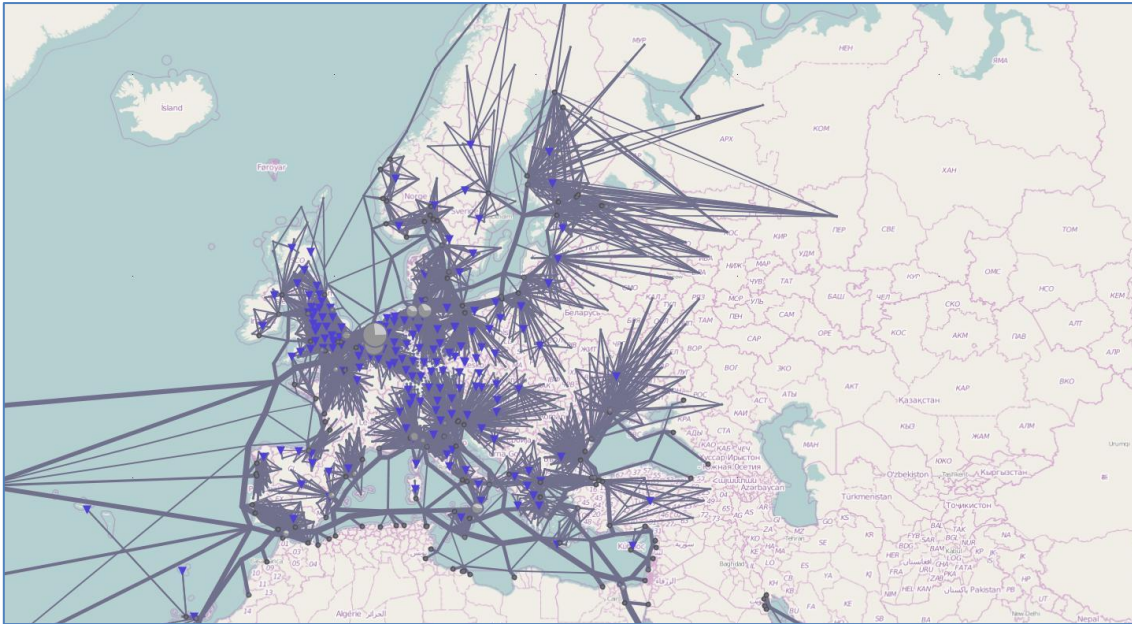
Figure 3.17 Direct and indirect shipments on the European intermodal network

3.3.2   *Data, calibration, validation, and computation tools*

The OD data used in this research has been derived from publicly available international trade databases (Tavasszy et al., 2011). However, since there is no Origin-Destination data for container flows through EU ports, a special procedure was employed to derive this dataset. We disaggregate the OD data from the NUTS-1 level to the NUTS-3 level by dividing the flows which go into a country to smaller flows which go into NUTS-3 regions of that country. The division is based on the GDP per capita of the population in the relevant regions, i.e. regions with high GDP per capita are assumed to have higher economic activity and hence higher fraction of the flows. Using OD data at NUTS-3 level, the integrated model assigns the flow of containers over the choice set that is built for each of the regions.

Validation of the integrated model performed by means of predictive validation technique (Balci, 1998). We use the integrated model to produce port throughputs in the Bremen – Le Havre range for the year 2006, and we compare the modeled and the observed port throughputs. The calibration result of the port-hinterland model essentially provides a foundation to validate the integrated model since the port throughput volumes in the integrated model is affected by the structure of the distribution networks that are connected to the ports. When the modeled port throughputs and the observed data do not differ substantially, the integrated model can be considered to have a good validity for its application on the European port-hinterland networks. Table 3.2 provides a comparison between the modeled and observed port throughputs in the Bremen – Le Havre range. The comparison shows that the model output is in line with the observed data.

Table 3.2 Comparison between modeled and observed port throughputs in the Bremen - Le Havre range

Ports	Modeled (TEU)	Observed (TEU)	Absolute difference (%)
Hamburg	8 183 199	8 474 773	3
Bremen	4 041 727	4 092 787	1
Rotterdam	10 019 891	9 471 675	6
Amsterdam	63 151	65 844	4
Anstwerp	6 873 457	6 750 515	2
Le Havre	2 251 389	2 124 255	6
Zeebrugge	1 221 302	1 407 933	13
Dunkirk	209 665	204 563	2

To run the integrated model, we used a MacBook with 1.4GHz Intel i5 processor, and 8G memory. The CLONE model takes around 1 minute to estimate the logistics network, while the total computation using the integrated model takes around 3 minutes to complete. Since the model is foreseen to be used in a large scale experiment involving more than 10,000 model execution, computation speed has been given a separate attention.

3.3.3   *Application of the Integrated Model for Port choice Analysis in Europe*

For illustrative purposes, the integrated model was applied to estimate the impact of changes in trade flows in Europe on shipper's choice of port in a future scenario. A plausible global trade scenario in 2040 is the shift from global intercontinental trade to regional trade within continents worldwide. The rise of average labor cost in Asia and the increasing needs for customized products in large scale have driven many companies to move their manufacturing sites closer to the markets. A distinct situation in this scenario is that Eastern Europe and Northern Africa have grown to be suitable manufacturing regions for major companies as they offer competitive labor cost similar to China before its rapid growth

Figure below provides a visualization of the spatial pattern of container flows estimated to be shipped to 1455 NUTS3 regions in Europe in 2040. The logistic module in this model estimates the locations of the DCs (in blue triangles) and the network structures that connect the ports (in red circles), the DCs, and the consumption regions (in grey circles). Based on this network, the WCM assigns the container flows from the global maritime network to the hinterland network. From the size of the pie charts, it is apparent that port of Rotterdam has the highest throughput among all the other ports.
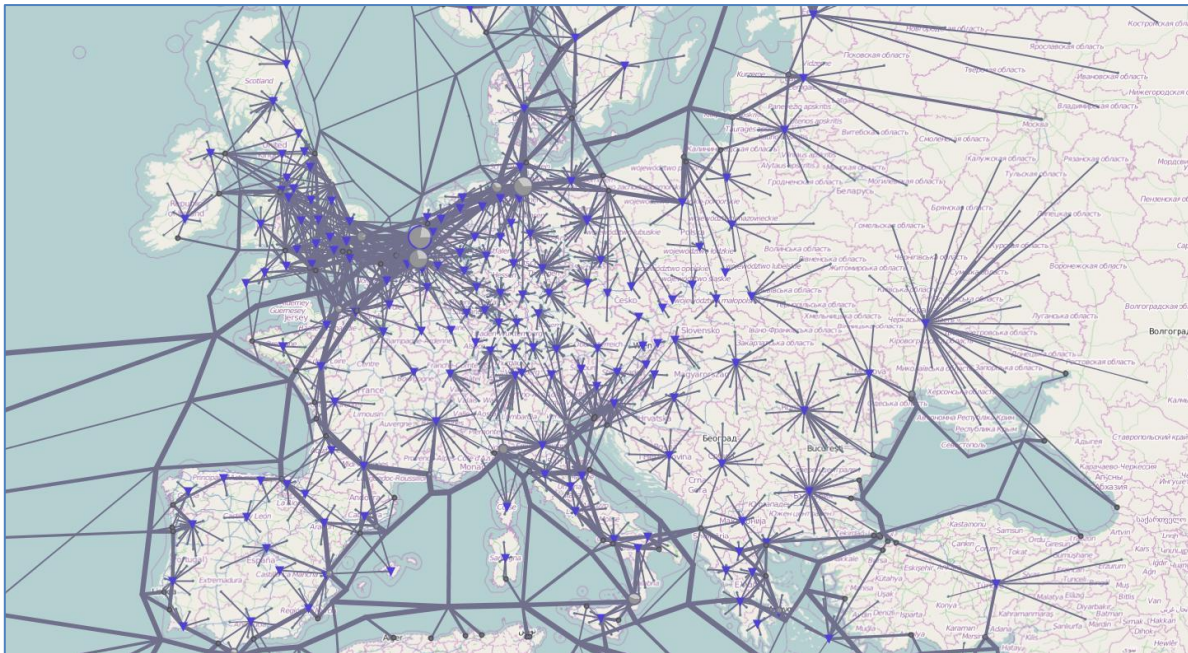
Figure 3.18 The distribution of container flows from the global maritime network to the European hinterland destinations

The figure below depicts the percentage change in transshipment and throughput values of the ports in Bremen – Le Havre range relative to the base year data in 2006. Most of the ports suffer negative impact from the trade scenario. Interestingly, it is apparent that in terms of throughput, Rotterdam is not negatively impacted in comparison to the rest of the ports. However, in terms of transshipment, Rotterdam appears to lose quite a large volume of container flows. This indicates that ports closer to the eastern European regions such as Hamburg and Bremen might be more attractive as transshipment hubs. This is logical as by using these ports, there can be a substantial reduction in transport costs and lead time to reach East European regions. Another reason for this trend can also be caused due to the increase in shipments using trucks from Eastern European to Western European regions, causing a decrease in the total volume transported with ships.

Percentage of change in port throughput and transhipment caused by the change of inland distribution structure (%)

	ROTTN	BREMD	ANTWB	AMSTN	ZEEBB	HAMBD	LEHAF	DUNKF
transhipment	-16.30	-6.52	-10.46	0.00	-0.01	-5.32	-9.24	-0.04
throughput	-3.80	-4.63	-12.23	-32.11	-24.14	-7.32	-11.58	-12.01

Figure 3.19 percentage change of container volume handled relative to the base volume caused by the change of inland distribution structure

3.4 Conclusions

Logistics considerations such as the locations of distribution centers are decisive influences on freight transport flows. This chapter has presented an approach to integrate logistics consideration in modeling freight flows on a large scale, such as on a continent. Specifically, we have shown how a continental distribution structure can be modeled and systematically integrated into the widely used 4-step freight modeling framework, resulting in an integrated model.

The model consists of a novel logistic optimization module (CLONE) which has calibratable parameters and an existing worldwide container flow estimation module (the WCM). The first model estimates the locations of distribution centers in continental Europe as well as the network structure which connects ports, DCs, and consumption regions. Based on this network structure, the second model assigns the flows o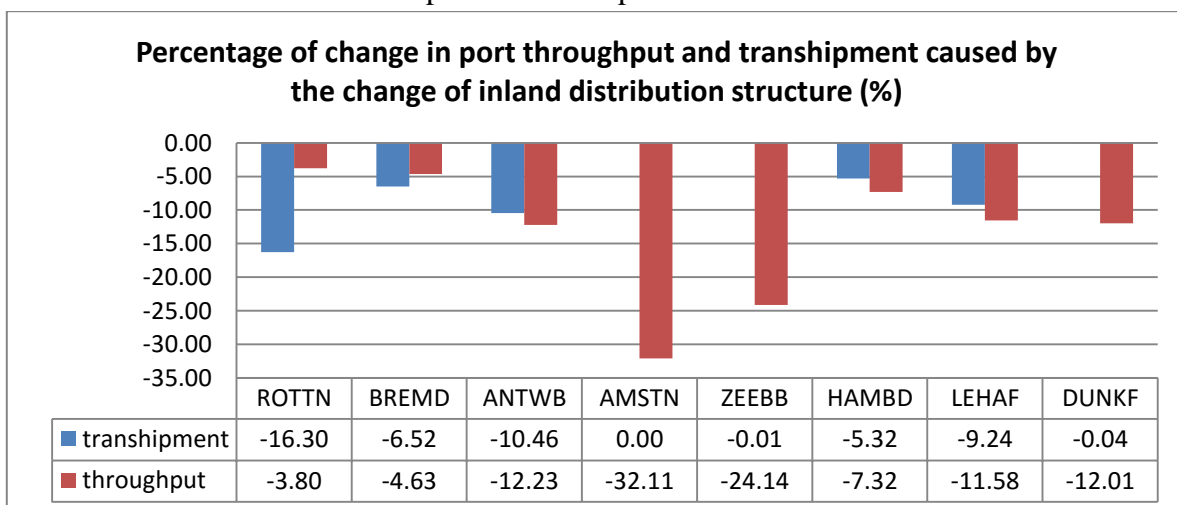f containers from the origin countries to the destination(s) in Europe. In this approach, optimization of logistics considerations is treated by the CLONE model, such as the trade-offs between inventory and transport costs. Thus, the CLONE model facilitates the conversion of trade flows into transport flows by providing the hinterland network structure, to which container flows are assigned. Furthermore, the WCM estimates how trade flows are distributed over the European freight network and which ports are consequently chosen by the shippers.

While the basic concept of the integrated model can be traced back to supply chain models that are developed for optimization studies, adding calibratable parameters on the cost functions of the logistics module turns the whole integrated model into an efficient descriptive model with relatively few parameters. This is advantageous, considering that calibrating a descriptive model, which normally has many of parameters, might be computationally expensive. Policy analysis exercises can benefit from this model by using it to gain insight into how different trade scenarios change the structure of the network flows between the European ports and hinterland destinations. Indicators of the transport system that are relevant for policies (e.g. costs of the intermodal transport system within Europe, etc.) can be easily incorporated into the model.

To illustrate the capacity of the model, we estimate the impact of a 2040 trade scenario on the ports in the Hamburg - Le Havre range and compare it with a reference scenario for 2040. In this scenario, Eastern European and Northern African countries are expected to experience more growth than the rest of the European regions. The Port of Rotterdam and the other ports in the Hamburg - Le Havre range are foreseen to be negatively impacted by this trend, with Rotterdam experiencing the smallest impact in throughput. Furthermore, ports in Germany are foreseen to be the least impacted in their throughput and transshipment. The hinterland connections between ports in the westtern and eastern Europe play important role in determining the outcome of the competitions between these ports. Ports that have good connections to regions in Eastern Europe are likely to experience the least negative impact when there is an increase in the economic activities in these regions. Specifically, this implies that these ports need to investigate measures that foster the development of cheap and reliable hinterland transport services and infrastructures to the Eastern European regions.

The computational framework laid down in this chapter has also opened a new research opportunity to model broader and larger freight transport systems systematically. These

systems include the global supply chain and global shipping networks which the logistics networks of different companies shape. The logistics network model presented in this chapter can be used to estimate the structure of these networks while the global transport demand model estimates the flows of containers over these networks. For that purpose, origin-destination databases on movements of containers need to be established. Current satellite technology such as automatic identification system (AIS) can be used to help creating such database. Furthermore, future research will also focus on improving the dataset used in calibration to find better approximations for the modeled throughput, such as using employment data that is specifically related to international flows between ports and DC's. Finally, another valuable extension of the model for policy analysis at the European level is to take the observed intra-European freight distribution structure into account such as those from plants, terminals, to distribution centers.

4 Modelling the impact of the emergence of direct shipping lines on port flows

Abstract

Chapter 3 has analysed the impact of port hinterland distribution structure on port flows. However, the result of the scenario discovery study in chapter 2 has also indicated the need to investigate uncertainties caused by changing global shipping networks. The scenario discovery application in chapter 2 did not consider changes in the network of shipping lines. This chapter presents a modelling approach that aims to investigate the impact of the emergence of direct shipping lines on global port flows. As such, the objective of this chapter is to answer research question: "How can we investigate the impact of the emergence of direct shipping lines on port flows?"

By using the modelling approach proposed in this chapter we conduct an analysis of the uncertainties caused by changes in the global shipping network for global ports and especially for Port of Rotterdam. In this study we discovered a threshold value for the scale of transport between two ports above which direct shipping service are likely to emerge. We use this empirical observation to model the emergence of direct shipping services in 2040. Finally, we present the impacts of the emergence of direct shipping lines on the performance of ports worldwide in terms of their throughput and transhipment.

This chapter is structured as follows. Chapter 4.1 provides an introduction on the emerging trends and patterns in global maritime shipping networks. Chapter 4.2 provides a brief review of the surrounding research environment of our topic. Chapter 4.3 introduces the

modelling approach used. Chapter 4.4 describes the application for global networks and the implications for the port of Rotterdam. Chapter 4.5 summarizes the findings of this exploratory paper and makes recommendations for further research.

4.1 Background

The world's trade of the past couple of decades has proven to be very dynamic. The economies of many developing countries has grown, while the economies of most developed countries have been stagnant or only witnessed sluggish growth. The world's maritime transport network will continue to adapt itself to these changes. The foreseen increase of trade between the BRICS (Brazil, Russia, India, China, South Africa) countries and the rest of the world, is an example on a trend that will stimulate and promote the emergence of new shipping lines in the world's shipping network. New direct connections might emerge in response to this trend, and existing routes might be adapted. The global maritime shipping network evolves over time to in order to continue to provide adequate sea transport services for the growing demand between developing countries and the rest of the world. Insight in how trends and developments such as the growth or decline in demand for shipping between the BRICS countries and the rest of the world will influence or shape the future global maritime shipping network is therefore highly valuable.

Without knowledge and understanding on the future transport demand pattern at the global level, parties such as port authorities, governments, and international organizations such as the United Nations will have to deal with undesired uncertainties. Such uncertainties, when not addressed systematically, will not only negatively impact the plan to develop adequate transport infrastructure of many countries, but also at the higher level, will give a negative effect for the economy of world. It is clear that under and over-utilization of maritime transport infrastructure, especially ports, will incur a high cost due to congestion and under-utilization respectively.

Scientifically, there has been limited research on the global maritime shipping networks such as in (Ducruet and Notteboom, 2012, Song et al., 2005). However, It can also be observed that the majority of the studies aim at interpreting the network structure using graph theory and spatial analysis such as those which can be found in (Ducruet et al., 2010, Kaluza et al., 2010), and complex adaptive system theory in (Caschili and Medda, 2012). Hence, it is clear that there are few studies aimed to build a predictive capacity on how the restructurization of the global maritime shipping services impact the behaviour of the shippers and consequently the performance of the ports. Another commonly used approach is to use optimization models in modeling the most efficient network structure that connects ports worldwide (Zeng and Yang, 2002). However there has not been any attempt to model the mechanism with which liner shipping companies will start establishing direct shipping services and how this trend will impact port flows.

In this chapter, we aim at sketching the aggregated responses of shipping lines to foreseen trends of growth. To this end, we first examine how direct shipping lines between two ports can emerge in response to a change in the demand for freight transport. Second, as a case study, we investigate the influence of the emergence of new direct lines on European ports, in terms of port throughput. For this purpose, a strategic global freight transport model

is developed. Third, we also analyse how the direct lines affect container flows distribution worldwide and how the port choice of the shippers is affected by these lines, particularly for big ports in the US, and East Asia.

The model that has been developed to support these analyses is explicitly exploratory in character. It builds on the widely used freight modelling framework which finds its roots in discrete choice modeling approach (Tavasszy and de Jong, 2014). The model has been used for supporting the exploration of alternative scenarios related to changes in OD demand patterns globally. Here we use it to study the emergence of direct shipping lines in response to demand growth. The model can however, also be used to analyse the disappearance of direct lines in response to declining demand.

4.2   Literature review of the dynamics in global maritime shipping networks

Our research is focused on the emergence of direct maritime connections between ports in the world. A direct maritime connection is a freight transport service from one port to another port that is conducted without any transshipment or change in shipping service provider. The actual ship delivering the cargo might call different ports on the way to the destination port before heading back to the origin port. It is apparent from empirical observations that direct shipping lines have a significant impact on the throughput and transshipment values of a port. As can be seen in Figure 4.1, ports with high number of shipping service calls have high corresponding total container throughput. Furthermore, the high correlation (R^2=0.78) between number of calls and total throughput on each of the observed ports confirms this observation.
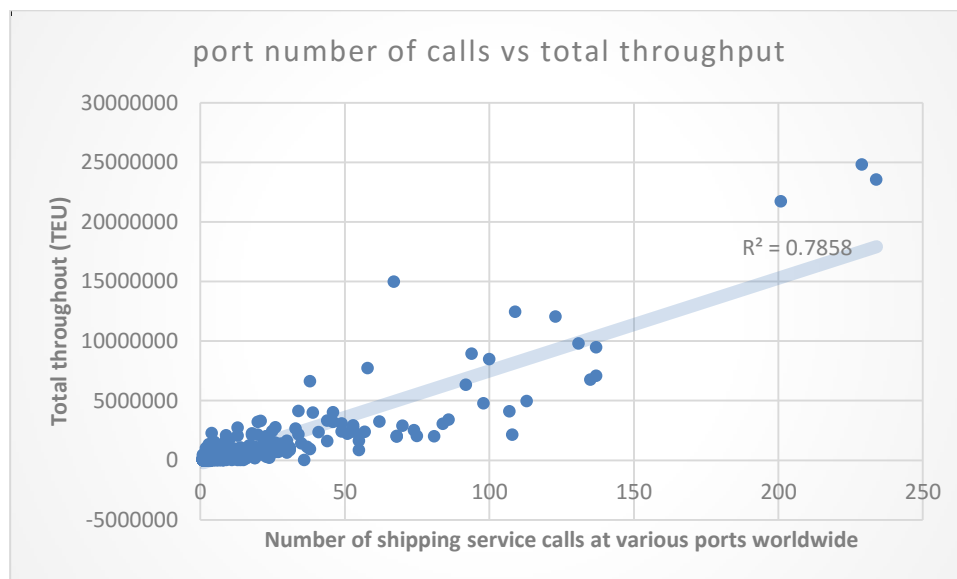

Figure 4.1 Relationship between number of shipping services calling at a port and its total throughput

Direct shipping lines are being used to transport large volumes of containers between two (typically large) ports. These direct lines carry high volumes and have substantial

economy of scale advantages, resulting in reduced transport costs. From our observation, it is clear that the emergence of direct lines is tightly related to the scale of transport demands between two ports. In general, the higher the amount of flows between two ports, the more likely it is that a transport service will be done with less transshipment or even directly. An example of this phenomenon can be seen in the shipping services that connect the port of Rotterdam and the port of Singapore. Being the biggest ports in both Asia and Europe, with very high transport demand between the two, there are more than 32 direct shipping services connecting these two ports. This is not surprising as shipping companies would be able to gain higher profit from providing services that have better cost-revenue ratio per goods transported. Figure 4.2 provides an illustration of economies gained at the ship level, where increasing ship size can reduce unit costs of transport considerably (Cullinane and Khanna, 2000).
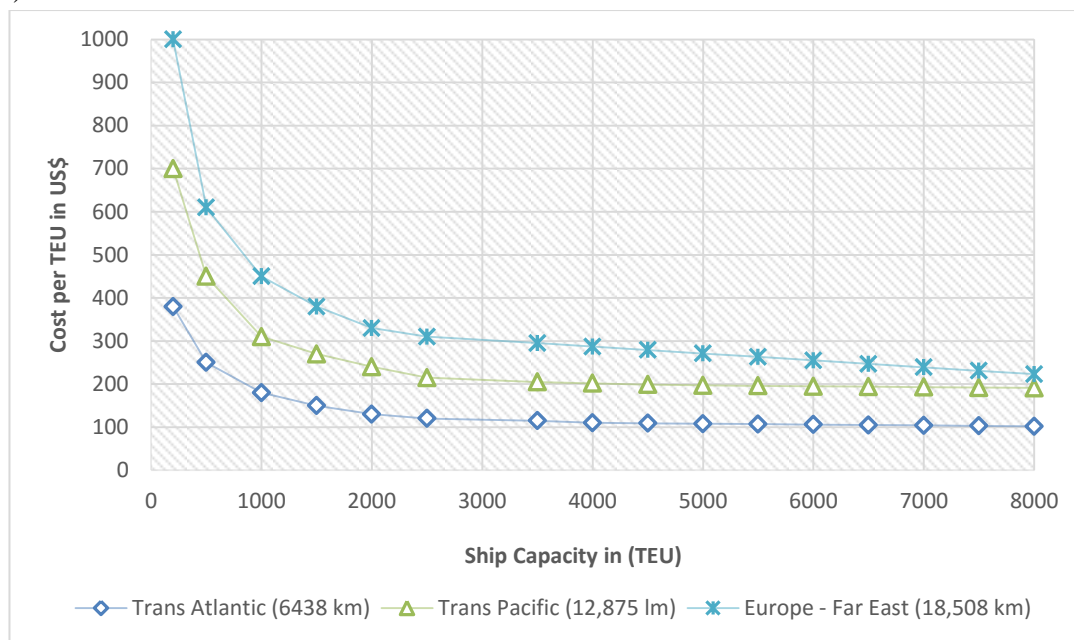
Figure 4.2 The relationship between unit cost of transport and ship capacity, source (Cullinane and Khanna, 2000)

To date, there are many models that have been developed to optimize the network of a liner shipping company. Generally such models are developed to minimize the total transportation costs while fulfilling the demand or maximizing the profit of a liner shipping company (Wang and Liu, 2015). Since there are many operational factors that can be considered, a container transport network can be very complex. Therefore the specificity of the models depend on the specific factors that are of study interest.

For example, (Fagerholt, 2004) proposes a model where the main objective of the study is to optimize the routing of individual ships given a delivery time constraint, so that the total costs can be minimized. Another study uses a model that minimizes both the total distance travelled by the ships and the fuel consumption (Jepsen et al., 2011). An example of a more complex model that consider fleet design, ship schedule, and ship routing simultaneously can be found in Mulder and Dekker (2014). Another type of model in this class is also developed by considering extra constraints such as maritime cabotage and transit time between routes (Wang et al., 2013). Furthermore this kind of model keeps on being developed to take more

factors into account such as the model that is developed in Liu et al. (2014). This model optimizes the strategic routing of the containers on both hinterland and maritime sides using both discrete choice model and mixed integer linear programming approach respectively.

A major drawback of network design models is that they cannot be used to analyse the emergence or disappearance of shipping lines globally, or the impact of this trend on the performance of individual ports. There might be several shipping companies that plan to provide a direct shipping service in response to growing demands globally. In this case, optimizing the routes of all individual shipping companies would not be computationally tractable. Another approach to model the global maritime shipping network is applying a graph theoretic perspective and use indicators such as centrality indices to interpret the structure of the network (Ducruet and Notteboom, 2012). However this approach does not aim to predict the impact of new trade scenarios on the structure of the network.

We need a more aggregate and holistic approach for analysing the plausible impacts of future trends in demand for global container transport. This approach should be able to reckon the changes in the structure of the global maritime shipping network based on the changes in the demand for freight transport and vice versa. For this reason, we develop a rule-based method that can be used on a global scale. This approach is rooted in the science of descriptive freight modelling as described in Tavasszy and de Jong (2014).The next section provides an elaboration of this method.

4.3   Approach to evaluate emergence of direct lines

We implement a rule-based method to model the changes in the shipping networks caused by the emergence of the direct shipping lines. This method is integrated into an existing model of world container flows (Tavasszy et al., 2011). We investigate how changes in the network of shipping lines impact the throughput and transhipment of the ports in the Le Havre-Bremen range (including Ports of Bremen, Hamburg, Amsterdam, Rotterdam, Antwerp, Zeebrugge, Dunkirk, Le Havre).

4.3.1   Emergence of direct shipping lines

To investigate the impact of a new shipping network with more direct shipping lines, we employed an approach which systematically adds new shipping lines between two ports, based on a rule reflecting the impact of the economies of scale on the network. Figure 4.3 gives an overview of the approach used in this analysis. Using the WCM, the port choices of the shippers using the new network can be simulated and the volumes expected for all ports can be obtained. The following paragraphs elaborate the steps that were taken in the analysis.
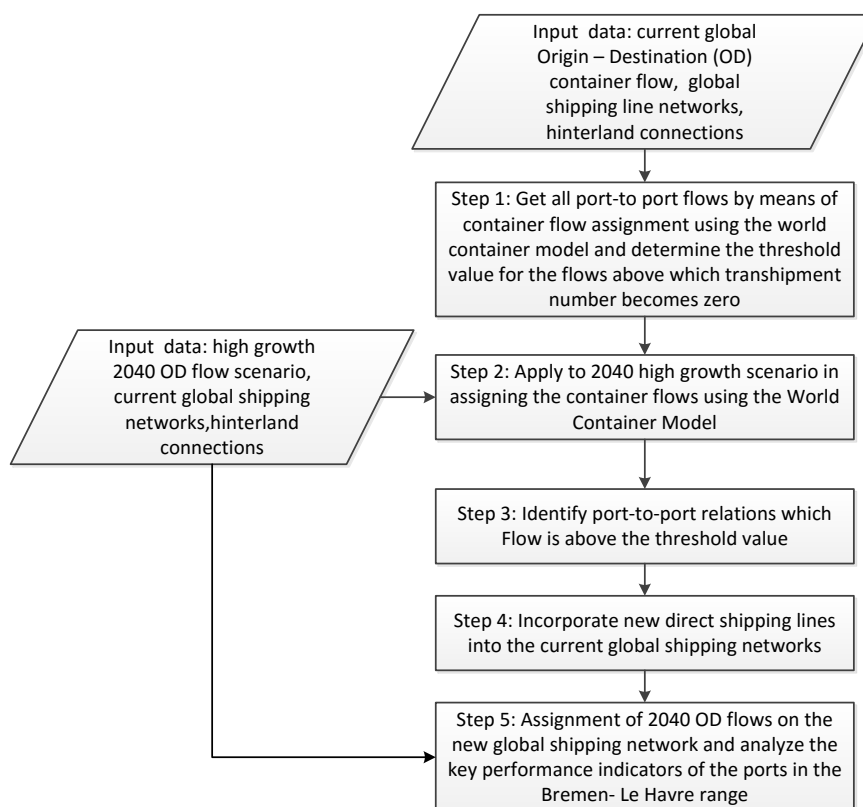
Figure 4.3 Steps used to model how the emergence of direct shipping lines effect the choices of ports by the shippers

Step 1: Identifying port to port flow thresholds for availability of a direct connection

As the first step to model the change in the shipping network, we investigate the threshold value by which shipping companies would provide a direct shipping service or a new shipping line between two ports. We obtain this threshold value by observing both the volume of container flow and transshipment in more than 160.000 port-to-port flows of which the transport is served by the available shipping lines. From this analysis we obtain a flow value above which the transshipment number becomes zero. This is the threshold value

Step 2: Applying growth scenario to flows

Next, we use a scenario for 2040, where there has been a significant increase in the transport demand. In this scenario, most of the countries in the world are expected to experience growth in their export and import activities leading to higher transport demand between countries. This growth in transport demand takes into account a significant economic growth in the developing countries such as Brazil, Indonesia, China, and India. The increase in demand varies between 30-140% depending on the forecasted increase of trade between the corresponding countries. Transport demand data for the scenario was obtained using a global Spatial Computable General Equilibrium model (Ivanova, 2013) that estimates the amount of container flows worldwide as a result of the global trade.

Step 3: Identifying port to port relations which flow is above the threshold found

The high growth scenario is used as an input for the WCM. Subsequently, the WCM is used to assign the OD demand to the existing shipping line network. From this assignment,

we derive port to port container flows. Next, assuming that the threshold value found in step one will remain the same in the future, we identify all port-to-port flow that exceeds the threshold value. These port-to-port flows represent flows that are expected to be handled by direct services.

Step 4: Creating the direct lines between the ports in the shipping line network

Next, based on the identified port-to-port flows, new shipping lines are automatically created and added to the current network. That is, if for a given pair of ports with sufficient flow to warrant a direct service no direct service exists, we add such a direct service to the model. The new shipping line provides a direct connection between two ports where the flow is above the threshold value. We assume that the capacity and frequency of the new shipping line will suffice to accommodate the increased demand. Furthermore, it is also assumed that all the old shipping lines will remain in the new network. Figure 4.4 illustrates the case where the container flow between Jakarta and Rotterdam is above the threshold value found in step 1. Before the addition of a new direct shipping line, containers from Jakarta to Rotterdam are transhipped at multiple ports (i.e. at Singapore, Jeddah, Le Havre) and they are shipped with different shipping line services. After a new direct shipping line emerges between Jakarta and Rotterdam, containers from Jakarta can be shipped directly to Rotterdam without transhipment (illustrated with dotted line). This procedure is applied to all port-to-port relations found in step 3. A shortest path algorithm is used to construct the route that is used by the direct shipping lines.
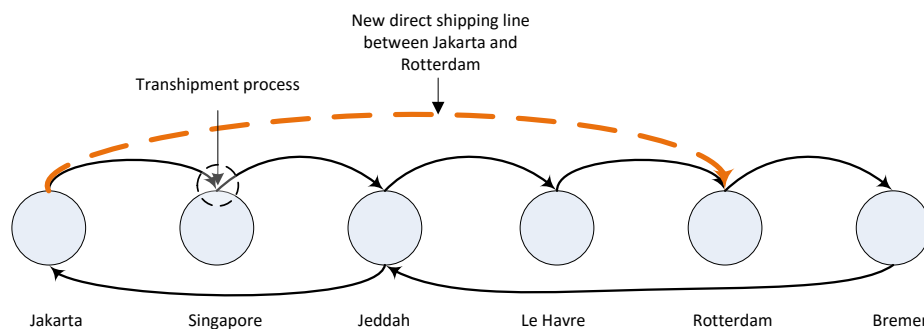
Figure 4.4 The procedure to adding a direct shipping line into the global shipping network

Step 5: Re-assigning Port-to-Port flows based on the new shipping network

Once the new shipping lines have been created and have been added to the network, the WCM is used once more to assign the flows for the high growth scenario over the new shipping network. From this assignment of flows give the modified service line network; we can derive the throughput and transhipment for the more than 400 ports that exist in the network given the high growth scenario.

4.3.2   Implementation

We implemented the algorithm using Java technology to achieve good portability in running the model on different operating systems. Furthermore we also use a set of libraries that help us to optimize the computation process such as JUNG (Java Universal Graph) library (O'Madadhain et al., 2005). Specifically, we use JUNG to implement both the global

maritime and hinterland transportation networks. Finally, the UNFOLDING library (Nagel et al., 2013) is used to create maps that visualize the distribution of the flows over the intermodal freight network worldwide.

To run the computation of the model, we use a desktop PC with 2.4GHz Intel i5 processor, and 4G memory. The total run time of the model is around 3 minutes and the memory usage is at 1.5G in average. Computation speed and memory usage have been given a proportionate attention since the model is foreseen to be used in a large scale experiment involving more than 10,000 model executions.

4.4 Results

4.4.1   Observed threshold value

In order to obtain flows that are relevant for determining the threshold value, we retrieved the biggest flow that is transported by each of the shipping lines in the world. Hence, with more than 840 service lines in the world serving global routes, we obtained 840 biggest flows of these service lines. The figure below plots the data points for each recorded port-to-port flows and its corresponding number of transshipments. As can be seen, there are many small flows with direct connections. Most of these flows are served by the same shipping lines that transport bigger flows for long-distance destinations. This implies that there is a "piggybacking" phenomenon from the smaller port-to-port flows that can be ignored in our analysis. We determine the threshold value by looking at the highest flow value above which the transshipment number for the flow becomes zero and this value lays around 200.000 TEU/year.
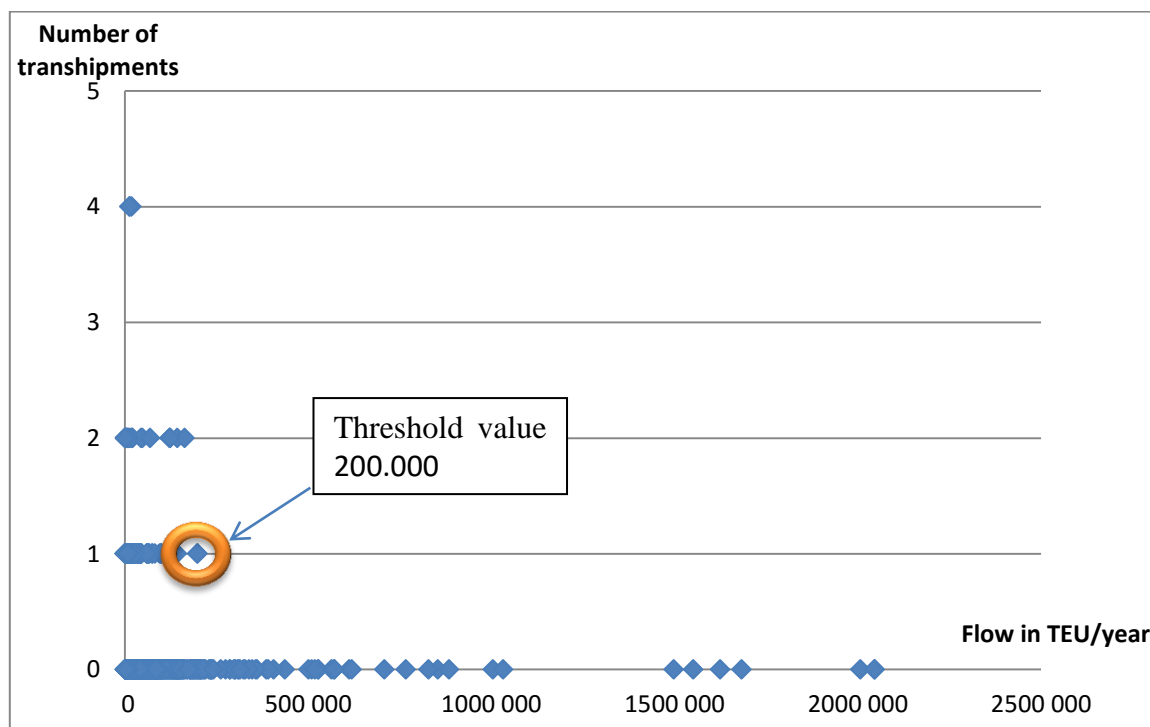
Figure 4.5 Threshold value for ptpFlow with direct connection

Next, we run the WCM with the hight growth scenario. Given the threshold value of 200.000 TEU/year, we identify 528 port-to-port flows which values exceeded the threshold. New direct shipping lines are created to connect these ports, and these new lines are added to the current shipping network.

4.4.2   *Impacts of the direct shipping lines on the Ports in the Hamburg - Le Havre range*

Using the new structure of the global shipping line network, the assignment of the flows is performed once again and the throughput and transshipment values of the ports are derived. As can be seen in Figure 4.6 below, in comparison to the base year in 2006, most of the ports in the Hamburg - Le Havre range are expected to handle more container flows. This can be seen from the growth in their throughput values ranging from 95% for Port of Amsterdam to 172% for Port of Antwerp. This indicates that in 2040, there is substantially high growth on the volume of containers being transported from and into Europe. With regards to transshipment values, we can observe an interesting pattern where Port of Rotterdam is expected not to experience as much growth as the other ports in the Bremen- Le Havre range. Interestingly, while Port of Dunkerque loses 5% of transshipment volume, Port of Zeebrugge is expected to handle more than 3.5 times transshipment volumes than the base year.

Relative growth of TEU in 2040 with emerging direct shipping lines, when compared to the base year (%)

	ROTTN	BREMD	ANTWB	AMSTN	ZEEBB	HAMBD	LEHAF	DUNKF
transhipment	57.84	126.45	136.27	0.00	341.85	141.71	120.06	-5.30
throughput	163.02	168.15	171.75	95.67	148.94	171.89	154.75	104.43
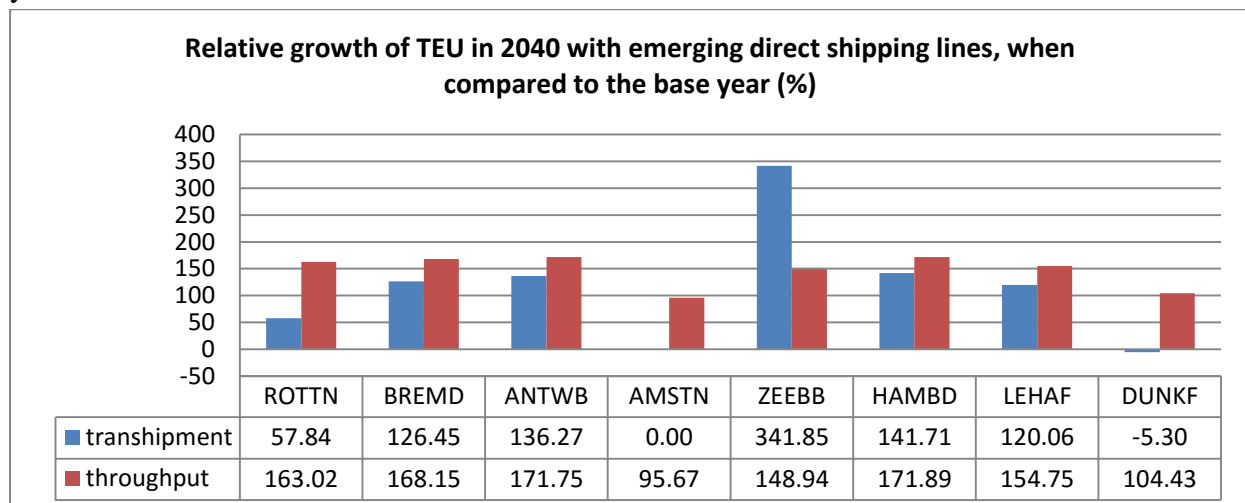
Figure 4.6 Relative change of ports' transhipment and throughput when compared to the base year

Next, we also compare ports' performance in 2040 between two scenarios: when direct shipping services emerge and when there is no change in the current shipping services. Figure 4.7 depicts the percentage change in transshipment and throughput values of the ports in the Hamburg – Le Havre range relative to the values when there are no new shipping lines in the high growth scenario.

Relative loss of TEU in 2040 due to emergence of direct shipping lines (%)

	ROTTN	BREMD	ANTWB	AMSTN	ZEEBB	HAMBD	LEHAF	DUNKF
transhipment	34.10	8.60	3.41	0.00	0.01	4.89	16.22	0.04
throughput	2.24	5.48	6.13	23.11	17.47	8.84	11.41	12.01

Figure 4.7 Percentage decline in throughput and transhipment caused by the addition of new shipping lines, high growth scenario

As can be seen from the result, most of the ports in the LeHavre-Bremen range suffer from the addition of the new lines. In terms of throughput, the Port of Rotterdam is not severely impacted by the emergence of these lines. While the rest of the ports in Europe suffer considerable negative impact in their throughput, the Port of Rotterdam only has a small reduction in throughput. This indicates that the loss in transshipment is compensated by the increase in flows of containers going from and to Europe through the hinterland of Rotterdam. This also indicates that there are also direct lines calling Port of Rotterdam, connecting it to the countries where there is significant economic growth.

It appears that the Port of Amsterdam is the most negatively impacted, followed by Port of Zeebrugge. In terms of transshipment, Port of Rotterdam's performance is the most negatively impacted. This is followed by the Port of LeHavre and the Port of Bremen. It is noticeable that the transshipment values of the rest of the ports in the Hamburg - Le Havre range are not severely impacted. For Port of Zeebrugge, this particular trend means that the emergence of direct shipping service does not significantly impact them.

The loss of transshipment by the Port of Rotterdam indicates that in the scenario where there's a high growth in trade between countries, many of the emer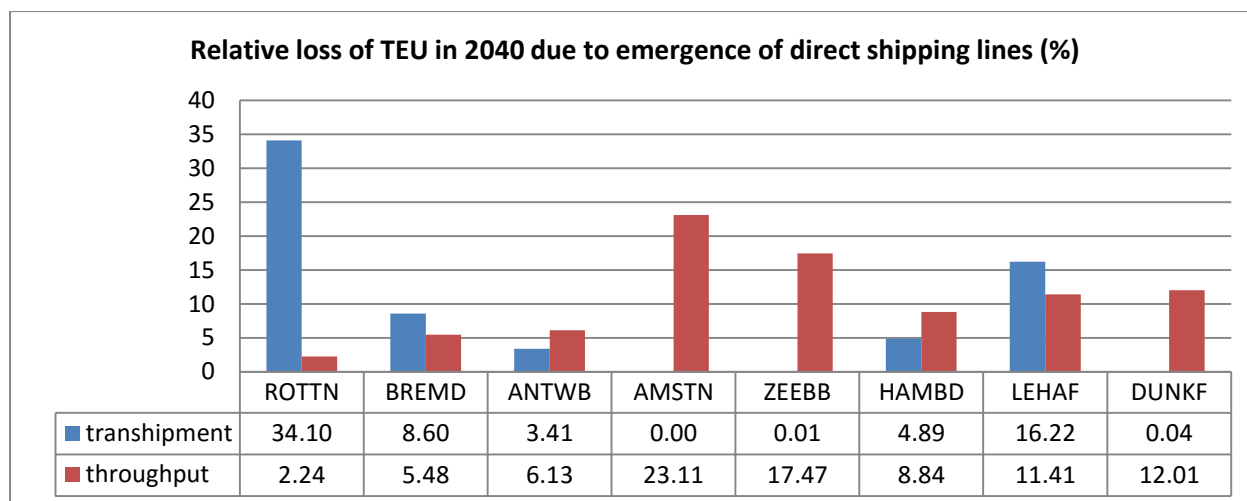ging shipping lines would not have transshipment anymore in Rotterdam. Several factors might cause this. One, there might emerge new transshipment hubs driven by these new lines and the overall growth of transport demand. These transshipment hubs typically emerge in the ports where the new shipping lines make a call or in the nearby ports that are connected to these ports by previously available shipping lines.

Second, the direct shipping lines take over the transshipment market of the big transshipment ports such as the Port of Rotterdam, Port of Bremen, and Port of Le Havre. This is logical, as with better economy of scale, transporting containers using the direct lines would be cheaper and hence is more attractive for shippers. Shipping lines which call the ports in the Hamburg - Le Havre range will have less demand for container transport when there are direct lines calling these ports. As a result, big transshipment ports such as Port of Rotterdam, Port of Bremen and Port of Le-Havre are foreseen to suffer from the emergence of new direct shipping lines. Third, this also indicates that there are more direct shipping lines

calling the port competitors of the Port of Rotterdam such as Port of Bremen, Port of Antwerp, Port of Hamburg and Port of Le Havre.

4.4.3   *Impacts of the direct shipping lines on global ports*

Figure 4.8 visualizes the effect of the changes in global container flows caused by the addition of the new shipping lines. As can be seen on the figure, the new shipping lines have caused certain routes to have more volume and certain ports to have more transshipment. The size of the pie charts on the figures indicates the magnitude of the total throughput of the port, with light grey section indicates the transhipment fraction of the throughput value.

Figure 4.8 The world container flows without (left) and with new shipping lines (right), in high growth scenario in 2040.

Specifically, we notice in the right picture of Figure 4.8 there are direct shipping lines that call ports in Southern America and connecting them with ports in Eastern Asia. More flows are also visible in the southern part of Argentina indicating that there are direct shipping lines that call the ports in this region. In terms of throughput and transhipment, we see big ports in the US like the Port of Los Angeles and New York to have more transhipment when with less total throughput values when direct shipping services are available. Figure 4.9 and Figure 4.10 provide visualization for the throughput of the ports in the U.S. when there are no new direct shipping services and when direct shipping services emerge respectively.
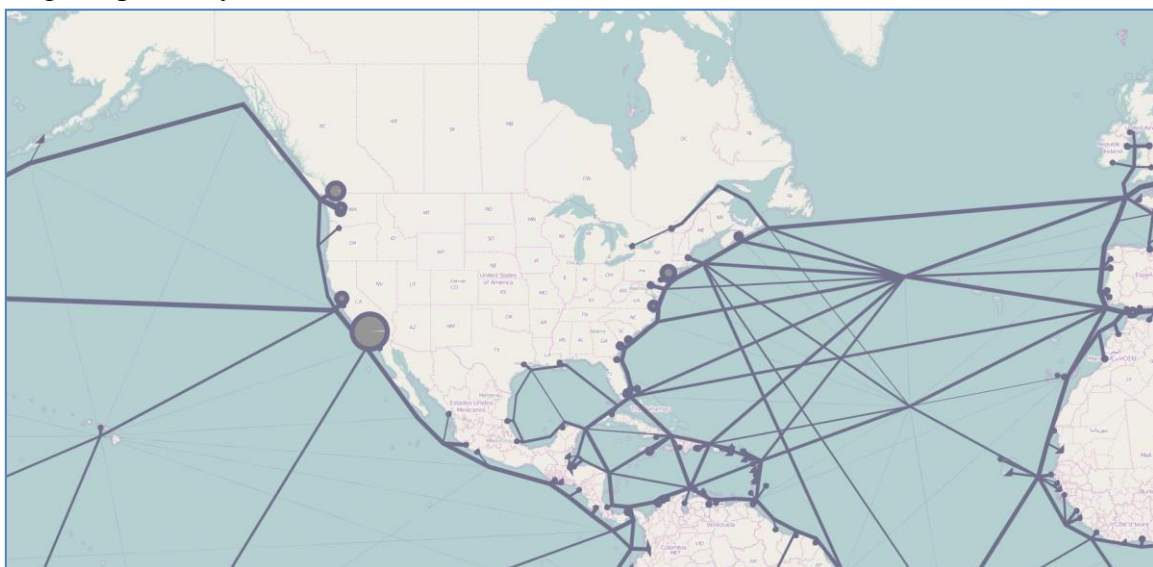
Figure 4.9 Throughput and transhipment in the US ports without new direct shipping services
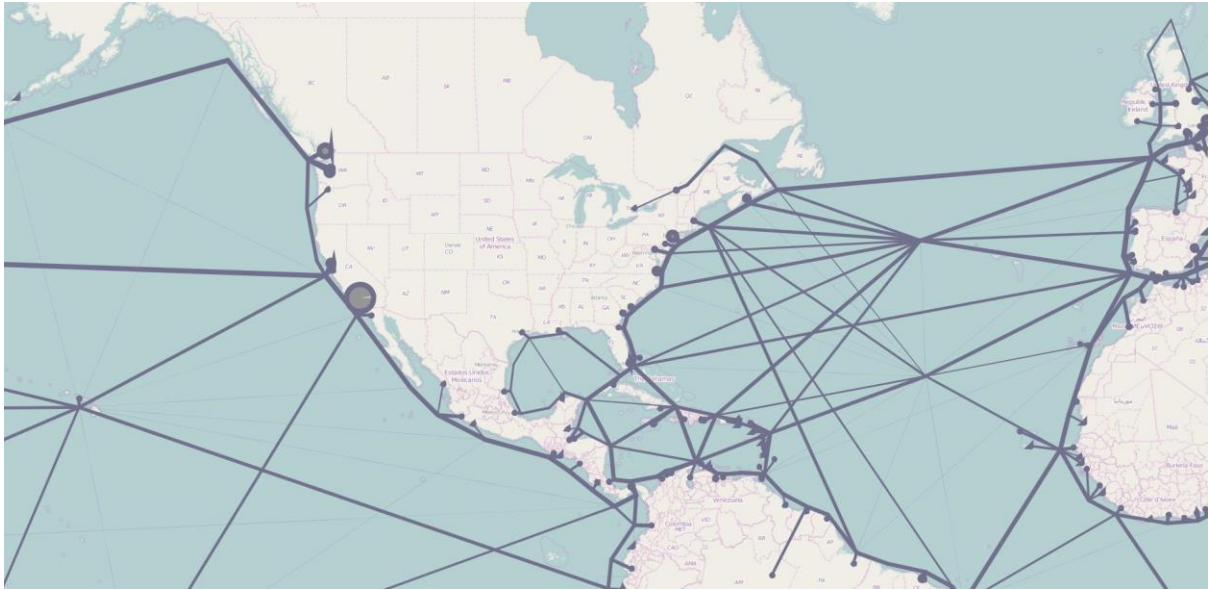
Figure 4.10 Throughput and transhipment values in the US ports with emerging direct shipping services

Similarly, big ports in East Asia such as Singapore and Shanghai seem to have a decline in their transhipment market, especially Port of Singapore caused by the emergence of the direct shipping services Figure 4.11 and Figure 4.12 illustrate the ports' throughput in Asia with and without direct service shipping services respectively.
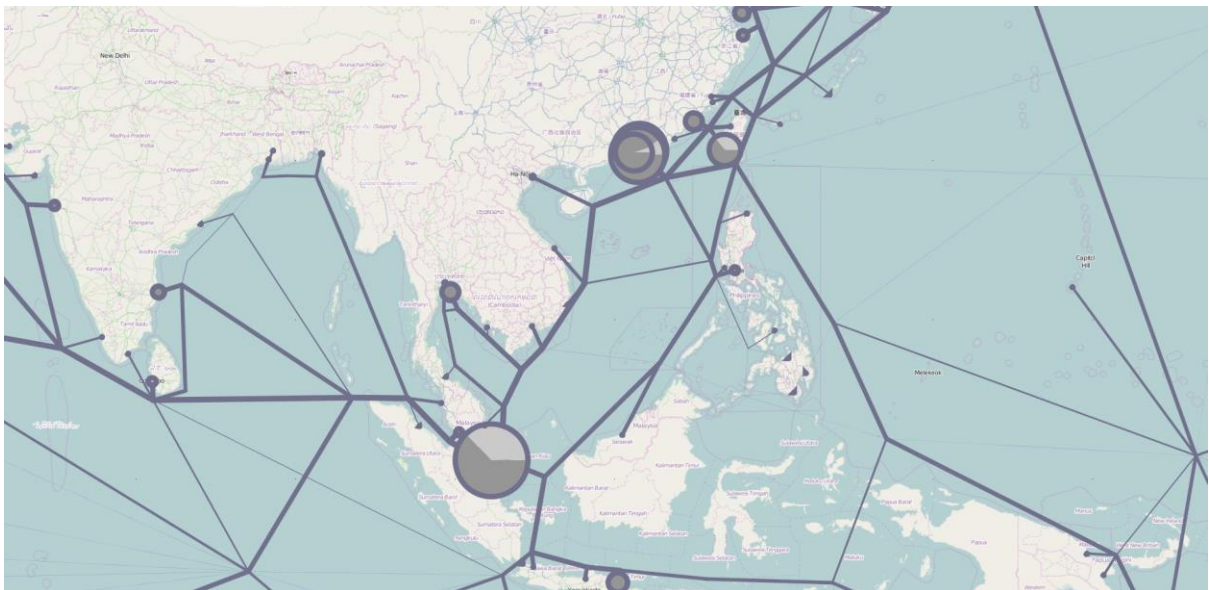
Figure 4.11 Throughput and transhipment values in Asian ports without emerging direct shipping services
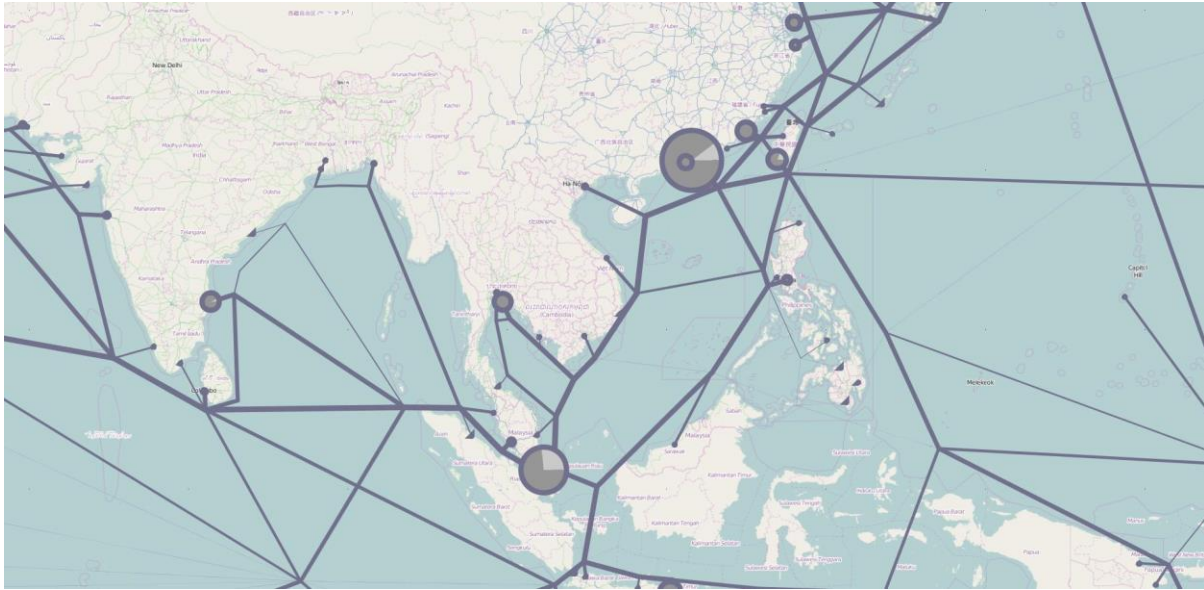
Figure 4.12 Throughput and transhipment values in Asian ports with emerging direct shipping services

These results seem to indicate that the emergence of new direct shipping lines causes big transhipment ports worldwide to have a decline in their transhipment market, especially those which support the growing trade between the western and eastern countries like port of Singapore. Ports that have a strong own hinterland may compensate these losses due to the increase of direct flows of these regions. This is the case with the Port of Rotterdam.

It is noteworthy that an important reference point for this analysis is the threshold value above which direct shipping service would emerge -that is at 200,000/TEU year. The observation of this phenomenon is based on the shipping service networks data in 2006. It is plausible that changes in global shipping networks will likely also change this threshold value, which in turn, also lead to changes in the future network structures. Eventually, these changes in network structures will give different impacts on the flows of containers in the ports in Hamburg -Le Havre range. Hence, in such case, new analysis using new service network data needs to be conducted to find the new observed threshold value with which new the impact of new direct shipping lines on port flows can be assessed.

4.5 Conclusion

We have presented a systematic analysis which can explain how the demand for freight transport can structure the future global maritime shipping networks. Particularly, we have investigated the underlying principle which governs the emergence of direct shipping services between two ports. Furthermore, using this principle, we explored future changes in port flows caused by the emergence of these direct shipping lines. The analysis makes use of a simple rule-based method to model and systematically update the existing global shipping networks with plausible direct shipping lines. The results show that the proposed method is useful in providing insights on how direct shipping lines can impact the performance of ports worldwide.

We discovered that a direct shipping service between two ports would likely to emerge when the volume of flow transported is above 200,000 TEU/year. When we run the model with the high growth scenario in 2040, we discover that the emergence of new shipping lines would have a significant negative impact on the transhipment of the Port of Rotterdam and an overall negative impact on the ports in the Bremen – Le Havre range. Furthermore, our experiment also shows that big transhipment ports in East Asia such as Singapore and Shanghai are severely impacted by the emergence of direct shipping lines. Similarly, big ports in the US such as Port of Los Angeles and Port of New York seem to be also negatively impacted by these direct lines.

Finally, the model presented here also opens up a new opportunity in developing a holistic and efficient heuristic to approximate the future structure of global shipping network. More future trade scenarios can be investigated to assess the impact caused by the uncertainty concerning the increase of scale in the maritime transport system. In this regard, it is also highly valuable to have a strategic model which can explain the formation of the global shipping network, based on simple rules. When calculations can be done in an efficient manner, this type of model can be used to explore vast amounts of scenarios. Eventually, this model can be used to assist policy makers in anticipating on possible negative outcomes of major uncertainties that shape the structure of the future global freight network.

5 Modeling the impact of the plausible configurations of global shipping network on container flows

Abstract

The previous chapter has investigated the impact of the emergence of direct shipping lines on global transport patterns and port throughput. In the analysis, it was assumed that established shipping lines would remain the same even in the case when container transport demand changes in the future. This is not realistic in all cases because liner shipping companies continuously adjust their networks to the changes in global transport demand to improve their operational efficiency. This is a gap that needs to be addressed in analysing the impact of changes in the global trade demand on the routing of containers. Therefore, the objective of this chapter is to develop a more generic model for aggregate shipping networks that can be used to estimate the impact of changes in global transport demand on port flows. Together with chapter 4, this chapter addresses the question: "How can we model the plausible future structures of global maritime shipping networks to gain insight into the impact of these structures on port competitiveness?". While chapter 4 attempts to approach this question by making use of the observation on previously established liner shipping

networks, this chapter attempts to model the future global shipping networks based on global trade patterns.

This chapter is structured as follows. Section 5.1 provides an introduction to the main challenge of modeling plausible alternative structures of global maritime shipping networks. Section 5.2 presents a literature review of theories and models that are relevant to address the problem. Section 5.3 explains the underlying principles that guide the design of efficient alternative shipping networks. Section 5.4 presents a method for identifying alternative plausible network configurations. Section 5.5 provides the application for the proposed method on the case study of the design of the Indonesian maritime shipping network. Subsequently, Section 5.6 presents the application of the method to the global shipping network, paying particular attention to the impact of alternative network configurations on the ports in the Hamburg – Le Havre range. Finally, Section 5.7 summarizes the findings of this chapter and outlines directions for further research.

5.1   Introduction

The global maritime shipping network is a dynamic structure that continuously adapts itself to support the ever-increasing world's trade. One of the notable trends is that liner shipping companies are increasingly using bigger ships. As more ships with bigger capacity come into service, opportunities to better exploit economies of scale also increase. In turn, this stimulates shipping companies to take strategic moves to reduce the unit transport cost further. Among the possible strategies which have been employed, we see that big shipping companies start to form alliances to better utilize the capacity offered by bigger ships, and smaller shipping companies begin to utilize bigger ships to accommodate the expected future demand (Davidson, 2014).

Economies of scale are exploited in pursuit of increased market share by increasing vessel size, leading to lower unit costs of transporting containers. In order to maximize scale effects, shipping alliances form new network structures - altering the ports of call schemes that have been established before (Cullinane and Khanna, 2000). The new network covers the markets of the members of the alliance and is geared towards maximizing the efficiency for long-haul shipments. Furthermore, individual shipping lines that utilize bigger ships also connect distant destinations to reduce the unit cost per ton-kilometer of the containers transported. In doing so, these shipping lines might reduce the transshipment at different ports where the demand is not very high. Taken together, this brings about structural changes in the global maritime network.

At present, there have been no models that were specifically developed for analyzing the impact of changes in global trade patterns on maritime network structures, and how these structures would influence the flows through ports. There have been works aimed at studying the global maritime shipping networks, such as (Ducruet and Notteboom, 2012, Song et al., 2005). However, these studies generally aim at interpreting a given network structure using graph theory and spatial analysis (Ducruet et al., 2010, Kaluza et al., 2010), or by using complex adaptive system theory (Caschili and Medda, 2012). Another commonly used method is to approach the problem of alternative shipping line network configurations as a network design problem (Liu et al., 2014, Wang and Liu, 2015, Wang et al., 2013, Zeng and

Yang, 2002). In this approach, typically an optimization model and a solution method are developed to find the most efficient network structure that can determine port rotations worldwide with minimum cost. However, such a method is normally applied at the level of individual liner shipping companies.

Given the trend where liner shipping companies continuosusly adjust their service networks and partnerships in response to growing transport demand, it is valuable to have a strategic model that can investigate the emerging aggregate shipping networks. Specifically, such a model can be used to analyze the impact of changes in global shipping networks on port flows and the efficiency of the global transport chain. Methodologically, a macro-level optimization approach that considers the global maritime shipping networks as an aggregate network of shipping companies can offer a promising alternative to current approaches, in which the networks of different liner shipping companies are optimized individually.

This chapter proposes a model of emergent aggregate shipping network structures. Specifically, we model how different network topologies might emerge that differ in terms of transport costs and network distance. The model consists of a freight demand model and a service network design model. We specify the demand and supply subsystems of the freight transport system and propose algorithms to identify plausible future structures of the shipping network based on the interactions of these two subsystems. In our approach, we avoid having to model individual carriers and their clients, which reduces data needs and decreases run times of the model computation.

The contribution of this chapter is threefold. First, it provides a novel model to explore plausible global shipping networks. Second, this chapter gives an insight on how changes in global maritime shipping networks impact the throughput of ports in the Hamburg - Le Havre range. Third, this chapter also gives an insight into the efficient design of Indonesian shipping network through a case study used to assess the effectivess of the model proposed.

5.2 Literature Review

Many models have been developed to optimize the network of individual liner shipping companies. Tran and Haasis (2013) and Christiansen et al. (2007) provide an extensive literature survey covering a wide range of models and their characteristics. Typical structures that can be observed in a liner shipping network are the Multiple Port Call (MPC) and Hub and Spoke (H&S) structures (Figure 5.1, left and right panel, respectively).
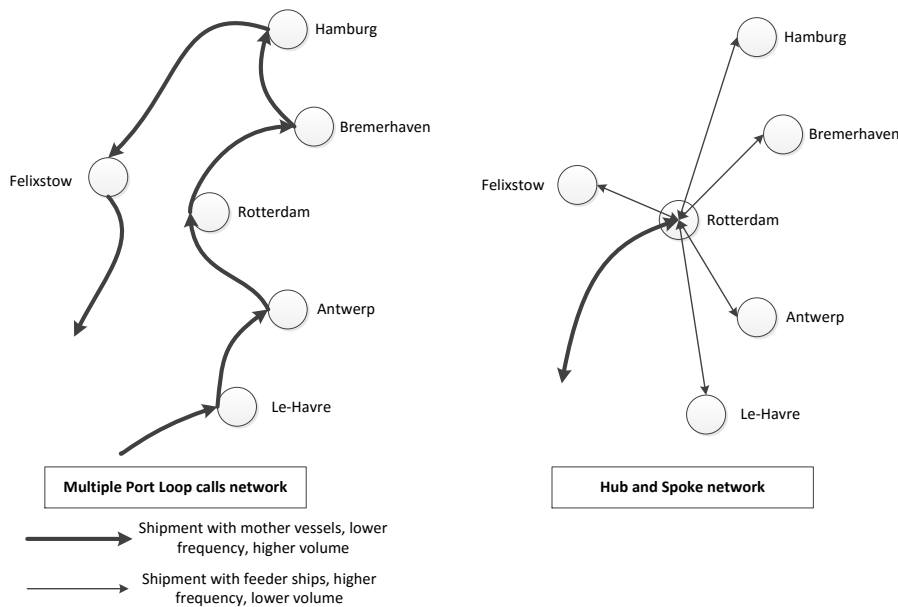
Figure 5.1 Multiple Port Loop call network (left) and Hub and Spoke network (right)

In the H&S structure, large ships such as mother vessels only call at an essential hub port (such as Rotterdam) that is connected to other smaller (feeder) ports in a region. Feeder services are deployed to transport cargo from the hub ports to the feeder ports and vice versa. In a MPC structure, the main vessels call at different ports in a region to load and unload cargo. The total distance travelled by a container will typically be smaller in a MPC structure as compared to a H&S structure. This is because in the H&S network, containers are typically diverted to a hub port first before further shipped to the end destination, often causing a longer travelled distance than the direct shipping services that are typically available in MPC structure.

Francesetty and Foschi (2002) have shown that a H&S structure has cost advantages over a MPC structure when economies of scale are properly exploited. A significant reduction of the total transport costs can be achieved, when mega vessels are used for high volume, long haul transport. Given that the current global shipping network is a combination of both H&S and MPC structures (Tran and Haasis, 2013), a shift toward a stronger presence of the H&S structure is quite plausible when this trend continues.

To the best of our knowledge, there is currently no research that explores the aggregate impact of different plausible maritime network structures on port throughput. Generally network optimization models are developed to minimize the total transportation costs while fulfilling demand or maximizing the profit of a liner shipping company (Wang and Liu, 2015). Fagerholt (2004) proposes a model where the main objective is to optimize the routing of individual ships given a delivery time constraint, while minimizing total costs. Jepsen et al. (2011) uses a model that minimizes both the total distance travelled by the ships and the fuel consumption. An example of a more complex model that considers fleet design, ship schedule, and ship routing simultaneously can be found in Mulder and Dekker (2014). A similar model, which considers maritime cabotage and transit time between routes can be found in Wang et al. (2013). Liu et al. (2014) continue in this line by including even more factors in order to optimize the strategic routing of the containers on both hinterland and

maritime sides using both a discrete choice model and a mixed integer linear programming approach.

All these studies aim at optimizing the network of a single liner shipping company. They do not consider the aggregate global shipping service network as a superposition of many individual liner shipping networks. Song et al. (2005) is a notable exception. They study the global shipping network at an aggregate level by using an optimization model in the form of a pipe network where trade volumes are assigned to the container shipping network under study. Based on this assignment, the authors analyze the cost-efficiency and the trade patterns on the network. However, the structure of the container-shipping network is a necessary input to the model to perform the assignment and not itself subject to optimization.

In this chapter, we propose an approach for identifying optimal shipping network structures at the aggregate level through the trade-off between total transportation costs and total network distance. A network generation model is developed to generate different shipping network structures based on these trade-offs. Furthermore, a routing model is also developed to determine the routing pattern of the containers given the network structures and the demand for transport between countries. By aggregating container flows across all shipping routes, we study the consequences of alternative network configurations for ports. The next section will present and elaborate the underlying modeling principles used to explore the possible global shipping networks.

5.3 Cost and distance trade-off in the design of maritime shipping networks

When studying the plausible optimal structures of any network, it is useful to define objectives and indicators by which one can measure performance. Hu (1974) provides a primal example where different optimal communication spanning tree networks can be found depending on the priorities given to total network distance and total communication costs. Gastner and Newman (2006) have demonstrated how different road transportation network structures emerge depending on the trade-off between total transportation costs and total network distance. Despite the simplicity of their model, the results explain elegantly different optimal road network structures given a certain transport demand pattern.

Exploiting the analogy between maritime shipping networks and uncongested road transport networks, different structures of aggregate networks can be studied based on the trade-off between total transport costs and total network distance. In both maritime and road networks the total transport time or costs relate to the demand side, i.e. the cost for users that travel between nodes in the networks, with flows at O/D level. For road networks, the total distance (i.e. sum of all road link's length) is used to reflect total supply side costs, for construction and maintenance. Unlike the total transport costs of the demand side, the distance based cost of the supply side is not associated with the volume of the transport flow. Note that this analogy is not perfect as we do not model individual shipping lines and their economies of scale.

Dense road networks will provide more possibilities to connect origins and destinations with less detours, at the expense of higher road construction costs. Similarly, a dense aggregate maritime network with more direct shipping services (depicted in the picture on the

left-hand side of Figure 5.2) reduces the need to have detours through ports, and consequently also reduces travel time for users. It will however be more expensive to operate and maintain than network with fewer direct shipping services (depicted in the picture on the right-hand side of Figure 5.2). This is because a dense shipping network has a longer total operation distance and thus, requires higher number of ships to provide direct shipping services to destinations. Therefore, we use total network distance to approximate operation costs of the network.
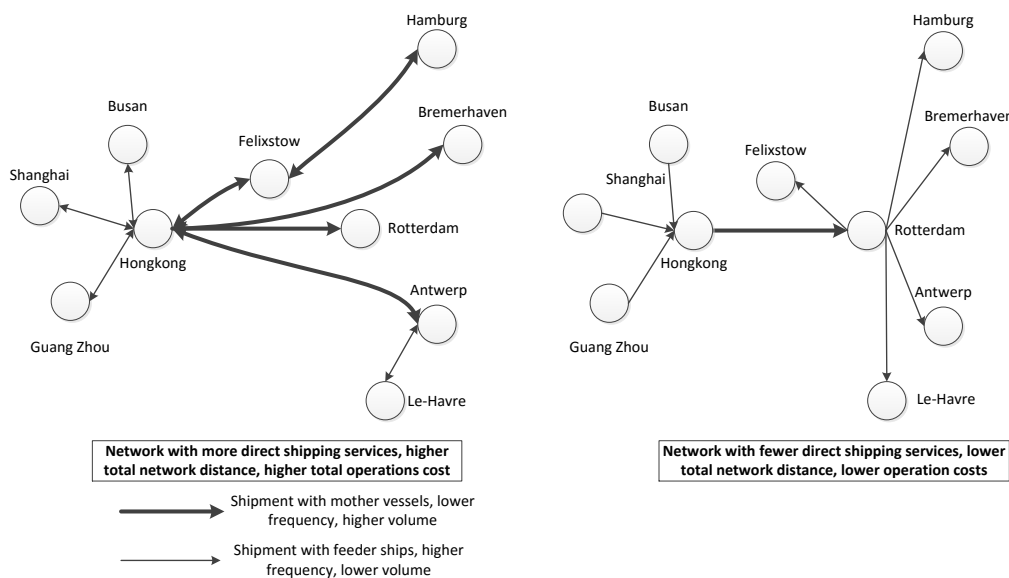
Figure 5.2 Aggregate shipping networks with more direct shipping services (left) and with fewer direct shipping services (right)

5.4   Modelling approach

5.4.1   Multi-level structure

To explore plausible future shipping network structures, we need to model the spatial patterns of global trade and the route choice behavior of the shippers. In order to do this, we need to specify the rationalities of the actors both in determining the structures of the shipping networks and in routing the containers from origins to destinations, given the shipping networks. We approach this problem using a bi-level programming approach where a nested optimization problem (i.e. upper level and lower level problems) is defined.

The upper level problem is described as the shipping network design problem where the objective is to find aggregate shipping network structures that minimize total transport costs and total network distance, given container routing behavior in global trade flows. Next, the lower level problem represents the container routing and volume assignment problems, given the network structures that are found as solutions for the upper level problem. In this approach, the shipping network design model represents the supply subsystem and the container routing and volume assignment represent the demand subsystem (Figure 5.3).

In the light of the main purpose of the research, which is to explore plausible future shipping network structures, we take the trade-off between supply side and demand side objectives as the key starting point and innovation. Several simplifications are used to be able

to design this model. Firstly, we do not optimize detailed sub-problems such as shipping frequency, fleet size deployment, and port rotation schedules of liner shipping companies. Secondly, as a consequence of the above, we also do not model the effect of economies of scale and congestion on the routing of container flows. New aggregate cost functions would need to be developed to properly compute the effect of congestion and economies of scale on the routing of the containers. Addressing these limitations in one model design poses an additional computational challenge as the complexity of the model grows significantly. As such, the modeling of these detailed aspects is taken to lie beyond the scope of this research.

The main input to the model in terms of Origin and Destination (O/D) flows is provided by global trade databases. We obtained the OD data as an output of a global trade model (Ivanova, 2013). This Spatial Computable General Equilibrium (SCGE) model takes production, consumption into account to estimate the trade flow of containers. To represent the demand sub-system, a worldwide container network choice model is used ("The World Container Model"). This model assigns global container trade to different shipping routes within the intermodal shipping network. To represent the supply system, we developed a network design model that generates shipping networks that connect ports worldwide ("Network Design Model"). We solve this problem using a multi-objective optimization algorithm to locate efficient solutions (being the plausible networks) under the trade-off between network costs and distance.
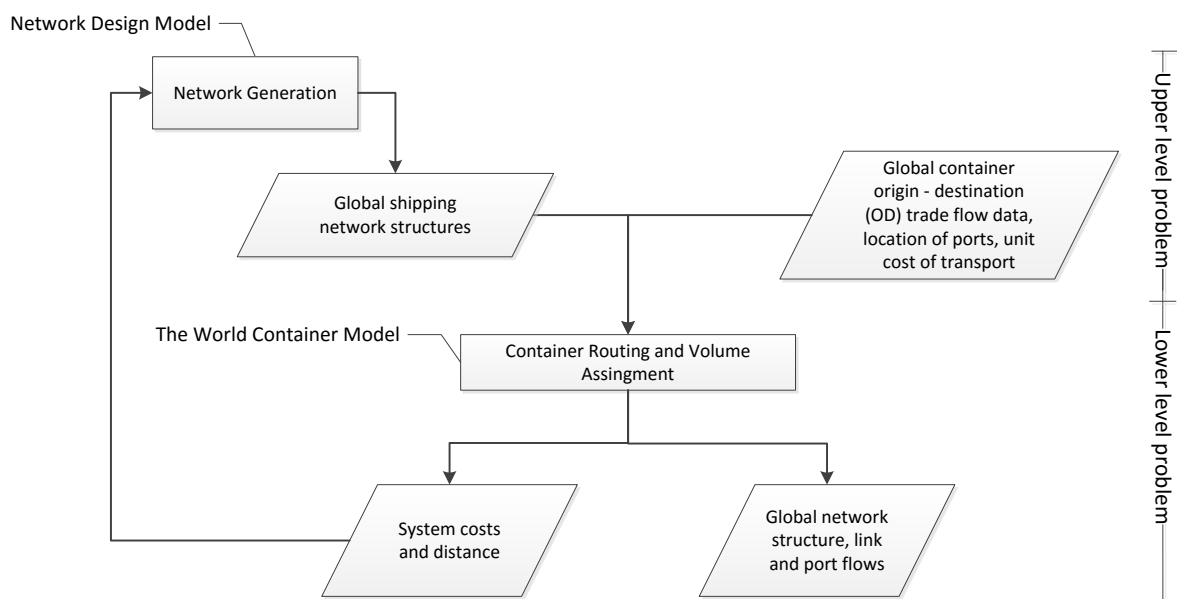
Figure 5.3 Bi-level computational framework

The next sections describe the sub-models used to describe the pattern of global container flows on a given shipping network and to evaluate a global intermodal shipping network respectively.

5.4.2   Demand side model

We use the World Container Model (WCM) to analyze the container demand distribution worldwide as described in section 2.3. In this computational framework, the WCM is used to describe the behavior of container transport demand, where shippers and

forwarders make decision with respect to the use of available shipping lines. Hence, the model assumes the shipping line networks as given. The linkage to the supply side of the global container shipping system, which accounts for changes in the shipping services, is elaborated in the next section.

5.4.3   Network design model

We formulate the service network design problem as a multi-objective optimization problem in which total transportation cost (T) and total network distance (Z) are minimized as two independent objectives. The model developed here is inspired by the Minimum Cost Spanning Tree model (MCST) for communication networks (Hu, 1974). Transportation and communication network design problems share important characteristics. Both address the construction of a spanning tree network that minimizes the total cost of transporting objects (i.e. data, goods, etc), given the transport demand between the origin and destination nodes. The design of such optimum spanning tree networks is useful to determine the backbone networks for both communication and transport activities. As such, we further develop the MCST model into a shipping network design model by specificying additional cost structures and parameters that are relevant in designing shipping networks such as cost of using a port service, cost of time, and cost of using specific modes of transport.

The model formulation as a multi-objective optimization allows us to study different aggregate shipping network structures that reflect the trade-off between user costs (T) and shipping network construction and maintenance costs (Z). The output of a multi-objective optimization model is normally a set of solutions that are optimal in terms of both costs. That is, there is not a single solution within the set that is superior to other solutions in both objectives simultaneously. This set of optimal solutions is called the set of non-dominated solutions. Within the objective space that is defined by both T and Z values, the non-dominated solutions form a frontier which distinct these solutions from the sub-optimal solutions behind the frontier. This frontier is called the Pareto frontier, where each of the non-dominated solutions represents a certain maritime shipping network structure that has distinct T and Z values.

We use a schematized global maritime shipping network from the WCM as an initial network for which the optimal shipping service networks are sought. Furthermore, for simplicity sake, the shippers are assumed to have perfect knowledge of the shortest routes from any origin to any destination. The behavior of these shippers in choosing their routes is described using a logit choice model. The following section specifies the notations used.

Let W be the set of all OD pairs between regions, D_{od} be the demand between these OD pairs, P be a set of ports, and N be a set of nodes in the maritime shipping network. A choice set for an OD pair CS_{od} contains several alternative routes-r. A route-r is defined as a combination of maritime and hinterland links that connect different nodes $m,n \in N$ along the path from origin $o \in W$ to destination $d \in W$. A shortest path algorithm is used to calculate the length of the route-r. Z_{pq} is the distance between port p and q, and l_{mn} is the length of a link between node m and n. Flow for a given route that connects an OD pair f_r^{od}, is calculated based on the logit model that is formulated in Eq. (2.2). We use an average unit cost of transport C_{mn} (in US\$/TEU.km) for each link in the path connecting node m and n. Note that he value of C_{mn} can be different depending on the mode of transport being used. Furthermore

we use handling cost H_p (in US\$/TEU) that represents the cost for loading and unloading the containers at port-p. Hence, a shipment of container would at least incur both loading cost at the origin port and unloading cost at the destination port. The model also considers costs that are associated with time spent by the containers to reach their destinations. The value of time parameter α describes the average monetary value (in US\$/day) of travel time spent by the container. TA_p is the turn-around time of a container in port-p (in days/TEU) and t_l is the travel time spent by the container in each link (in days/TEU). The decision variable is binary variable X_{pq}, where $X_{pq} = 1$ if there is a route from port p to port q and $X_{pq} = 0$ otherwise.

$$min\ T : \sum_{(o,d)\in W} \sum_{r\in CS_{od}} f_{mn} Z_r c_{mn} + \sum_{(o,d)\in W} \sum_{r\in CS_{od}} f_r^{od} H_p + f_r^{od} \alpha. \left(\sum_{p\in r} TA_p + \sum_{l\in r} t_l \right) \tag{5.1}$$

$$min\ Z : \sum_{p=1}^{P} \sum_{q=p+1}^{P} X_{pq} Z_{pq} \tag{5.2}$$

Where,

$$Z_r : \sum_{m,n \in r} l_{mn} \tag{5.3}$$

$$Z_{pq} : \sum_{m,n,p,q \in N} l_{mn}^{pq} \tag{5.4}$$

$$f_r^{od} = P_r D_{od} \tag{5.5}$$

$$f_{mn} = \sum_{m,n \in r, o,d \in W} f_r^{od} \tag{5.6}$$

Subject to:

$$\sum_{p=1}^{P} \sum_{q=p+1}^{Q} X_{pq} = P - 1 \tag{5.7}$$

$$\sum_{p=1, p\in S}^{P} \sum_{q=p+1, q\in S}^{P} X_{pq} \leq |S| - 1, \forall S\ C\ P \tag{5.8}$$

$$f_{mn} \leq UCap_{mn} \tag{5.9}$$

$$X_{pq} \in (0,1) \tag{5.10}$$

Where V is the complete set of port nodes, and S is a non-empty set of chosen port nodes.

Eq. (5.1) minimizes the total transport cost, including transport costs both on the maritime and hinterland networks, and handling costs which occur when there is a change in

mode of transport (i.e. from maritime to land transport and vice versa), and time cost of transport. Eq. (5.2) minimizes the total network distance. Eq. (5.3) defines the length of a route-r as the shortest path distance between origin and destination port. Eq. (5.4) defines the distance between port p and q, which is a sum of the length of all links that connect port node p to port node q. Eq. (5.5) defines the volume of container flow being assigned to route-r that connects country origin o and destination d pair. Eq. (5.6) defines the total volume of container assigned to the maritime links. That is, the sum of all container traffic from all OD pairs that is transported over link l_{mn}. Eq. (5.7) ensures that there are P-1 edges connecting all the ports worldwide. Eq. (5.8) enforces that there is no separate port network structures (formed by a set of port nodes S) that are mutually exclusive. Eq (5.9). Defines the maximum capacity of each maritime link, including those which go through canals. Eq. (5.10) defines X_{pq} as a binary variable. Herein, we use constraints 5.7 and 5.8 to prevent the network to have cycles and sub-tours for simplicity sake, as the number of choice alternatives between ports increase significantly when the network includes cyclical routes.

5.4.4   Solution algorithms

Network Design Problems (NDPs) are typically NP-hard and therefore exact methods will generally fail to find optimum solutions when the scale of the problems is large (Gen et al., 2008). However, we can find near-optima or good solutions for the problem using a non-exact, global optimization algorithm such as the Non-Dominated Sorting Genetic Algorithm II (NSGAII) (Deb et al., 2002). NSGAII is a multi-objective evolutionary algorithm that is rooted in evolutionary theory. The algorithm is an improved version of the original Genetic Algorithms found by Holland (1973). Despite many improvements and additional features, the fundamental theory regarding the adaptive capabilities that underlies NSGAII is the same as that used in standard GA (Goldberg, 1989). NSGAII is a population-based approach where multiple solution points are used to explore the solution space and find the best solutions for the (conflicting) objectives. In searching the solution space, NSGAII uses crossover and mutation operators that mimic evolutionary processes. Together with a solution selection routine, the algorithm explores and exploits the solution space efficiently (Črepinšek et al., 2013). Figure 5.4 shows the detailed computation steps that combines the generation of shipping network structures, the routing of containers, and the evaluation of the global shipping networks.
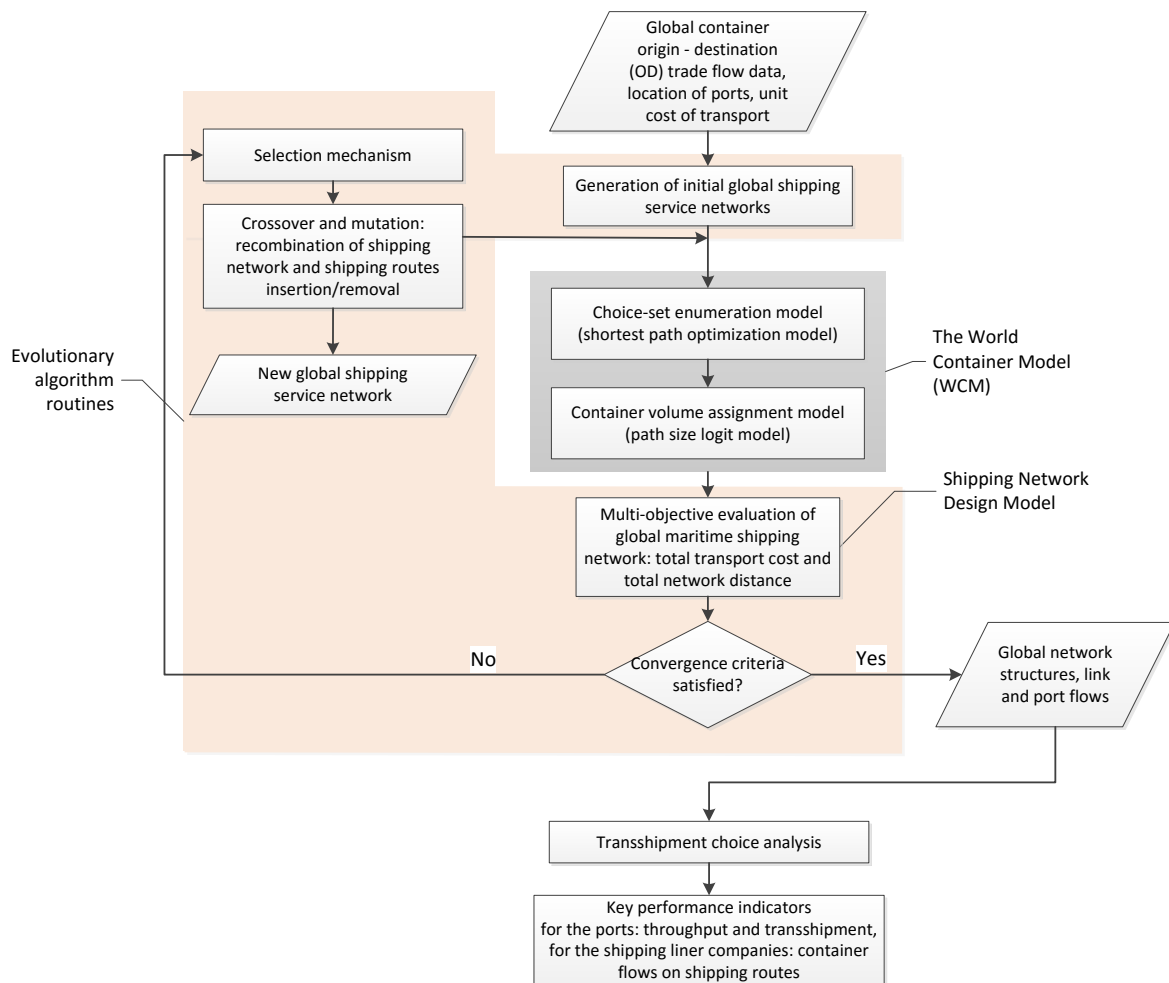
Figure 5.4 Detailed computational framework

Initially, different service network structures are generated randomly. Each of these service networks connects ports worldwide and the ports are in turn connected to the hinterland destinations through a fixed intermodal inland network. Thus a set of solutions typically consists of different intermodal global container networks. Next, a shortest path algorithm enumerates all plausible routes for each origin-destination country pairs for each of these networks. Subsequently, the global container trade flows are assigned onto the networks using the logit route choice model. The objective functions related to the service networks are re-evaluated in the network design model specified in section 5.3.3.

We use a maximum number of evaluations as stopping criterion. Until the maximum number of evaluations is reached, the algorithm performs routines such as selection, crossover and mutation. They function, in respective order, to select the best solutions in each iteration, recombine network structures which have good objective values, and introduce a variation to the network to prevent the solutions from converging towards local optima. Once the stopping criterion is met, we obtain the non-dominated solutions which represent different global shipping network structures. For each of these networks, as will be explained in the next section, an additional sea-sea transshipment analysis is conducted for the ports under study. Finally, we can obtain indicators such as port throughput and transshipment values for each of the service network structures.

In GAs, candidate solutions need to be represented or encoded in a structure (typically called chromosome) that allows evolutionary processes such as crossover, selection and mutation to be performed. The strategy to represent a candidate solution is a crucial aspect in GAs as it significantly affects the effectiveness of the algorithm in finding the best solutions (Rothlauf, 2006). We use Network Random Keys (NetKeys) as a solution representation strategy (Rothlauf et al., 2002) within NSGAII to find a set of edges that optimize the aforementioned objectives. This solution representation has been tested for relatively large instance problems and has been proven to perform better in comparison to other representation strategies such as prufer number, characteristic vector, and edge-set (Rothlauf, 2009). Furthermore, NetKeys encoding offers a practical advantage because standard genetic operators such as simulated binary crossover and polynomial mutation can be used. This means it is not necessary to build a special mechanism to handle infeasible solutions (such as when there is a cycle in the network).

Although the best representation that can be used so far is link-biased encoding, we do not use this representation as additional information such as the bias weight of each of the maritime links is currently not incorporated into the model. Technically, the bias weight can represent the information regarding the availability of a service line on a maritime link. In this research we avoid to use such information to make the model independent of big data needs. A consequence of the simplified network design approach taken here is that sea-sea transshipment flows cannot be calculated with one computation step. The network is link-based, as opposed to the line network used in the World Container Model, and therefore does not require transshipment movements between lines. As one of the important port performance indicators is the transshipment volume that can be attained by the port, we would like to approximate the transshipment share of flows as well.

5.4.5   Transhipment analysis

The potential of a port to attract container transshipment might be attributed to many factors such as their geographical location, hinterland connections, trade barriers, and many more. However, it is clear that the structure of global shipping service networks has a significant influence on the potential of a port for transshipment market. For instance, ports that are situated close to global shipping routes, and have a competitive port tariff will have a better opportunity to function as transshipment ports. Similar to Jiang et al. (2015), we adopt the perspective of a global shipping service network to calculate the transshipment market of a port using a freight demand modeling approach.

For each of the shipping service networks found by the solution algorithm, a transshipment choice network is created for each origin and destination port pair. For simplicity's sake, we assume that transport operations between all origin and destination port pairs will involve at most one transhipment. Furthermore, it is also assumed that the liner shipping companies have the perfect knowledge to choose the most cost-efficient route among alternative routes between the ports. To model this behavior, we use a shortest path algorithm to determine both the shipping services from the origin port to the transshipment port and from the transshipment port to the destination port. The ports which are included in the choice network, consist of two groups: the top 50 transshipment ports worldwide and the ports that are located along the shortest path between origin and destination port pairs. For

instance, the shortest path analysis for a shipment from port of Jakarta port to port of Rotterdam indicates that there are 3 potential ports for transshipment: Port of Singapore, Port of Jeddah, and port of Le-Havre. Based on these ports a choice set containing 3 alternative transshipment routes can be constructed: Jakarta- Singapore (T1)- Rotterdam, Jakarta- Jeddah (T2) –Rotterdam, Jakarta- Le-Havre (T3)- Rotterdam. Figure 5.5 illustrates the choice network for the transshipment analysis.
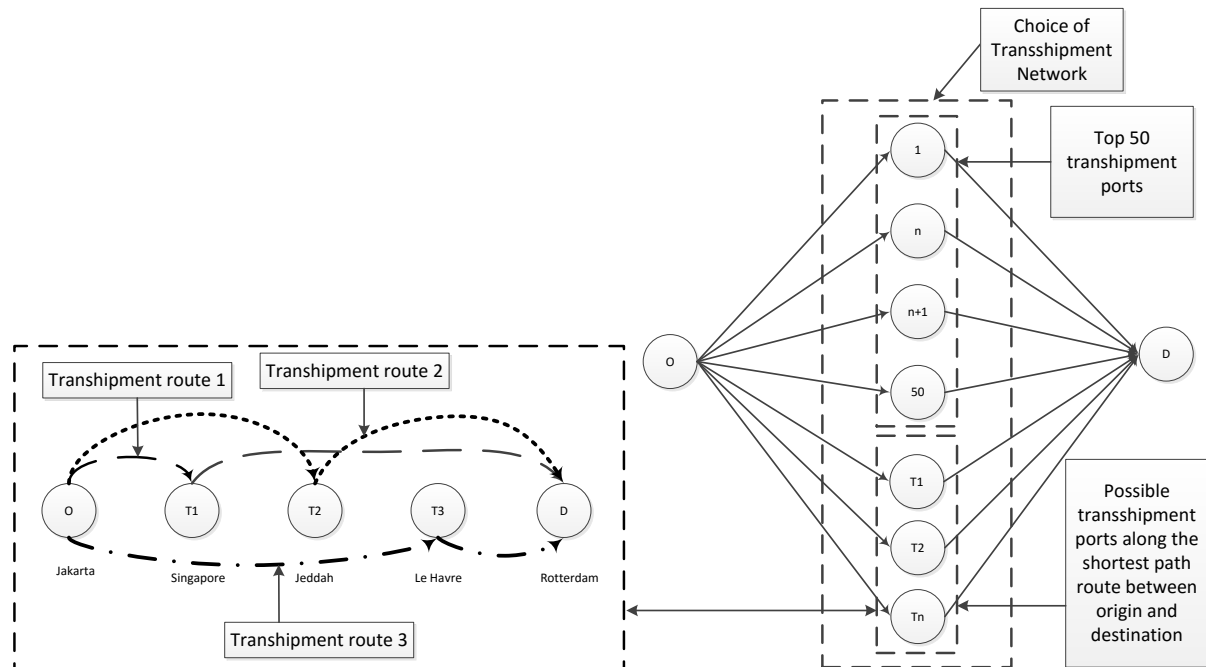
Figure 5.5 Choice network for transshipment analysis for an OD port pair

After the transshipment choice set is constructed, container volumes are assigned onto the network using the logit route choice model as described in section 2.3.1. Note that the container trade flow data used in this analysis all concern port-to-port flows with volumes less than 200.000 TEU. We obtained this threshold value as described in Chapter 4. Thus, we also obtain the indirect port-to-port flows also by assigning the container trade flow on the given service network structures using the aforementioned route choice model.

5.4.6 Implementation

We implemented the World Container Model in Java software to achieve good portability in running the model on different operating systems. We also used a set of additional libraries to optimize the computation process. JUNG (Java Universal Graph) library (O'Madadhain et al., 2005) is a tested library that allows network objects to be constructed efficiently. For this reason, we use JUNG to construct network objects in the models. Furthermore, we use the UNFOLDING library (Nagel et al., 2013) to create maps that visualize the distribution of the container flows over the intermodal freight network worldwide. The UNFOLDING library is an open source package with many useful features that can be used to create an interactive graphical user interface for the results of our model. Finally, the computation process is carried out using a simulation-based optimization framework called SIMEON (Halim and Seck, 2011).

To run the computation of the model, we use a Macbook Air with 1.4GHz Intel i5 processor, and 8G memory. A single network generation and evaluation takes around 5 second to complete and the memory usage is at 1.5G in average. Since we use NSGAII with 20,000 evaluations, the model evaluations takes approximately 1 full day.

5.5   Test case: the design of an Indonesian shipping network

We use Indonesia as a study case to demonstrate the effectiveness of the model in finding alternative shipping network structures that are efficient in terms of network construction by the operators and transport operations by the users. This test case can also be seen as a way to validate the model through dynamic verification, validation and testing method (Balci, 1998) where the model is executed and its output values are evaluated.

5.5.1   Background problem

Indonesia, as the biggest archipelagic country in the world, has unique geographical features that suit the application of the global model developed in this research. Indonesia consists of more than 17.5000 islands with more than 32 major ports and 36 provinces spread across the main islands (Java, Sumatra, Kalimantan, Sulawesi, Maluku, Nusa Tenggara, and Irian Jaya). Figure 5.6 shows the map of Indonesia.

Figure 5.6 Geographical characteristics of Indonesia

The fact that those islands are separated by the sea makes maritime transport to be a crucial mode of transport to support the connectivity and the economy of the nation. Thus, these properties of the Indonesia's freight transport system are very similar to the global container transport system, where intercontinental trade flow occurs between countries over a global maritime shipping network. However, unlike the global maritime shipping network, the Indonesian shipping network is regulated by a centralized government (Ministry of Transport), with both private and state owned companies providing shipping services across the nation. While private operators mostly serve container shipping between major economic regions, the government, through state-owned operators, takes the leading role in providing

shipping services that can connect less-developed remote regions to the major economic regions. Both private and state-owned operators are allowed to design their shipping routes independently. Furthermore, the Ministry of Transport, through the Port Authorities as their operating units, also has responsibilities in establishing policies for port infrastructures and services. Specifically, the Port Authority is responsible for:

1. developing the master plan for the port and its related infrastructure
2. regulating how the port lands and real estate are used
3. establishing standards for port operational performance
4. representing the government in concessioning logistics services such as the ferry system
5. acting on behalf of the government in developing agreements with the port business partners.

The modelling exercise presented here is aimed at predicting the future domestic shipping networks to gain insights into the needs for the development of infrastructures and services that can best serve the country.

A major problem faced by Indonesian freight transport is that it has high logistic costs (Bahagia et al., 2013, Varela et al., 2012). In a report published by the World Bank Group logistic costs for Indonesia were estimated at 26% of GDP (Bahagia et al., 2013), which is among the highest in South-East Asia. Domestic container transport costs are high compared to international shipping costs from Indonesia to foreign destinations, hindering the competitiveness of domestic trade. Besides the dependence on maritime transport and transshipment, this condition is caused by a combination of other factors comprising: the large distances, low demand in remote regions, inadequate inland freight infrastructure capacity, the imbalance in trade between central and remote provinces which result in high volume of empty containers being transported accross the islands, the use of small ships, high turn-around time at ports, high port handling costs, and low integration of logistic activities.

A recent market study (Varela et al., 2012) indicated a low market integration for remote provinces in the Eastern part of Indonesia where 70% of price differences can be explained by remoteness. High distances and the lack of adequate transport related infrastructure are two determining variables, whereby freight transport infrastructure can partly compensate for large distances. Therefore, improving inter-island connectivity has been indicated as critical to achieve economic integration. In light of this problem, a key challenge to improve connectivity in Indonesia is the minimization of maritime transport/logistic costs, especially to the Eastern regions. This is because maritime transport plays a key role for an economy/society scattered over many islands separated by large distances over water. Widely varying densities of population and economic activities in different parts of the country further add to the challenge to provide cheap transport.

A particular cause of high cost in the Indonesian maritime transport system is the lack of efficient shipping routes and the lack of economies of scale in most of the routes. Figure 5.7 illustrates the current Indonesian shipping services network. Most of the shipping services are direct services from Java to the rest of Islands in Indonesia. There are only a few shipping services that call at multiple ports along the Java and Sulawesi coastlines.
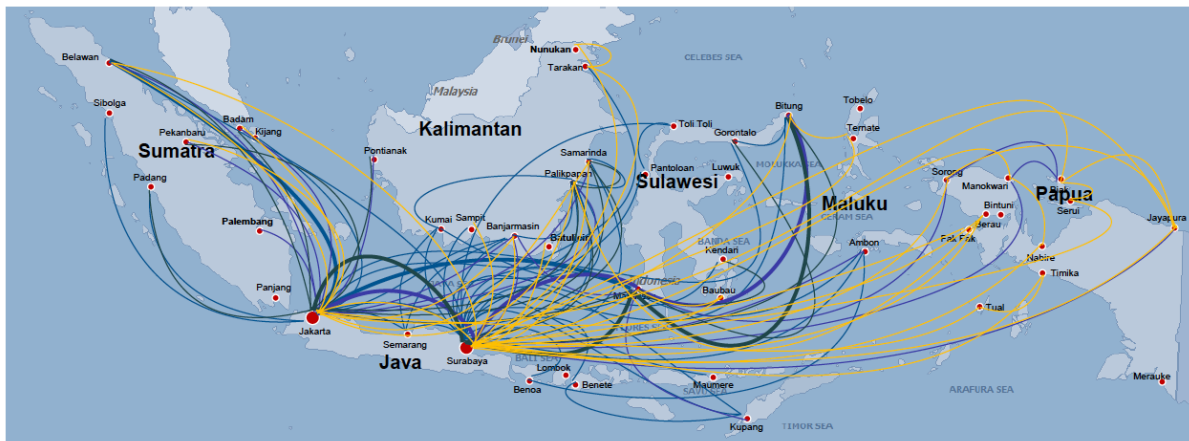
Figure 5.7 Existing shipping service network in Indonesia (Source: Drewry Maritime Advisory, 2015)

Using the DGST (Directorate General of Sea Transport) database in 2013 on commercial shipping, we can obtain various statistical indicators that can give an insight into the current condition of Indonesia's shipping services. Figure 5.8 presents the distribution of the total TEU load over the network to different ship sizes and the load factor for different ship sizes measured in the percentage of ship capacity in TEUs. It can be observed that a wide range of ship sizes is in use and most TEU.km is delivered by ships in the 400 - 600 TEU range. The load factor for the small ships (<200 TEU) is reasonably high but larger ship sizes have low to very low load factor. Unsurprisingly, the current large demand connections (for example: Belawan-Priok, Perak-Makassar) are mostly served by relatively small ships and the transport to low demand-large distance locations has very low load factors.
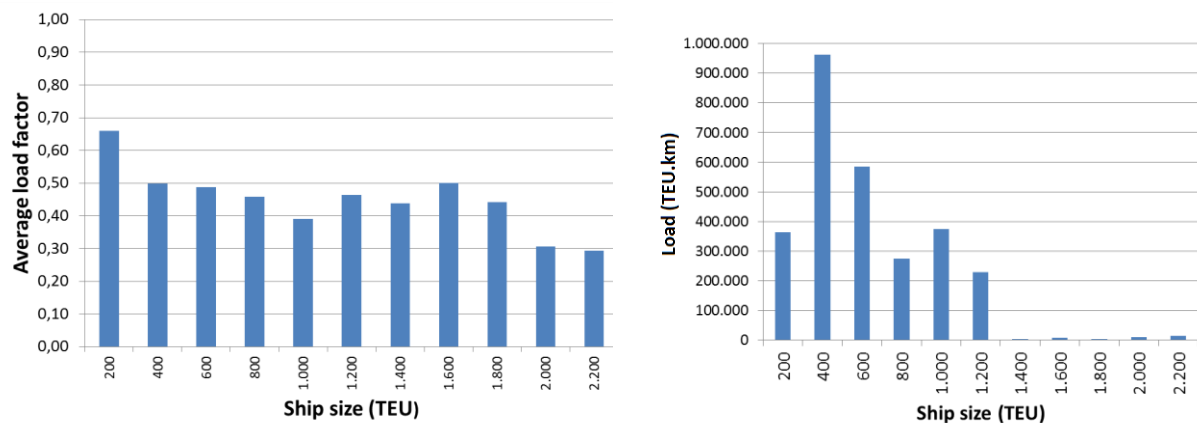
Figure 5.8 Average load factor of different ship size (left) and total annual load (right) of different ship size

To improve domestic connectivity, the government has established a plan to develop a national maritime freight transport network that connects the 32 major ports in Indonesia, also called the Marine Highway program. However, this plan has proven to be a very challenging undertaking, especially because the size of the shipping network that has to be designed and the characteristics of the inter-island demand pattern that are very diverse. The later problem is especially challenging as there are many imbalances between inbound and

outbound trade volumes between Java and the rest of Indonesia. The model proposed in this chapter can be used to find alternative efficient shipping network configurations that minimize total transport costs and total network distances as two independent objectives.

5.5.2 Data, experimentation, and results

Previous research has indicated that the bulk of logistics cost in Indonesia is caused by the time spent by the containers at the ports (Verhaeghe et al., 2016). Most of the ships spend around 74 % of their total operation time at the port as ship turn-around time is as high as 2 days in average (Varela et al., 2012). Despite this apparent bottleneck, there have not been any network design studies that take into account the costs associated by time spent in the door-to-door freight transport transport chain in Indonesia. In order to test the sensitivity of the efficient network structures to the cost of time, we perform experimentations with 2 distinct value of times (α) : scenario 1 where α is 0 US\$/day and scenario 2 where $\alpha = 50$ US\$/day. This test exercise also contributes to verification, validation, and testing of the model. Specifically, the experimentations defined here respresent sensitivity analysis of the model (Balci, 1998). The value of time here means that one TEU container costs 50 US\$ per day of the travel time it spends to reach the destination. We only use two different α values because the costs associated with time (i.e. time spent sailing and port turnaround time) have a linear relationship to the overall cost structure specified in eq 5.1. In addition, data are lacking that could be used to differentiate turnaround times between ports. This implies that a higher value of time will only lead to higher total costs without necessarily affecting the efficient network structures. On the other hand when α is 0 US\$/day, the cost structure of the model is altered substantially as the design of the network will solely consider the weighted distances and handling costs at ports.

The first experiment concerns solely the minimization of total costs associated to shipping operations of the carriers and the total sum of the port-to-port network distance. Thus, in this experiment, the impact of value of time is neglected. This experiment can be seen as a simulation of government policy that aims at improving the efficiency of the shipping network without any improvement measures in the performance of the ports. Specifically, the ship turn around time which typically includes time to berth, load, unload the cargo, and unberth are not taken into account in finding the efficient network structures. Thus, this experiment assumes that the the performance of the ports will not change from the existing condition. The second experiment takes into account the impact of value of time on shipping network structures, and thus the existing ship turn-around time, including handling operation at port for containers export and import will be included in finding efficient shipping networks.

Future efficient shipping networks are searched based on 2030 transport demand data. This data is estimated based on the observed domestic port-to-port flows in 2013. We used this data set because the global container trade data which was used for the world container model lacks detailed container trade between major regions in Indonesia. The domestic transport demand (O/D) data is obtained from the Directorate General of Sea Transport who conducts a national survey on container transport periodically (DGST, 2013). The 2013 demand data was the most recent data available which reports a total of 2.8 Million TEU (MTEU) container movements across 32 ports in Indonesia. It is estimated that in 2030, the

total domestic container transport demand will be, on average, 5 times than that of 2013, with average annual growth rate of 6.3% (Indii, 2012). We applied this growth rate to each port to port flow to estimate 2030 demand of 15 MTEU container transports between the islands, with Java being the main exporting island. Figure 5.9 presents the projection for the demand of domestic container transport in Indonesia between 2009- 2030.
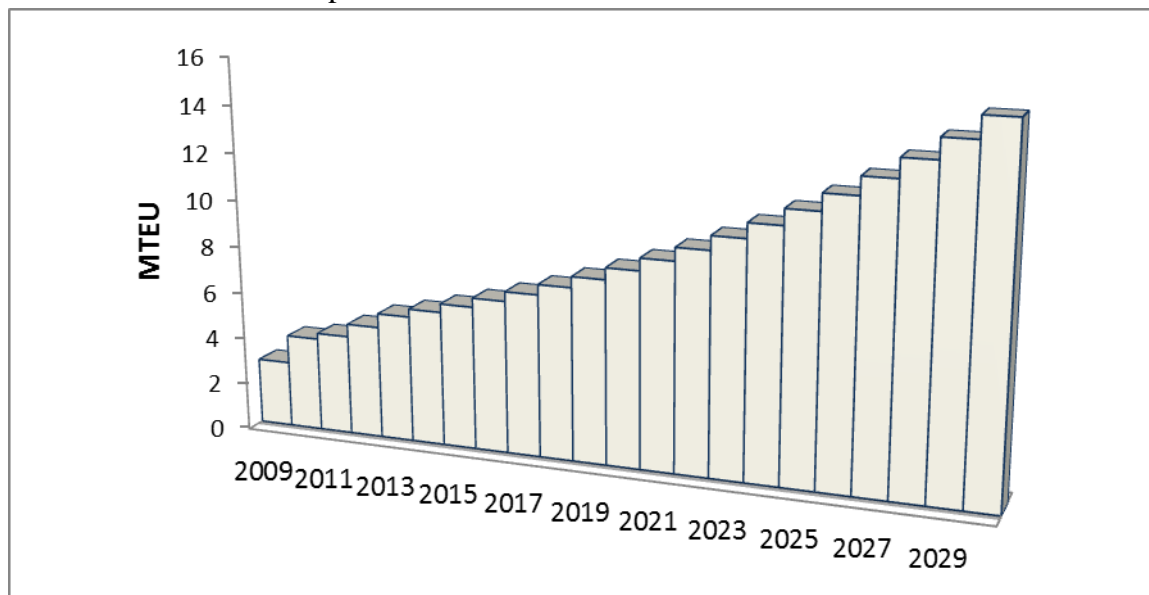
Figure 5.9 Projected demand for container transport in Indonesia 2009-2030

Maritime transport costs are estimated by means of a cost model that takes into account the life-cycle costs of commercial ship operations. This cost model considers aspects such as capital cost, salary, fuel cost, etc to compute the average unit cost of maritime transport. Interested readers can find the cost model in (Verhaeghe et al., 2016). Based on this cost model, the average unit cost of container transport in Indonesia in 2030 is estimated at 0.15 US$/TEUkm. Since truck is the main mode of transport for hinterland transport in Indonesia, we assume fixed unit cost for road transport of 1.71 US$/TEUkm. This cost is derived from WCM database. Furthermore, based on previous research, port handling cost is, in average, at 150 US$/TEU (van Tujl et al., 2015). Ship turnaround time is estimated at 2 days in average. Using the transport demand data, we schematized a trade network between 32 major ports in Indonesia (Figure 5.10). Each of the lines in the network depicts the trade relation between two ports that are connected with the line. The aim of the network design exercise is to find sub-network structures connecting these 32 major ports with minimum total transport cost (sum of weighted door-to-door costs) and total network distance, as specified in equation 5.1 and 5.2.
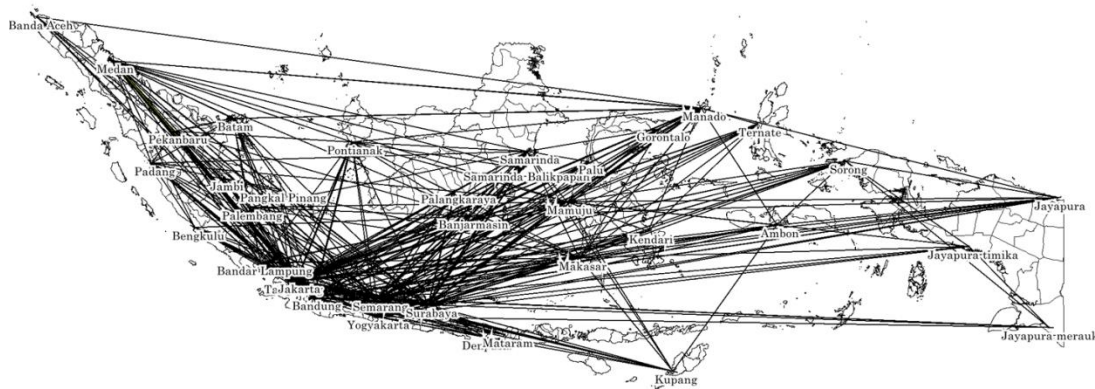
Figure 5.10 Port Network of 32 Indonesian major seaports

Experiment 1

We parameterized the NSGA-II algorithm as follows: a population size of 100; with 20,000 evaluations as the stopping criterion;we use simulated binary crossover with a crossover rate of 0.9, polynomial mutation was used with a rate of 1/number of variables. The distribution index for both crossover and mutation is 2.0.

Figure 5.11 shows the resulting Pareto set for value of time $(\alpha) = 0$ US\$/day. The x-axis represent the values of the non-dominated solutions for the first objective function, while the y-axis represent the corresponding total network distance for the second objective function. The solutions from the set indicate that there is a non-linear trade-off between total transport cost and total network distance. It can be observed that there can be a considerable reduction (15%) in total network distance with relatively small increase in total transport cost (0.2%). This means that significant changes in total network distance or shipping network structure do not reduce the cost to the user drastically. This means solution that minimizes total network distance (on the far right) could be an attractive solution for policy makers.
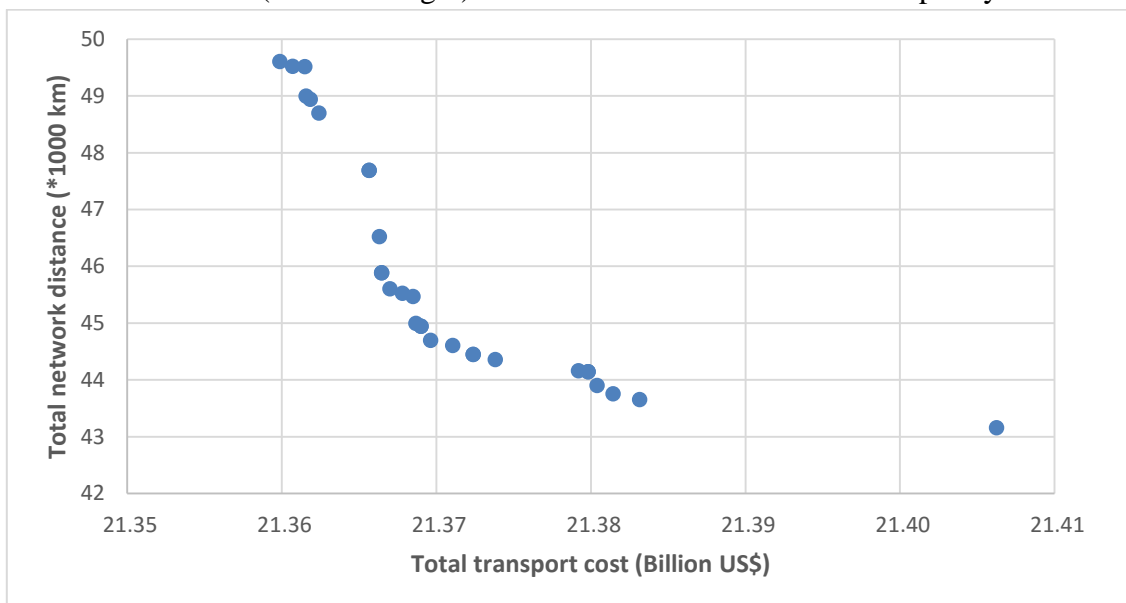
Figure 5.11 Pareto approximate set for alternative Indonesian shipping networks without value of time

Using the DGST database and the network design model presented in section 5.3.3, we also calculated the position of the current network. The total transport cost in 2013 is estimated at 29,295 Million US$ and the total network distance is 62,000 km. Note that this cost calculation does not include the cost of time. If we compare these costs with a solution that has the minimum total transport costs, there can be a reduction of 27% in the total transport cost, with 20% reduction in the total network distance. Figure 5.12 illustrates the position of costs of the Indonesian transport system in 2013 relative to costs indicators of the non-dominated solutions.
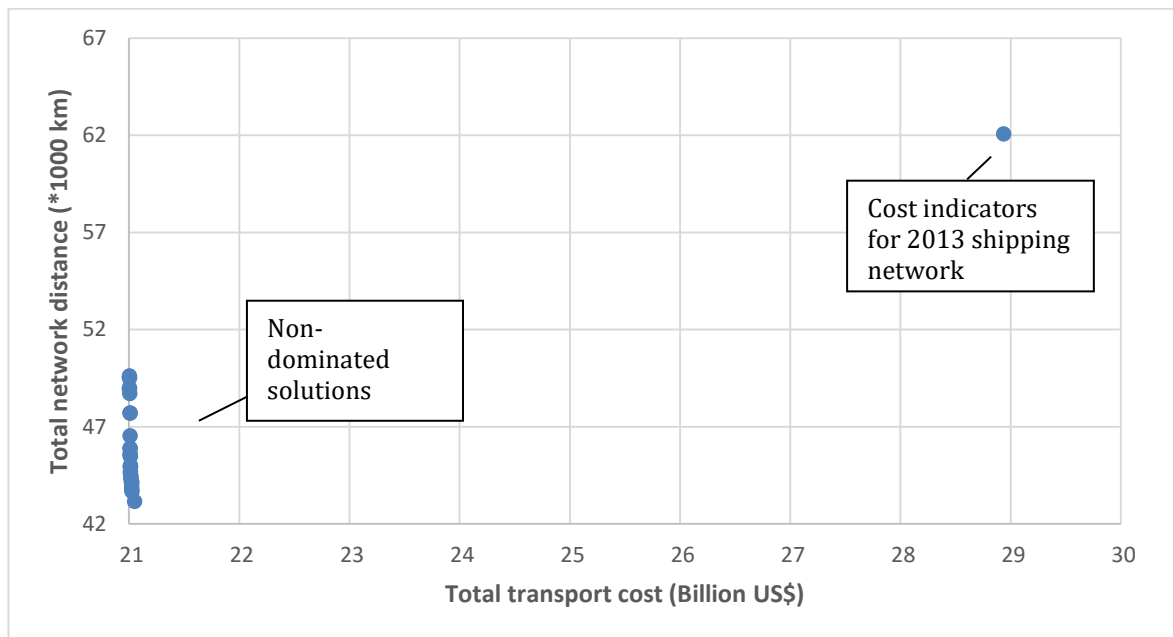
Figure 5.12 Costs comparison between the 2013 port network and the non-dominated solutions of experiment 1

Figure 5.13 shows the resulting port-to-port shipping network which minimizes average ship operational cost without considering the value of time. Note that this port-to-port network is an aggregate shipping network that connects the major Indonesian ports and it is different from the actual shipping routes from port to port. Figure 5.14 visualizes the routing of container traffic volume across the Indonesian shipping routes for a given port-to-port network visualized in Figure 5.13. The volume of containers transported over a route is an aggregation of container traffic volume between ports that is transported using that route. The number within the labels in the actual shipping routes (Figure 5.13) indicates the total volume of containers being transported over the routes while in Figure 5.14, this number indicates the volume container transported over port-to-port connections.

An apparent pattern that emerges in the network is major direct connections between big hub-ports in Indonesia (Belawan, Jakarta (Tj. Priok), Surabaya (Tj. Perak), and Makassar) that form a multiple port calls network similar to maritime transport corridor. The volume of containers being transported through this corridor is estimated to encompass almost 80% of the total national container shipping in 2030. Furthermore, it is also interesting, that the model suggests Tj. Priok as the hub port for the western regions (except for Manado) and Tj. Perak and Makassar as the hub ports for these Eastern regions.

This network configuration is essentially very similar to what has been planned in the Marine Highway program of the ministry of national development and planning and ministry of transport (Bappenas, 2014). The only difference can be found in the government plan to establish a hub port either in Manado (Bitung) or Sorong for the eastern part of Indonesia. Our result indicates that the most efficient way to connect Manado to Jakarta is by means of direct shipping service, considering that there is transport demand for more than 600,000 TEU containers between Jakarta and Manado.

Figure 5.13 Least cost Indonesian port network with cost of time (α)= 0

Figure 5.14 Container traffic flow over the least cost network in experiment 1

Experiment 2

The demand data and parameters used for the optimization algorithm are identical in experiment 2. However, we included the cost of time in the model to investigate the impact of ship turn-around time at the ports on shipping network structures. The value of time for different commodities shipped using container is estimated to be, on average, at 50 US$/day. The estimation for value of time is often a difficult process that requires a dedicated study as there are different methods to perform the estimation (Zamparini and Reggiani, 2007). The value of time for different commodities typically depends on the cost of capital tied up in the cargo, and relates further to the benefit of a tighter scheduling (e.g. saving in labour costs of firms which transport the commodities, and ship operation costs), influence on spatial

concentration of the business, opportunities for market expansion, and consumer valuation represented by the clients willingness-to-pay for having goods earlier available. For simplicity's sake, we estimated the value of time for freight in Indonesia based on the value of time that is used in earlier research on world container transport (Tavasszy et al., 2011), in which the value of time is related to commodity value. Since the main commodities that are transported domestically are agricultural products, live animals, foodstuff and animal fodder (Indii, 2012), we used the highest value of time among these commodities in our analysis which is the value of time for Foodstuffs and Animal Fodder (50 US$/day).

Figure 5.15 presents the Pareto approximate set for the second experiment. Compared to the Pareto set for the first experiment, the solutions for the second experiment have relatively smaller range of total network distance (6%) over a slightly larger difference in terms of the total transport cost (1.2%). As can be seen, the incorporation of the value of time makes the the total transport costs of the solutions to be significantly higher and the total network distance to be lower. Again, this result implies that there is more gain in reducing total network distance for each increase in the total transport cost of the alternative networtk structures. On the other hand, even though the reduction in total transport cost is marginal, the result also shows that the presence of more direct shipping routes between ports will result in reduction of the total transport costs.

The Pareto front shows an emerging clustering pattern for the solutions. In most of the clusters, the difference in the total transport cost is marginal while there can be a slightly more visible difference in the average ship operation cost. This can be related to a technical caveat of the solution algorithm. The pattern observed is primarily caused by the presence of solutions that have very similar fitness values in the early iterations of the algorithm, which in turn, causes the crowding distance operator of the algorithm to not be able to eliminate these solutions (Fortin and Parizeau, 2013). As a result, solutions that have similar objective values are kept throughout the algorithm's iterations. However, looking at the small difference in the objective values between the most extreme solutions, it is safe to consider that this anomaly will not affect the convergence and the diversiy of the solutions significantly. Another factor that also contributes to this pattern is the shape of the solution space for the objective functions that is non-linear.
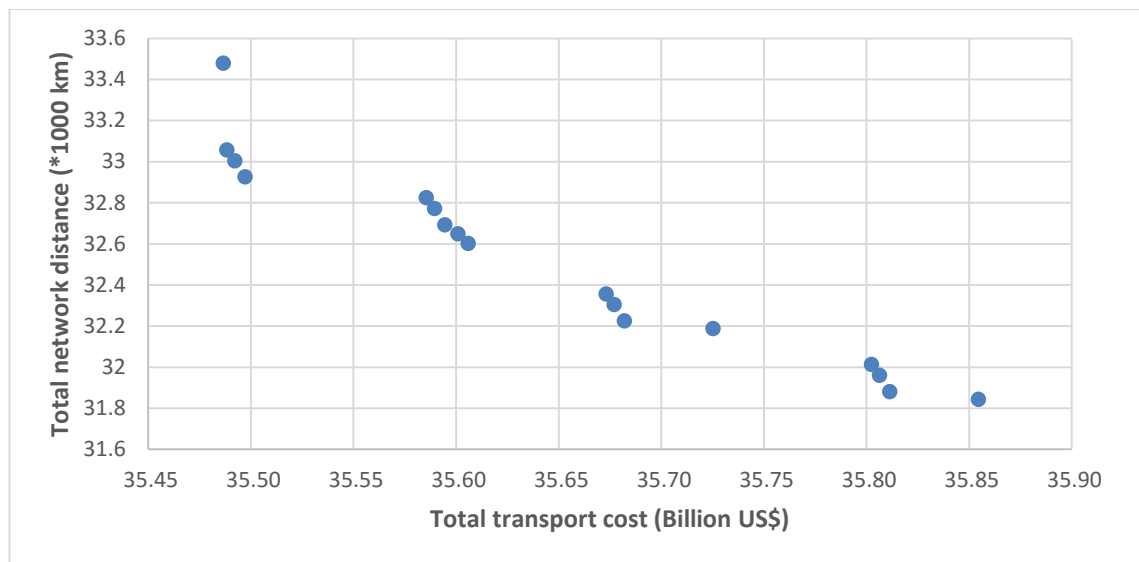
Figure 5.15 Pareto approximate set for Indonesian shipping network with cost of time
(α)= 50US$/day

In the second experiment, we also compute the cost indicators for the 2013 port network based on the DGST database. In this experiment, the cost of time is taken into account using the value of (α)= 50US$/day. The total transport cost is estimated at 57,000 Million US$ with the total network distance at 62,000 km. Compared to the non-dominated solution with the minimum cost, there can be a 38% reduction in transport cost and 47% reduction in the total network distance.
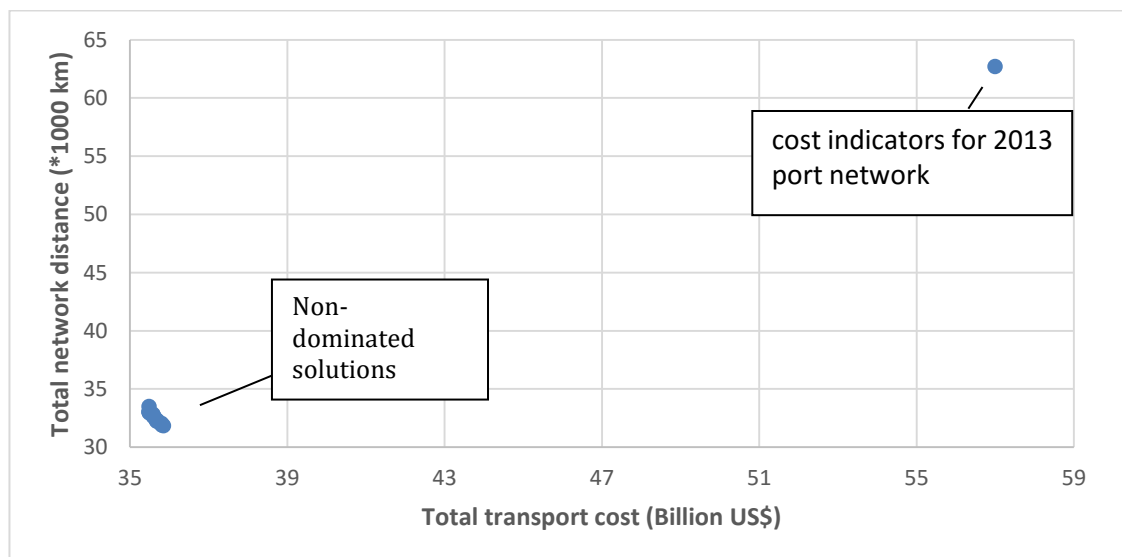
Figure 5.16 Costs comparison between the 2013 port network and the non-dominated
solutions of experiment 2

Figure 5.17 shows the port networks for both the first experiment (top picture) and the second experiment (bottom picture) that have minimum average ship operational cost. The efficient port network from experiment 2 indicates that there are more direct connections between the major hub ports in Java such as Tj. Priok (Jakarta) and Tj. Perak (Surabaya). Specifically, Tj. Priok serves as a hub for most ports in Sumatra and western part of

Kalimantan island and Tj. Perak serves as a hub for most ports in Eastern regions of Indonesia such as Eastern Kalimantan, Sulawesi, Maluku, Nusa Tenggara, and Irian Jaya. We observe a strong H&S structure in the network, indicated by Jakarta and Surabaya's role to be major hubs for almost the rest of major ports in Indonesia.
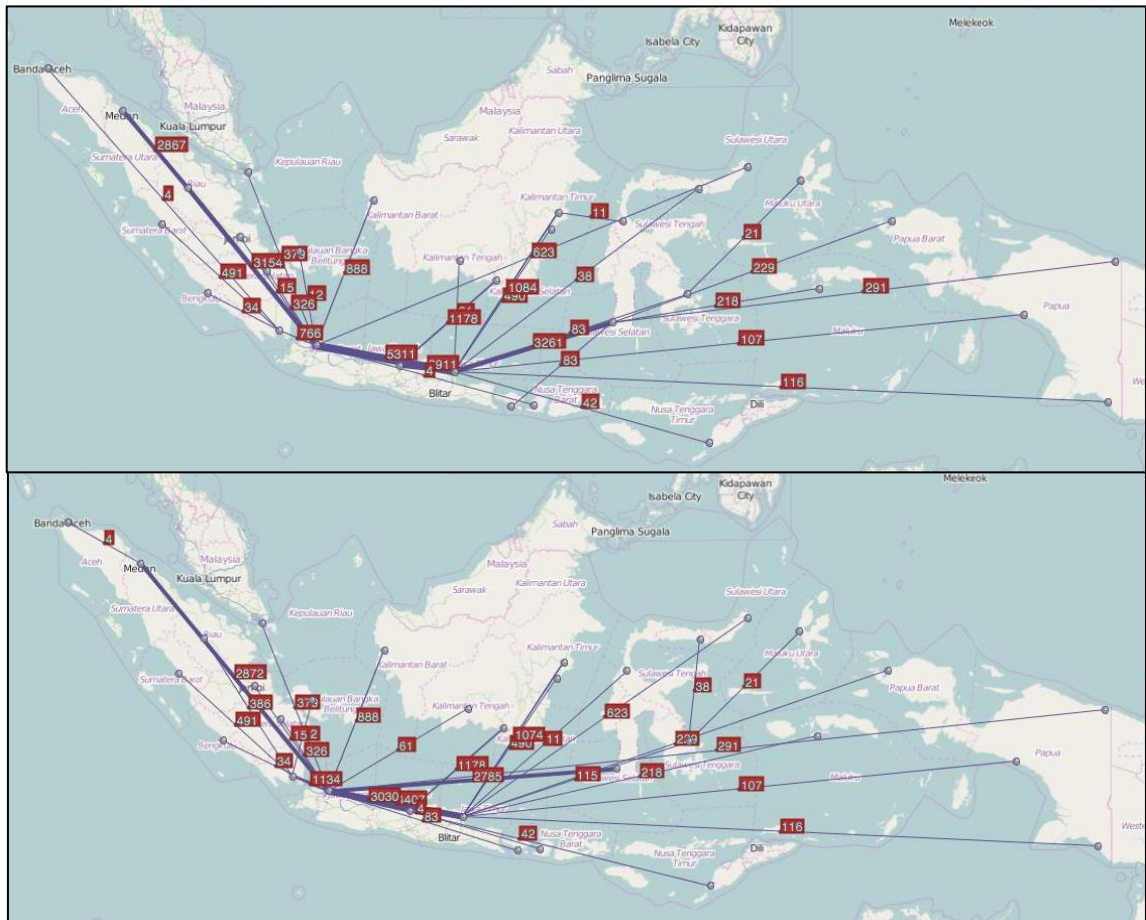
Figure 5.17 Efficient shipping network for experiment 1 (top) and experiment 2 (bottom) with cost of time (α)= 50US$/day

Compared to the port network in experiment 1, port network in experiment 2 has a direct connection between Jakarta and Makassar and more direct connections between Surabaya and smaller ports in Irian Jaya. The multiple port loop calls or pendulum structure between Belawan, Jakarta, Surabaya, and Makassar in port network of experiment 1 also disappears in experiment 2. Thus, this result indicates that the efficient shipping network structures that take the cost of time into account are those that utilize direct shipping services between major ports such as Belawan, Tj.Priok, Tj. Perak, Makassar. Furthermore, this result also implies that provision of direct shipping services to the Eastern regions will be crucial to reduce the total transport costs of the system. Contrary to the current widely endorsed plan, the efficient port network for experiment 2 shows that building a hub port for the eastern region might not be useful to reduce total logistics costs for the West-East trade activities. This is also mainly caused by the turn-around time of the ships that remains, on average, 2 days. Establishing a hub port in the Eastern region will therefore add extra turn-around time for the ship and cause the total time spent by the ships to reach the eastern regions to be

higher. In turn, this will increase the logistics cost for west-east trade significantly. Figure 5.18 presents a comparison of container traffic distribution for different port networks that are part of the Pareto approximate set presented in Figure 5.15. The solutions depicted in figure 5.15 are sorted in ascending manner where solution 1 is the most left point in the graph, and the last solution is the most right point in the graph. It is observable that all the solutions suggest direct shipping services from Java to the smaller regions in Irian Jaya such as Sorong, Timika, and Merauke and Jayapura. This result also underlines the importance of developing efficient port services across the nation (e.g. through improving port capacity, and equipments) such that ship turn-around time at ports can be reduced to avoid high logistics costs. Based on this result, it is useful to analyse further how sensitive is the network structure to different port's service efficiency scenarios. The work in (Faisal, 2016) has provided some preliminary analysis of the impact of improvement in port infrastructures on Indonesia's shipping network.

Figure 5.18 Comparison of container traffic distribution across different solutions in experiment 2

5.5.3   The impact of network density on the efficient shipping networks

The maritime shipping network design problem addressed in this case study can be expanded to account for variations in the network density (measured by the number of links) that can further minimize total user costs and total network distance. Through the Indonesian case study, we have demonstrated that the MCST model can be use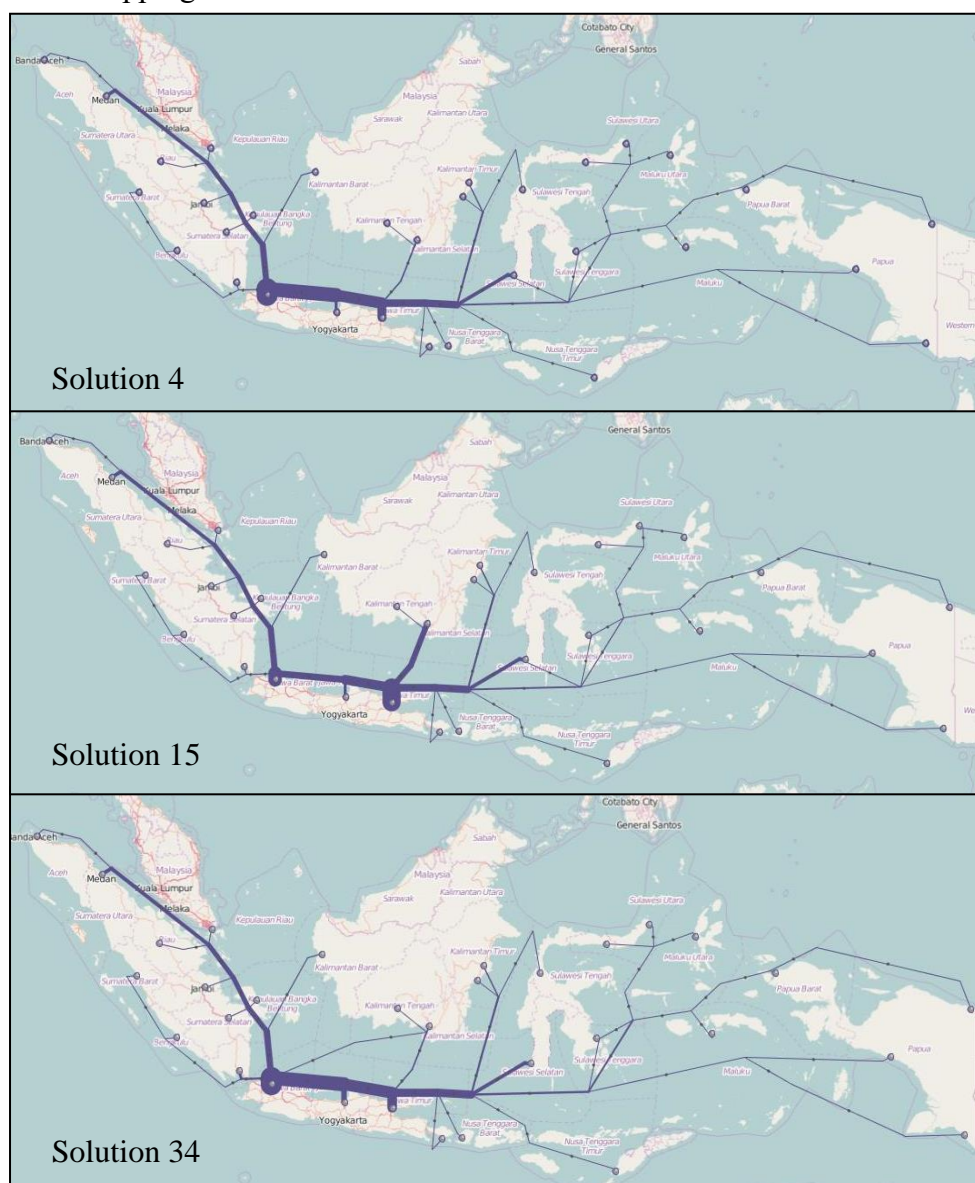d to identify the major efficient shipping connections between ports. However, some of the model constraints might limit the networks structures found by the solution algorithm. In this section we expand the MCST model into a more general transport network design problem such as formulated in (Billheimer and Gray, 1973, Drezner and Wesolowsky, 2003, Gastner and Newman, 2006, Los and Lardinois, 1982, Magnanti and Wong, 1984) to investigate the possible efficiency improvements on the network design objectives.

Due to the nature of the MCST networks, ports are generally connected with a single efficient route. That is, there are no alternative routes between ports (while there are multiple routes that can connect origins and destinations at the centroid level). This is due to the constraints of MCST model that forbids the creation of sub-tours (eq 5.8) and number of links to be higher than number of ports-1 (eq 5.7). The use of these constraints might cause non-direct port-to-port connections to have a considerable detour, which eventually can cause the networks to be less efficient in terms of total user costs.

In order to find efficient shipping networks that allow multiple alternative routes from origin port to destination port, we eliminate constraint 5.7 and 5.8. This implies that the solution networks are allowed to have cycles and varying density (measured by the total number of edges). Similar to MCST, this is a generalized network design problem also called minimum cost (MC) network design problem or fixed charge design problem, which belongs to the class of NP-hard (Gao et al., 2005, Magnanti and Wong, 1984). There have been numerous efforts to solve this problem where most of the solution algorithm proposed uses metaheuristics as exemplified in (Drezner and Wesolowsky, 2003, Gastner and Newman, 2006). This is primarily because the complexity of the problem grows exponentially along with the increase in problem scale.

To solve this problem, we extend the solution algorithm specified in section 5.4.3 with an additional heuristics that enables the algorithm to search for efficient network structures with varying network density. The central notion of this algorithm is that a random spanning tree network can be firstly constructed to connect the major ports and subsequently additional direct shipping connections can be established between ports that have high transport demands but do not have direct connections. These additional direct shipping connections are predefined based on the historical transport demand data between the ports. Specifically, we only consider top 20 port-to-port flows which total transport demand constitutes 80% of the national transport demand.

In order to account for the impact of additional direct shipping networks on the design objectives, we introduce an additional decision variable delta (δ), which value can effectively reflect the density of the shipping network. Zero delta value represents network with no additional port-to-port edges and delta value of one represents the addition of all top 20 port-to-port edges into the network. Essentially small delta value corresponds to sparse network and high delta value corresponds to dense network. We include delta value in the solution

representation of the NSGA-II together with other variables that correspond to the decision to include/exclude the edges for the spanning tree. This way, the algorithm effectively searches for the efficient network structures that take into account the variation in the number of additional direct shipping connections.

Figure 5.19 shows the comparison between Pareto sets that are obtained based on MCST and MC networks. Both models use the same input parameter values such as value of time and handling costs. We also use the same parameter values for the NSGA-II in obtaining both Pareto sets. Based on our calculation, the variation in the network density results in a Pareto set that outperforms the Pareto set obtained by MCST model. Solutions for MC network have wider variations in terms of total network distance. Compared to the solutions for MCST network, the least cost solution of MC network is 2.5% lower than that of MCST network. In terms of total network distance, the least distance solution of MC network is similar to that of MCST network with a difference less than 1%.
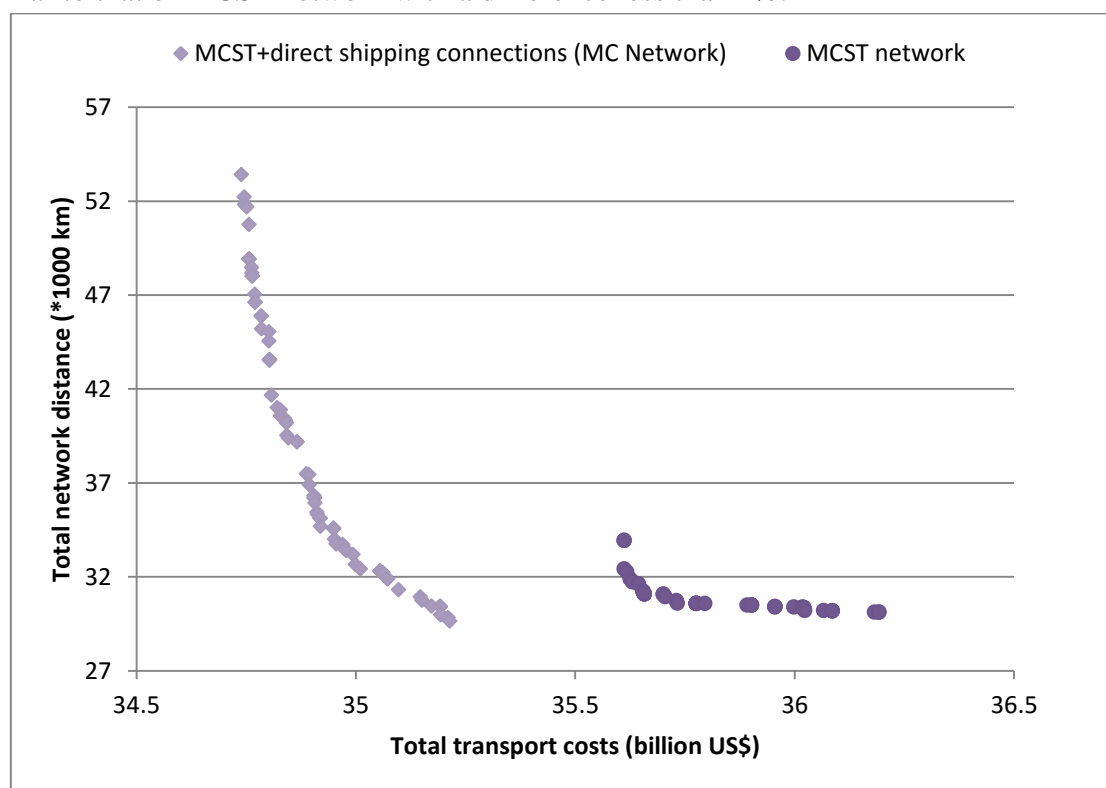
Figure 5.19 Comparison of Pareto sets for MCST and MC model

Figure 5.20 shows the visualizations for port networks based on the non-dominated solutions for MC network. When $\delta = 0$, there are no additional direct shipping lines, and the shipping network is essentially in the form of minimum spanning tree. This network has the least total network distance but the highest total transport costs which resembles a preference towards minimizing total operational cost of the liner shipping companies at the expense of user transport cost. In this network, a shipping corridor that resembles a trunk route seems to emerge. This corridor connects major ports from the Western to the Eastern regions such as Belawan, Tj. Priok, Tj. Perak, and Makassar with the least distance. Smaller ports are connected to this main trunk route via the closest hubs in the region. Because there are not alternative routes between ports, transport flows are concentrated along the main trunk routes

along the coast of Sumatra, Java, and Makassar. The absence of direct shipping connections also implies that goods transported between certain ports will have relatively longer travel distance.

As delta increases, few major direct shipping connections are added as part of the initial shipping network. When $\delta = 0.1$, Tj.Priok begins to play a role as a hub port with direct connections to other major ports such as Belawan, Tj.Perak, and Makassar. The emerging network therefore starts to utilize the efficiency of direct connections between major ports while at the same time also keeping the total network distance to be low.

At $\delta = 0.65$, there are more direct shipping connections from and to Tj. Priok and Tj. Perak. In this case Tj. Perak ,as the second biggest port, starts to emerge as a hub port in the eastern of Java with direct connections to major ports in the Western and Eastern regions such as Belawan and Makassar. As there are more direct shipping connections between ports with high transport demand, the distance travelled by the majority of the goods is reduced. This results in lower total transport cost and higher total network distance as compared to the network with $\delta = 0$. This network structure essentially offers a compromise between the total user cost and the total operational cost of the shipping companies.

In the case where $\delta = 1$, the network resembles hub and spoke structures where Tj. Priok and Tj. Perak play a stronger role as hub ports for ports with considerable transport demands across the country. Tj. Priok is directly connected to around 40% of all the ports and Tj. Perak has direct connections to 30% of the ports. The total transport demand served by these two ports constitutes 80% of the total transport demand of the nation. This solution network prioritizes the efficiency in total transport cost over total network distance. This is the case when there are many direct shipping routes operated by shipping liner companies between major ports in Indonesia. In this network, the presence of alternative routes for each port origin and destination also results in more dispersed flows across the shipping routes.
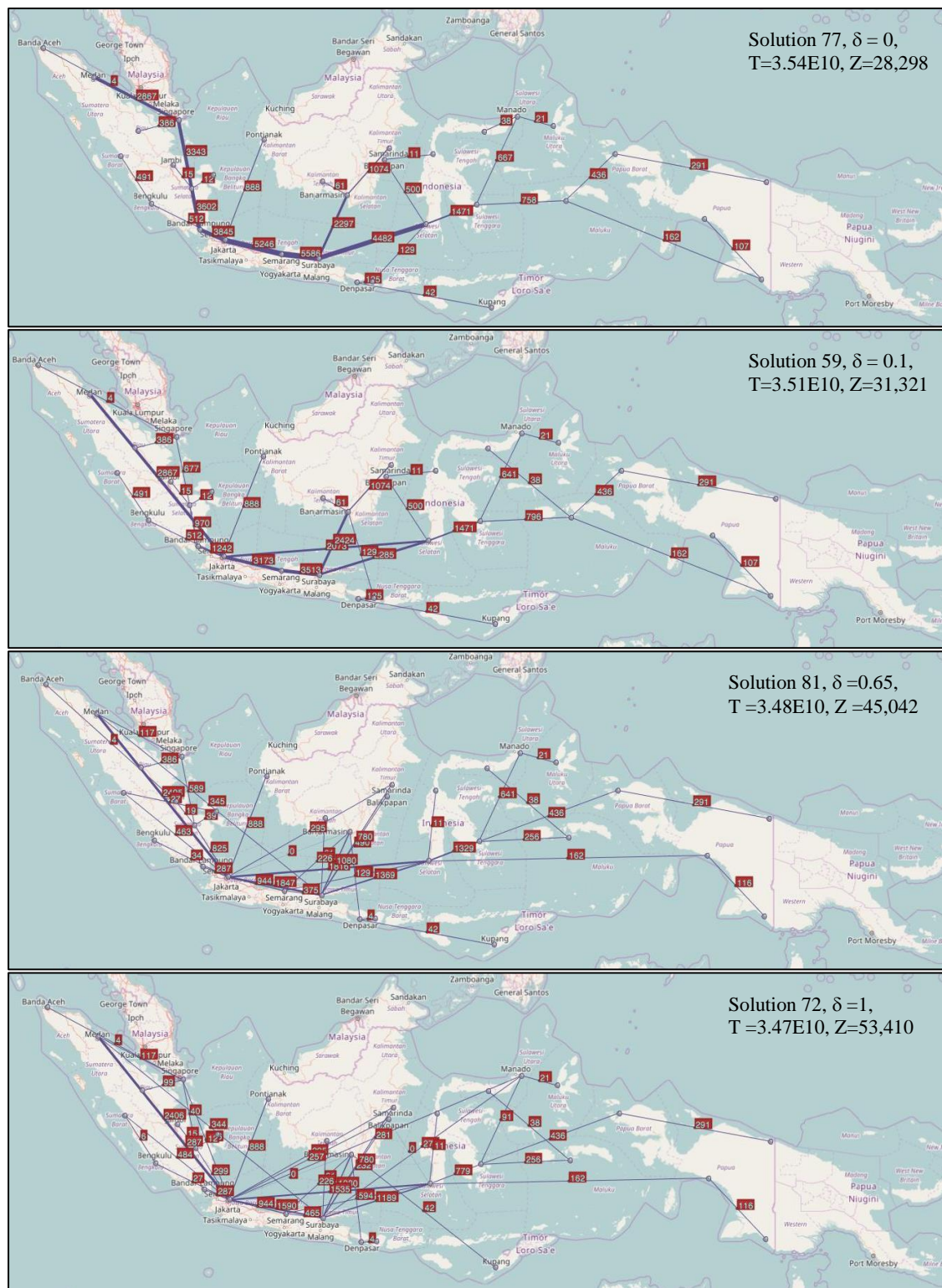
Figure 5.20 Port networks visualization for different δ values

The extension of the network design model to account for the impact of the availability of alternative routes between ports has proven to be successful in finding better solutions for the network design problem. Despite that there is not a substantial reduction in total transport cost, solutions for MC networks are more varied in terms of total network distance. Dense networks with many direct shipping connections result in lower user transport cost while sparse networks generally result in lower shipping operation cost. We also see that the Pareto

set for MC networks becomes steeper as the total transport cost decreases along with the increase in total network distance. This indicates that after a certain addition, the efficiency gain in total transport cost diminishes when new shipping lines are added. This is because the highest efficiency gains in transport cost have already been achieved in the lower part of the set where the added shipping lines serve the major port to port flows. Our solution algorithm which extends the algorithm we use to solve MCST network is also proven to be effective in finding efficient shipping networks for MC network design problem. The algorithm is able to find the optimal trade-offs between user transport cost and liner shipping companies operation cost by varying the structure and the density of the networks.

To summarize, we have presented a case study that demonstrates the efficacy of the approach proposed in finding efficient network structures for Indonesia's maritime transport system. The experiments performed in this test case can be seen as a dynamic verification, validation and testing exercise for the model (Balci, 1998). Using the bi-objective optimization model, we found a range of port network structures that minimize both the total transport cost and total network distance. Furthermore, we also investigated the sensitivity of the network structures for different values of time and network density parameters. Our findings suggest that, when value of time is taken into account, the efficient port networks are characterized by the presence of more direct connections between major ports in Indonesia with Jakarta and Surabaya as the central hubs of the networks. This is logical as the time needed to berth, and unberth the ship, load, and unload containers is very high in many Indonesian ports. In turn, this inefficiency at the ports cause high time costs for port networks that have many indirect connections.

Finally, this model opens possible further applications in analyzing Indonesian maritime transport policies. Firstly, the model can be used to give input on the efficient design of Indonesian maritime transport network under different trade scenarios. Secondly, the model can be used to analyze the impact of changes both in the supply and demand sides of the system such as port handling cost, unit shipping cost, shippers' choice behavior, the emergence of new transport infrastructure.

5.6   Application for global container shipping services

Based on the successful application of the model for Indonesian case, we scaled up the application of the model to the global shipping network. Due to the scale of the optimization problem of the global shipping network, we do not model the impact of differing network density on the optimal trade-offs between total transport cost and total network distance. The shipping network model used for the case studies in this section is based on the MCST network as presented in section 5.4.3. In this global case, our main goal is to investigate the impact of alternative network configurations on the competitiveness of the ports in Hamburg - Le Havre range instead of finding efficient global shipping networks. To this end, MCST network is proven to be sufficiently effective to estimate the main network structures that can connect major ports worldwide.

In order to achieve this goal, two relevant research questions need to be answered: "How do global trade scenarios influence the structures of global maritime shipping networks?" and "How do alternative shipping network structures impact port flows?". Three

global trade scenarios in 2040 were developed based on a previous study (Van Diepen, 2011). Subsequently, we used the model to investigate how changes in global transport demand as defined in these scenarios restructure global shipping networks. These scenarios include:

1. Continued Globalization
2. Local for local
3. Regional production, market driven

The next subsections present the calibration and application of the model to these scenarios. An elaborated description of each of the scenarios is provided as introduction.

5.5.4 *Data, and calibration of the model*

The main data used in this model are the global container trade flows (Origin - Destination flow) for 237 countries in the world, the geo-locations of the 436 ports, and the schematization of the global maritime shipping networks which describes all plausible routes from an origin to a destination country. We obtained these data from a previous study which was used as the basis for the development of the World Container Model (Tavasszy et al., 2011). The global container trade database which we use as the base scenario for our analysis is based on the observation in the year 2006.

We calibrated the port attractiveness values (A_p), and logit scale parameters (μ) based on the trade data and the given global maritime network. Herein, we did not incorporate service networks of the liner shipping companies in the calibration process, and we assumed that there can be direct shipments (without transhipment) between for container trade flows between all ports globally. The aim of the calibration is to find both port attractiveness and logit scale parameter values under a global maritime network that has direct connections between the ports. Subsequently, these parameters are used in the optimization process to identify plausible global shipping networks for the base scenario and the other scenarios. In this way, we assume that the port attractiveness and the logit parameter values will remain the same in different scenarios, while the solution algorithm searches the plausible network structures for the varying global container trade patterns. Figure 5.21 presents the calibration result for ports attractiveness values of ports in the Hamburg – Le Havre range. The port attractiveness values are calculated based on the ports handling costs and other costs which data are unavailable. The aim of the calibration is to minimize the absolute difference between observed values and model output in terms of gateway throughput and transhipment.
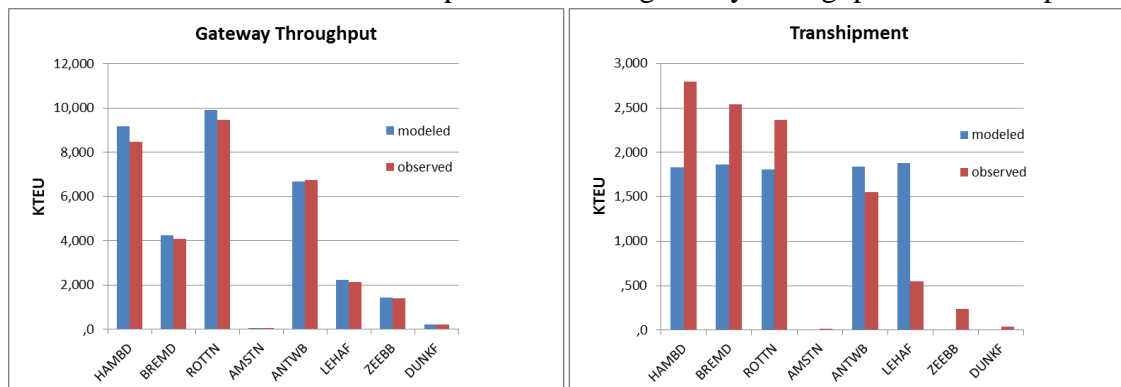
Figure 5.21 Calibration result for port attractiveness values, measured in total throughput and transhipment of ports

The calibration result shows that the model is able to produce a good fit for the gateway throughput of the ports. However, the model also has some deviation in the transhipment volumes of several ports. This result tells that an improvement on the transhipment sub-model can be beneficial to improve the model's accuracy. This can be done by introducing additional transhipment cost variable that specifically represents the attractiveness of a port for transhipment activities. This improvement will be subject for future research.

5.5.5   Model validation

The test case described in section 5.5 provides a good indication that the model behaves in accordance to multi-objective optimization theory for its application on a problem with relatively smaller scale. To validate the behaviour of the global scale model, we conduct an execution behaviour test of the model. We run the model with different number of evaluation/iterations, we assess the resulting output, and we visualize the resulting global shipping networks patterns to assess whether the model produces realistic output.

We run the solution algorithm using 10,000 and 20,000 evaluations using the base year data, as well as calibrated port attractiveness and logit parameter values to find global network structures that minimize both total transport cost and total network distance. We found that the improvement on the quality of the solutions after 10,000 evaluations is rather small for the additional 10,000 iterations of the algorithm. This implies that running the algorithm with higher number of evaluations might not improve the quality of the solutions significantly or that the convergence of the solutions can be achieved using 20,000 evaluations. Hence, we use 20,000 evaluations as the stopping criterion for the solution algorithm. Figure 5.22 presents the Pareto set found for the base scenario. The solution is labeled in ascending manner from left to right where solution with the lowest total transport cost is solution 1 and so on. As can be seen, the solution algorithm manages to find the non-dominated solutions for the test case.
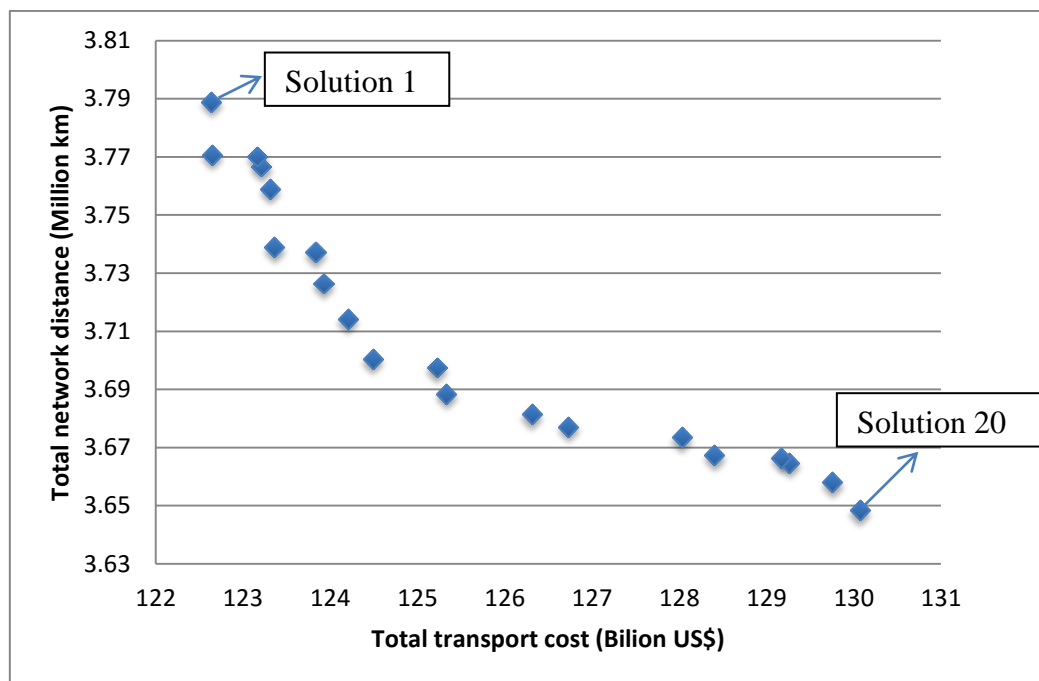
Figure 5.22 Non-dominated solutions for base scenario obtained by 20,000 evaluations

To illustrate how the result of the model can be used to support policies related to investment in shipping services, we measure the cost-efficiency of each of the solutions. We use the solution with the highest total transport cost and the smallest total network distance as the reference for our computation (solution 20). Next, by comparing all the other solutions with the reference solution, we compute the saving in total transport cost that can be achieved for each additional network distance. In other words, we compute the gradient of each solution relative to the base solution. Figure 5.23 presents the ratio between cost-saving and additional operational distance for each solution in the Pareto set. The solutions are ordered based on the distance in ascending manner, where solution 19 has the least total distance and solution 1 has the highest total network distance. We see that the additional shipping service coverage initially results in increasing cost-efficiency of the solution, but it reaches its peak at solution 12. This implies that after the shipping network reaches a certain service density, it becomes more difficult to reduce the total user transport cost. Furthermore, it also indicates that solution 12 is the most cost-efficient solution in terms of cost per km.
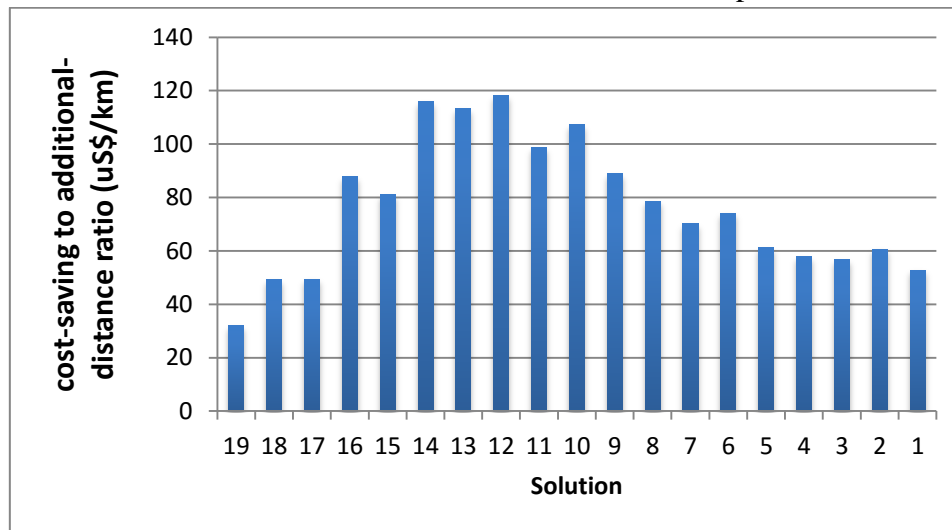
Figure 5.23 Cost-efficiency of the non-dominated solutions

Figure 5.24 presents the values of port throughputs for the extreme solutions. Solution 1 represents shipping network with the lowest total transport cost and solution 20 represent shipping network with the highest total transport cost. The ports in each of the solutions are ordered based on their throughput values in descending manner (i.e. ports with higher throughput are on the left and ports with lower throughput are on the right).

It can be seen that solution 1 has small number of ports with significantly high throughput volume whereas solution 20 has more ports that share similar throughput volume. Furthermore, in solution 1 the difference in terms of throughput between high-throughput ports (e.g. the first two ports) and low-throughput ports (on the right side of the graph) is quite stark and sudden while in solution 20, the difference between these ports occur in a more gradual manner. This pattern could indicate that solutions with lower total transport costs result in shipping networks with more hub ports and solutions with higher total transport cost result in shipping networks with fewer ports serving as hub ports.
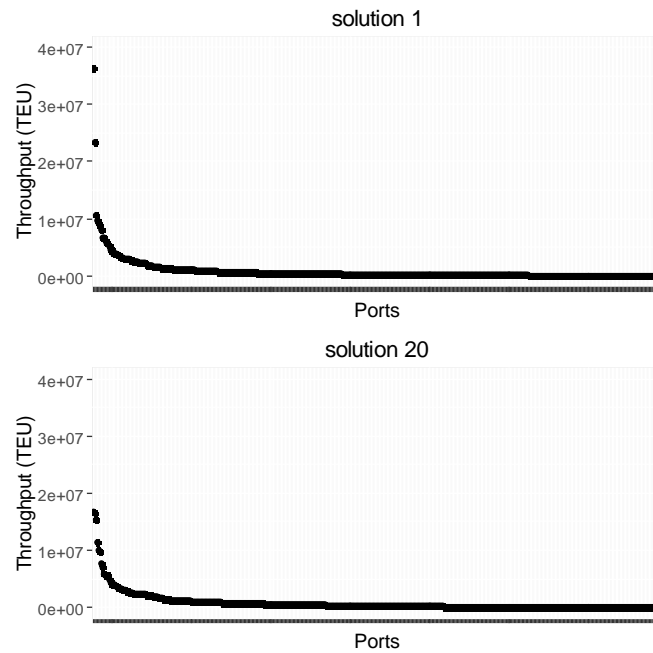
Figure 5.24 Port throughput comparison between extreme solutions

To better show the detailed difference between the extreme non-dominated solutions (i.e. solution 1 and 28), we present the comparison between these solutions in Figure 5.25 and Figure 5.26. Figure 5.25 shows the line plot of the two extreme solutions while shows the same plot with a log scale on the x-axis. As can be seen on Figure 5.26, there is a clear difference in the distribution of throughput volume across the ports between the two solutions. Solution 1 has a steeper change while solution 20 has a more gradual change in port throughputs. Furthermore, it is also apparent that solution 20 has several ports with high concentration of throughput volume. This indicates that shipping network in solution 1 has a few ports that plausibly play a role as hub ports for the gateway throughput market.
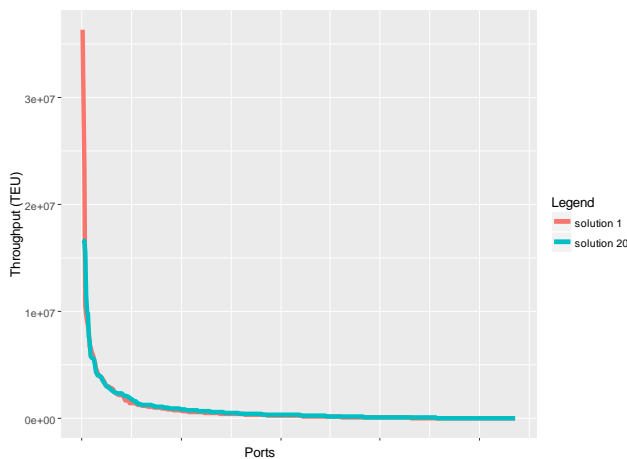
Figure 5.25 Line plot of port throughput distribution between extreme solutions
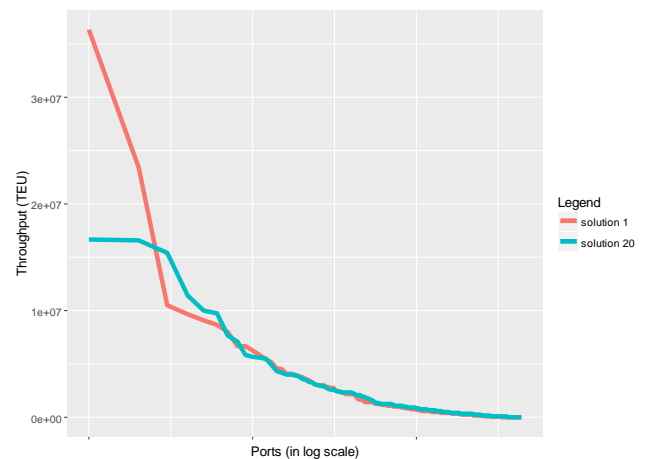
Figure 5.26 Line plot of port throughput distribution with log scale on x-axis

Figure 5.27 provides a visualization for selected network structures that correspond to the non-dominated solutions. Based on the visualizations, we see that the solutions can

represent networks with wide range of structures. For simplicity's sake, we only present shipping networks that have significant variations among the solutions.
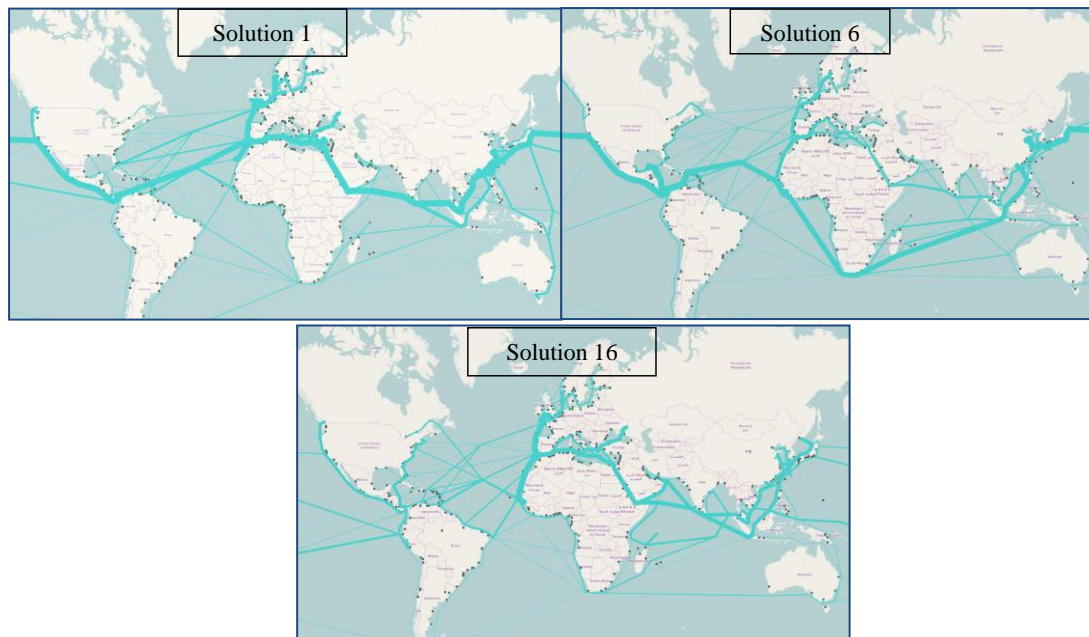
Figure 5.27 Visualizations of different network structures based

As can be seen in Figure 5.27, solution 1 resembles a global shipping network that forms a structure similar to "the global conveyor belt" scenario. In this scenario, major liner shipping companies would collectively use the most efficient routes and attractive ports (e.g. ports with low handling cost) to serve global transport demand. This results in the emergence of several hub ports that have high throughput volumes. A noticeably different structure starts to emerge in solution 6 where alternative routes between the Far-East and both Central and Northern America gain considerable transport volume. In solution 16, the shipping network has noticeably less consolidated flows across the atlantic ocean but has more shorter and direct transport flows between Southern American countries and Far-East countries.

5.5.6   *Application for global trade scenarios*

We used the same NSGAII algorithm parameters as that presented in the Indonesian case study. For each of the scenarios, the model gives a set of non-dominated solutions with respect to total transport costs and total network distance.To investigate the plausible impact of different global trade scenarios on the competitiveness of ports in the Hamburg -Le Havre range, we calculated both transshipment and gateway throughput of the ports for each structure. Transhipment volume is defined as the total amount of containers that is transferred between maritime shipping lines. We obtained the transhipment volume for each port using the analysis specified in section 5.3.5, where we used the logit route choice model to determine transhipment volumes. We define gateway throughput as the total amount of containers that is transferred between the maritime side and the hinterland side. For each scenario, we compared the calculated throughput and transshipment volumes of each port to a reference point that is uniquely measured for the corresponding scenario. This reference point describes the base values of ports' throughput and transshipment under the given global trade patterns, non-optimized maritime shipping networks, and a set of port attractiveness values.

By comparing modeled port throughput and transhipment to reference points, we study the percentage changes in volume for each port in the Hamburg – Le Havre range in each scenario.

1. Base scenario

In this scenario, we apply the model for the 2006 trade data to investigate the impact of the alternative shipping network configurations on the Ports in the Hamburg - Le Havre range. Figure 5.28 shows the percentage changes in volume for each port for the non-dominated solutions from a transport cost-led (left) to a distance-led network (right) for the base scenario.

Figure 5.28 Changes in port's performance indicators for base scenario

As can be seen in the graphs, two biggest ports in Europe, namely Rotterdam and Antwerp dominate the throughput and transhipment markets under different network configurations. In the first 7 structures Antwerp gains almost twice the volume of its reference gateway throughput and more than double the value of its reference transhipment figure. Rotterdam starts to dominate both gateway throughput and transhipment markets starting from the 8th solution on where the network structures have lower total network

distance and slightly higher total transport costs. This pattern indicates that when the shipping network is evolving towards cost-led structure, Antwerp shows a strong potential to become a hub port that dominates the competition in the Hamburg - Le Havre range. From connectivity perspective, this is mostly caused by Antwerp's good location which is in close proximity to the main trade lanes and its good connections to many hinterland destinations. However, the drastic change of port dominance starting in 8th solution also indicates that Antwerp and Rotterdam compete heavily in the Hamburg - Le Havre range. Slight changes both in total transport cost or the total network distance can lead to a significant impact on the port choice for the shippers. Specifically, when the network evolves towards distance-led structure, Rotterdam will dominate the port competition. This means that when there are more shipping lines that provide direct shipping services to ports in Europe, Rotterdam will outperform Antwerp in their competition.

It is also observable that Rotterdam performs relatively well for transhipment market over the different network structures. This indicates that Rotterdam has a strong competitiveness as a transhipment port over different efficient network structures. Note that, because the solution algorithm tries to minimize the total transport costs, ports that are not well connected to the shipping network such as Bremen, Amsterdam, Le-Havre, Zeebrugge, Dunkirk, and Hamburg can suffer a significant loss in their throughput and transhipment. Specifically, this is because the algorithm searches for the cheapest connections between ports such that the volume of containers that can be shipped through these connections can be maximized. Consequently, most of the container flows will be concentrated among those ports that are efficient and well connected to the hinterland destinations and less efficient ports will have limited flows.

2. *Continued Globalization*

This scenario describes the future situation in 2040, where the current trend of global trade grows steadily, leading to, on average, a 40% growth of trade flow. Major developing countries such as Brazil, Russia, India, and China are estimated to have a significant rise in their export and import activities compared to the rest of the world. Figure 5.29 presents the changes in volume for each port for the non-dominated solutions from a cost-led (left) to a distance-led network (right) for the continued globalization scenario.
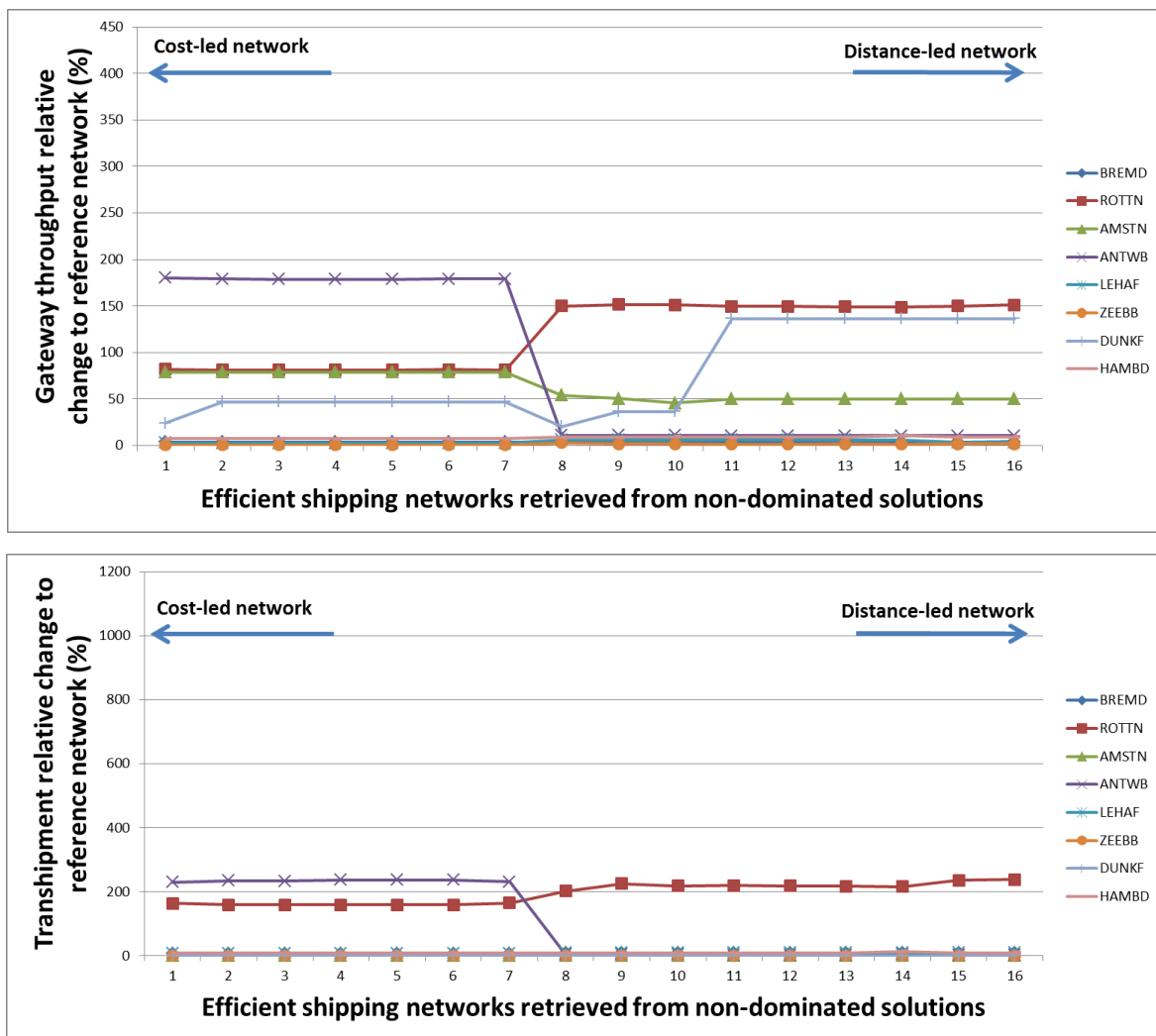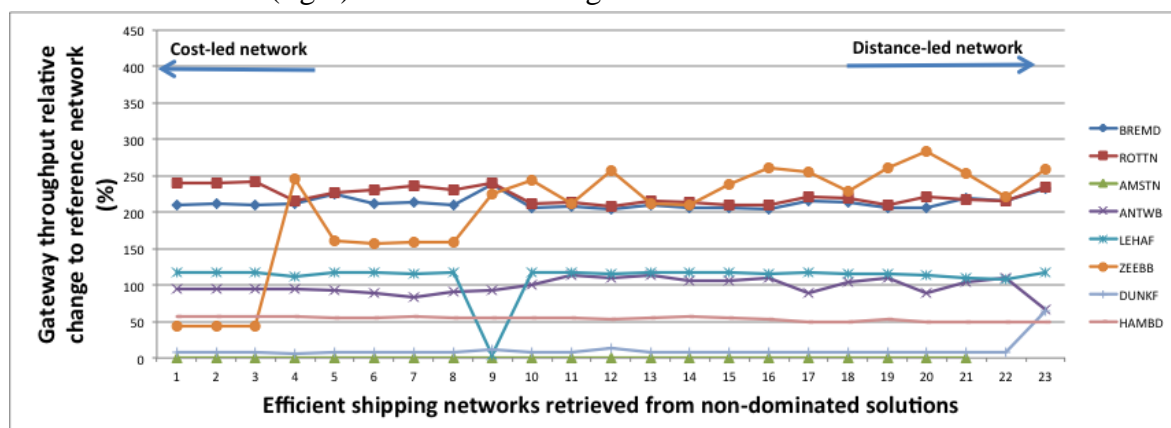
Figure 5.29 Changes in port's performance indicators for continued globalization scenario

In this scenario, most of the ports in the Hamburg -Le-Havre range gain a significant increase in their gateway throughput, except for Amsterdam, Dunkirk and Hamburg. Rotterdam, Bremen and Zeebrugge are the most strongly growing ports, with a gain of more than twice the volume of their reference over different efficient network structures. Antwerp is at a relatively stable performance with almost no change in its throughput and Le Havre also shows a similar pattern with a slightly higher gain in throughput for most of the networks except for network 9. A distinct pattern is shown by Zeebrugge port where it gains a significant throughput volume after solution 3. This could indicate that a shift in network preference towards distance led network (with lower total network distance) will benefit Zeebrugge. This drastic gain of Zeebrugge is partly caused by the increased trade activities between European countries and Brazil that allows Zeebrugge to gain more gateway throughput for container flows that are shipped to countries with large economic activities such as France, and Germany. However, since Zeebrugge and Antwerp are located in a very close proximity to one another, it is very likely that they both share the same gateway throughput market. This competition relation is also reflected in the throughput patterns exhibited by two ports in network 17, 20, 23. In this scenario, the close proximity of Zeebrugge to the main trade lanes has enabled the port to gain some share of flows that generally go through Antwerp.

We see a similar pattern for transshipment, where Rotterdam and Bremen gain a significant increase relative to the reference case while the rest of the ports perform rather stable at their initial reference value. Interestingly, Zeebrugge is completely outperformed by the other ports in terms of transhipment volume. This means, while Zeebrugge is a competitive port for gateway throughput market, it is not as attractive as a transhipment port compared to Bremen and Rotterdam. This is primarily caused by the gap in attractiveness between Rotterdam and Zeebrugge which causes transhipment operation at Zeebrugge for shipments from China to be unattractive. Furthermore, Bremen shows a significant gain in its transshipment indicating its favorable position over Hamburg.

3.   Local for local

In this scenario, various factors have caused production activities to be moved closer towards the market despite of the overall growth in global trade activities. Examples of those

factors include the rise of wages in developing countries that leads to the global convergence of wage levels, and stricter sustainability requirements that cause intercontinental maritime transport to become less attractive. All these factors have caused manufacturing sites to move closer to the markets worldwide and trade activities to shift towards intraregional trade within the same continents. The trend results in shorten distances within global supply chains and more environmentally friendly modes of transport. Furthermore, intraregional trade is estimated to increase 100% while intercontinental or interregional trade to decrease by 50%. Figure 5.30 show changes in volume for each port for the non-dominated solutions from a cost-led (left) to a distance-led network (right) for local for local scenario.

Figure 5.30 Changes in port's performance indicators for local for local scenario

Compared to the continued globalization scenario, this scenario results in overall lower port throughput in Europe. Among the major ports, only Rotterdam shows a significant gain in the first half of the solutions, while Bremen, Hamburg, and Antwerp lose their throughput almost across all network structures, except for solutions 12-15 where Antwerp has more throughput than Rotterdam. This pattern indicates that there can be a change of market dominance when the network evolves towards distance-led structure. This means that within a certain range of total transport costs and total network distance, two major ports (i.e.

Rotterdam and Antwerp) that compete which each other may dominate the container traffic market. Unlike major ports in the Hamburg - Le Havre range, smaller ports such as Zeebrugge, Dunkirk, and Le-Havre seem to gain throughput volume when the network prefers distance-led structures (starting from network 9 onwards) where these structures have shorter total network distance over total transport costs. This might be due to the increase in trade between neighbouring countries in Europe has driven the emergence of direct connections or short-sea shipping between European ports. This trend appears to benefit smaller South-Western European ports such as Zeebrugge, Dunkirk, and Le-Havre as they are located in close proximity to the centers of production and consumption activities such as France and Southern Germany. This strategic location also allows them to be gateway ports for trade flows between North-Western European (i.e. Germany, France, Belgium, Netherlands) and South European countries (e.g. Portugal, Italy, Greece, Spain)

Similar to the pattern we observe in throughput, transshipment volume of the ports are generally less than that observed in continued globalization scenario. Rotterdam shows a strong growth in the majority of the network structures until Le-Havre begins to gain significant increase transshipment volume from network 16 onward. Furthermore, similar to the throughput pattern, Antwerp also gains more transhipment volume than Rotterdam between networks 12 and 15. This is because, between these range of networks, Antwerp becomes more attractive as a transhipment port to facilitate intraregional trade between European countries. Overall, this result also shows the impact of a shift towards distance-led structure where there can be more direct shipping connections between the ports in the Hamburg -Le-Havre range that allow smaller ports in this region to gain more transhipment market.

4. Regional production, market driven

This scenario describes a trade pattern in 2040 that is characterized by the shift from global intercontinental trade to regional trade within continents worldwide. The rise of average labor cost in Asia and the increasing needs for customized products in large scale have driven many companies to move their manufacturing sites closer to the markets. This resuls in manufactured and high value goods being produced closer to European countries rather than in China. A distinct situation in this scenario is that Eastern European and Northern African countries have grown to be suitable manufacturing regions for major companies. These countries include Morocco, Algeria, Lybia, Tunisia, Egypt, Turkey, Bulgaria, Ukraine, and Romania. These countries are estimated to be suitable manufacturing regions due to their relatively good connectivity to to the consumption sites such as Western and Northern European countries and because they offer competitive labor cost similar to China before its rapid growth. Due to this shift, it is estimated that 70% of Chinese-Europe trade in manufactured goods are shifted to Eastern Europe and North Africa. Figure 5.31 shows changes in volume for each port for the non-dominated solutions from a cost-led (left) to a distance-led network (right) for regional production scenario.
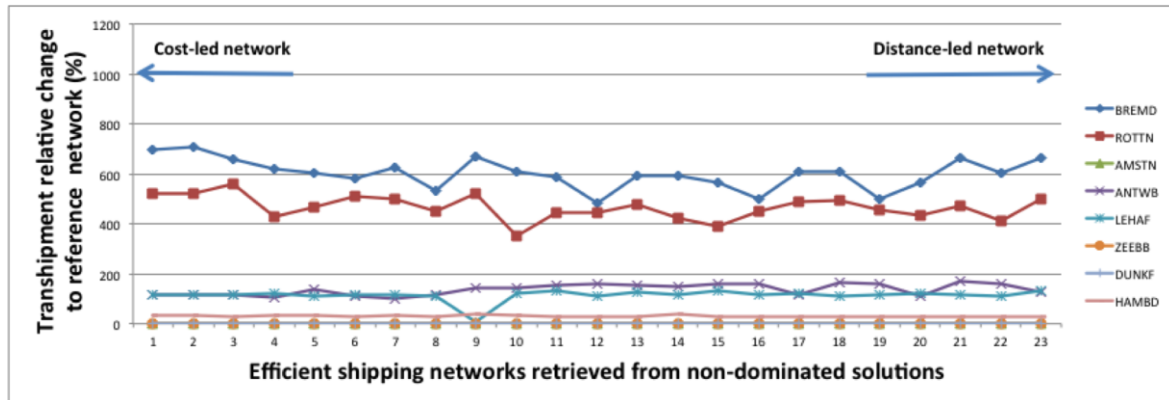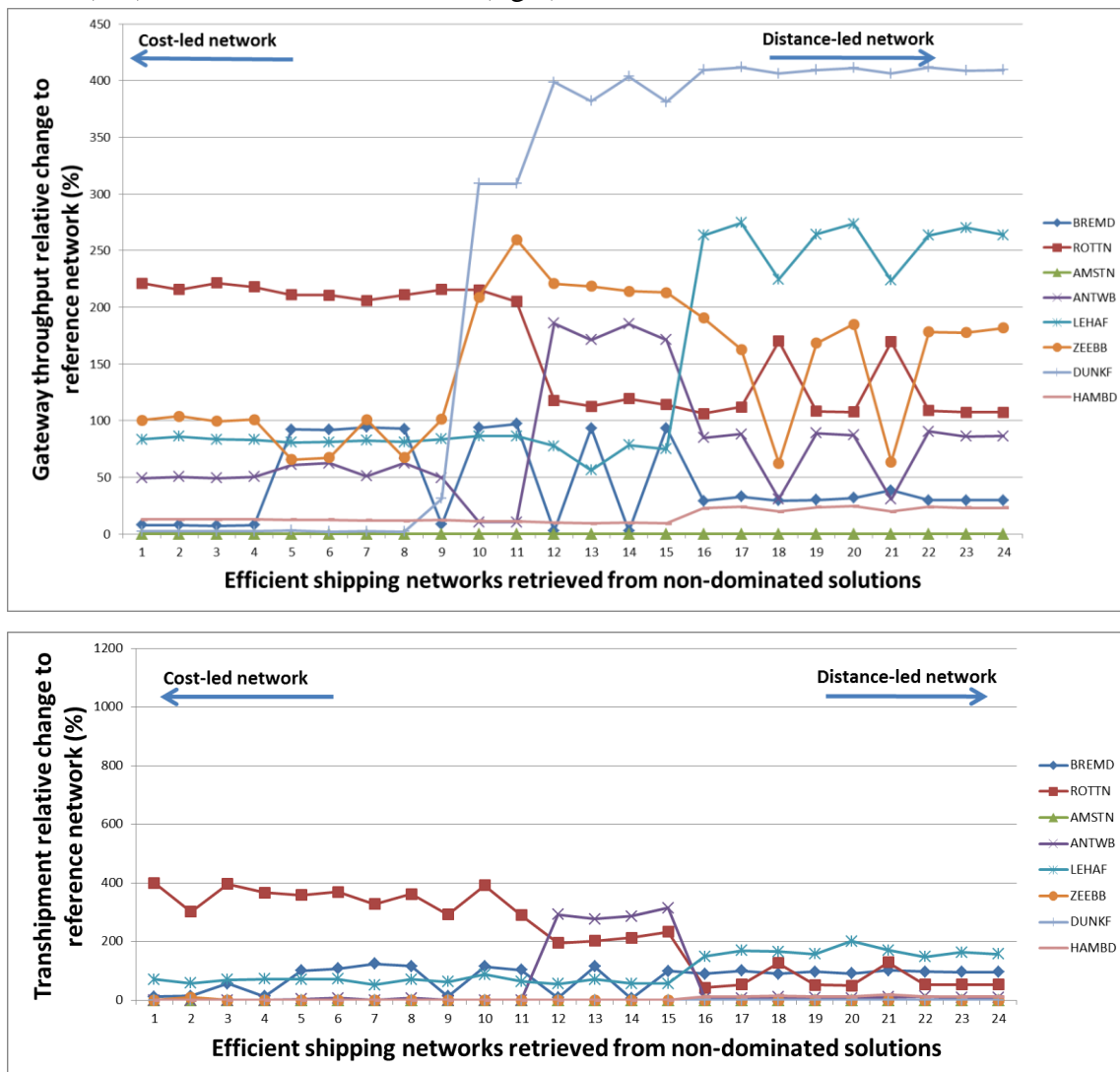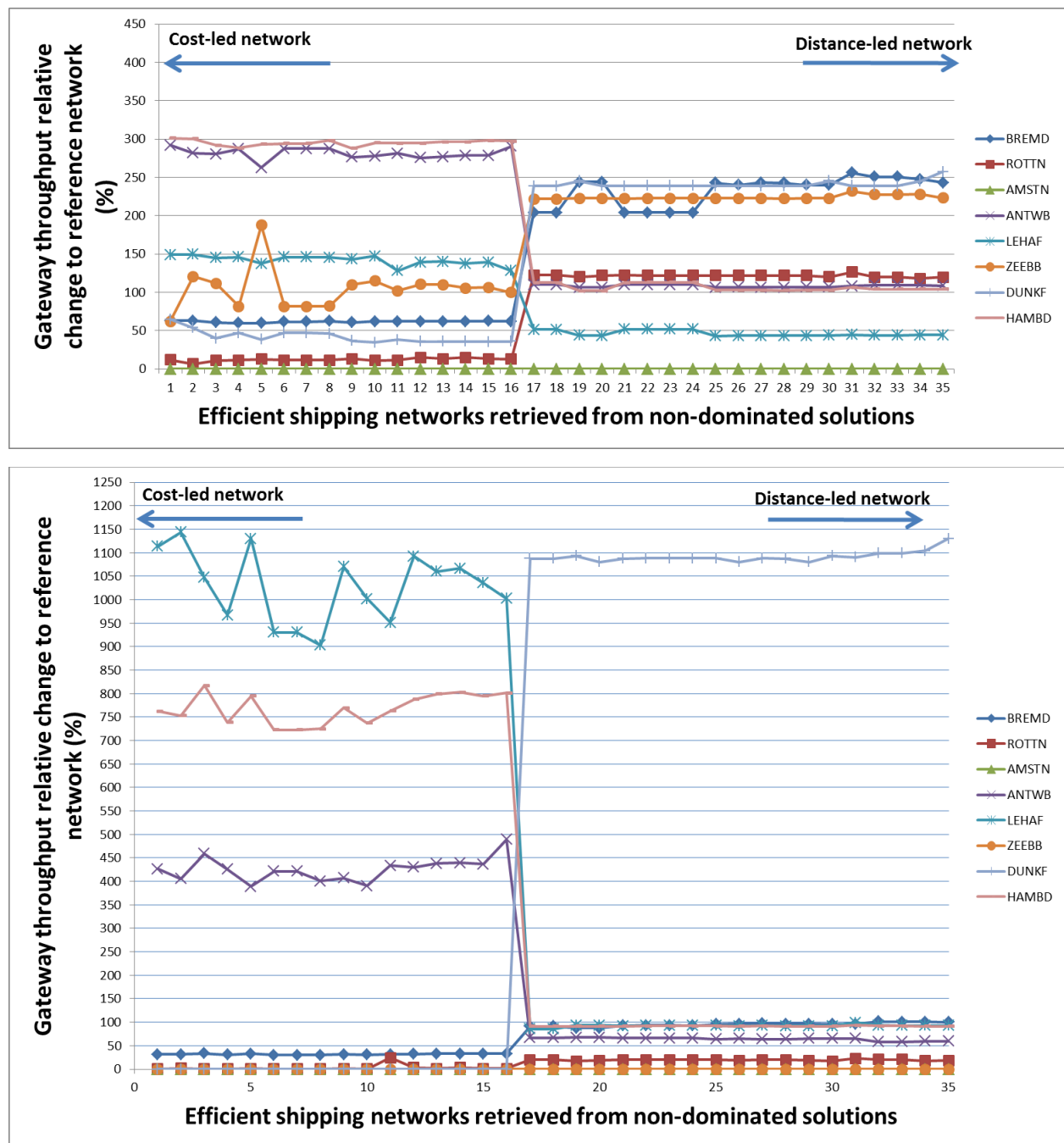
Figure 5.31 Changes in port's performance indicators for regional prodcution scenario

In this scenario, There appears to be 2 regimes across the spectrum of the efficient networks. The first regime is from network 0-16 where major ports like Hamburg and Antwerp together with Le-Havre gain a significant increase in their throughput volume. The second regime is from network 17 on where major ports such as Rotterdam, Hamburg and Antwerp stabilize close to the reference value with other ports such as Zeebrugge, Bremen, and Dunkirk gaining a significant increase (around 2.5x) in their throughput volume. This shows that, in this scenario Bremen, Zeebrugge, and Dunkirk are positively impacted by the shift of the network towards distance-led structure while big major ports such as Rotterdam, Hamburg and Antwerp manage to maintain their position similar to the basecase.

These patterns generally indicate that smaller ports in France and Belgium such as Le-Havre, Dunkirk, Zeebrugge benefit from the shift in trade from China to Northern African countries. These smaller ports become more attractive as gateway ports for the trade between Northern African and European countries. This is primarily caused by the proximity of these ports to both major production sites in North African countries and major consumption sites in Germany and France. In turn, this situation may drive the emergence of direct shipping lines that can reduce the total transport costs for the trade volumes between these countries. In practice, this can happen when the shipping lines call at multiple smaller ports rather than several big hub ports like Antwerp, Rotterdam and Hamburg to provide direct shipping services between countries with strongly increasing trade activities. Furthermore, similar to the case of Le-Havre, Zeebruge, and Dunkirk, it also appears that, ports in Germany i.e. Hamburg and Bremen, experience a positive impact from the shift of manufacturing sites to Eastern European regions. This is again due to their proximity to the Eastern European countries that in turn allows them to provide cheaper connections to the western European market regions such as France, and Germany. Competition relation seems also to be visible between Hamburg and Bremen. Hamburg dominates the gateway throughput market in Germany in the cost-led networks while Bremen starts to gains some share of this throughput market when the network shifts towards distance-led structure.

A similar pattern is observable in transshipment changes for the ports. Hamburg, Antwerp, and Le-Havre gain major increase in the transshipment volume for the first half of the network structures (untill network 16) and stabilize close to the reference value in the second half of the structures. From network 17 on, there is a sudden and massive change in the network where Dunkirk gains a sharp rise in transshipment volume (around 11 times than that of the reference case), while other ports such as Le-Havre and Hamburg remain at the reference level. Thus, in this scenario, Dunkirk seems to become significantly more attractive as a transshipment and gateway port when the network evolves towards distance-led structure. This is again primarily caused by the growing trade between Northern African countries and Western-European countries which may benefit Dunkirk with shorter distance to the main consumption sites in Europe such as France and Germany. In this scenario, it is also likely that Dunkirk gains some of the throughput share of Antwerp and Le-Havre considering their close proximity to one another. In the real-world, this can only happen when Dunkirk has enough capacity to accommodate such a significant rise in transhipment volume.

5.7   Conclusion

The structure of the global shipping service network strongly determines the maritime connectivity of ports. This chapter has presented a novel model to explore alternative global shipping service networks. Specifically, we have used a multi-level computation approach, modeling both network design and port choice to discover plausible structures for global shipping service networks.

By using this strategic model, we have demonstrated how alternative shipping network structures affect ports competitiveness. Firstly, we applied the model to the Indonesian shipping network to demonstrate the effectiveness of the model in finding efficient network structures. Secondly, we scaled up the application of the model to the global maritime

shipping network. Special attention was given to investigate how these structures impact the throughput and transshipment of ports in the Hamburg -Le Havre range.

The result of our analysis of the Indonesian case shows that the algorithm is able to find very different efficient shipping network structures for the given trade scenario and time value parameters. Specifically, we found networks with direct shipping connections to the less developed regions in the Eastern Indonesia to be the most cost-efficient to cope with the imbalance of demand between the Western and Eastern Indonesian regions.

The results of the case studies for global maritime networks show that the competitive position of the ports in the Hamburg - Le Havre range is strongly influenced by the structure of the global shipping service networks which, in turn, strongly depends on trade flow scenarios. Only in "continued globalization" scenario we see that port positions are relatively insensitive to network structure. Port positions are unstable in the "local for local" and "regional production" scenario. This instability is volatile or unstructured in the "local for local" scenario and structured into two regimes in the "regional production" scenario.

The results for different scenarios show that a sudden and profound change in port competitiveness is possible as a result of changing network structures. This finding applies to both throughput and transshipment performance of the ports. We observe a general pattern where both throughput and transshipment of the ports share similar trends across different scenarios, i.e. ports that are advantaged by the changing network structures normally show positive gain in both their throughput and transshipment and vice versa. Two exceptions are found in "continued globalization" and "local for local" scenarios. In "continued globalization" the increase in gateway throughput for port of Zeebrugge is not accompanied by increase in transhipment volume. Similar phenomenon is also observed for Dunkirk in the "local for local" scenarios.

In general, major ports such as Rotterdam, Antwerp, Bremen and Hamburg show relatively strong competitiveness across different scenarios and there are opportunities for smaller ports in "local for local" and "regional production" scenarios. Rotterdam can maintain its position even when the network changes in "continued globalization" and "local for local" scenarios. However, it is noteworthy that the competition relations among those major ports may change depending on the trade scenarios. In the "base" scenario, it is clear that Rotterdam competes with Antwerp strongly. Furthermore, it is also observable from the throughput pattern across the networks in different scenarios, that there can be clusters of ports that compete for the same throughput market with each other. In the "local for local" scenario, competition relationship can be seen in Dunkirk vs Bremen; Rotterdam vs Le Havre, Zeebrugge, and Antwerp. In the "regional production" scenario the competing ports are Rotterdam vs Antwerp, and Hamburg; Antwerp vs Zeebrugge; Dunkirk, vs Antwerp, Hamburg and Le Havre.

These results may provide input to the port strategy formulation processes, including investments and marketing decisions. Firstly, it is of strategic importance for ports to monitor how world trade develops. Secondly, it is valuable for the port authorities to answer the question on how, given a certain trade trend, a certain network structure can be predicted. Also, they provide a first indication of the robustness of a port's competitive position with a view to long-term changes in networks. Ports that do well in different scenarios will be more robust for change. Another important question is on how we can devise robust investment

policies looking at the plausible impacts of different network structures. The field of exploratory analysis may provide help to answer these questions.

This research also leaves several research avenues to be explored further. Firstly, the model we developed here assumes that efficient global efficient structures will dominate the whole network as a result of cooperation between different shipping liner companies. This is a rather simplistic assumption given that the global shipping networks are comprised of different actors that have different strategies and cooperation schemes. A more rigorous and realistic way to model emerging global shipping networks can be done using agent based modelling or a game theory paradigm where different shipping liner companies are modeled as autonomous actors who can devise their strategies and interact with one another dynamically (Angeloudis et al., 2016). Secondly, and perhaps more importantly, it could be interesting to include capacity constraints and the impact of the ship size on the unit cost of transport in the model.

6   Conclusions and Recommendations

This chapter presents the main research findings of this thesis, their implications for policies and recommendations for further research. While this thesis has exposed argumentations to answer the research questions throughout the content of the previous chapters, the main research question is answered in this chapter. We also revisit sub-research questions that have been defined in chapter 1 and provide the answers for these questions. We also elaborate policy implications for policy makers based on the insights gained from the results of this research. Finally, we present recommendations for further research based on the limitations of the studies conducted and also based on promising new research directions that have been identified over the course of this research.

6.1   Main research findings

1. How can we systematically identify key vulnerabilities that can affect the competitive position of ports in the face of deep uncertainties?

The global container transport network is constantly changing in response to a wide range of developments. It is virtually impossible to correctly anticipate the future dynamics of global flows of containers, due to the intrinsic complexity of the network and the wide range of uncertain factors affecting the network. For ports, this poses a profound challenge in the long term planning of their strategy and investments.

To address the combined challenge of complexity and uncertainty, we used a novel model-based approach to scenario development. To demonstrate the efficacy of our approach, we applied this approach to explore the consequences of uncertainty for the competitive position of the port of Rotterdam in the Hamburg– Le Havre range. Rather than predicting future container flows for a limited set of alternative assumptions, we systematically explored

what the container flows could be across 10,000 scenarios, covering 9 uncertain factors. Table 6.1 below provides the summary of key uncertainties that are treated in the study.

Table 6.1 Key Uncertainties that will impact the performance of ports in the Hamburg-Le Havre range

Name	Range
Cost of hinterland connections in Europe	0% – 25%
Hinterland cost for Rotterdam	-25% – +25%
Travel time of the hinterland connections of Rotterdam	-2 days –+2 days
Costs of the hinterland connection of Mediterranean ports	-25% – 0%
Handling costs of the Mediterranean ports	-25% – 0%
Handling costs of ports in the Hamburg - Le Havre range	-25% – 0%
Trade volume with Asia that is affected by availability of overland connection or shift of production to Eastern Europe	-25% – 0%
Northern passage	(present, absent)
Suez Channel	(present, absent)

Using the open exploration approach and the Patient Rule Induction Method (PRIM), it was found that the key vulnerability factor affecting the competitive position of Rotterdam is the quality of the hinterland connections. A modest increase in travel time on the hinterland connections from Rotterdam will shift flows away to other ports in the Hamburg – Le Havre range. In two follow up analyses, we used an optimization based search strategy in pursuit of two worst-case scenarios. First, we search for the presence of a "perfect storm" scenario where a set of small changes jointly substantially deteriorate the competitive position of the port of Rotterdam. We were not able to find such a "perfect storm", which suggests that the competitive position is quite robust with respect to small changes. In a second analysis, we tried to find a scenario where the Mediterranean ports become serious competitors with Rotterdam. We were able to find such a scenario, which is strongly determined by very unlikely situation in which the northern passage has to be used and there is a closure of the Suez route.

To conclude, we argue that the combination of exploratory modelling analysis, open exploration, PRIM, and optimization based search strategy offers a more systematic and better approach to discover the key vulnerabilities for port of Rotterdam in comparison to traditional prediction exercises. Equally important, without any loss of generality, this approach, due to its highly problem independent nature, can be applied to ports worldwide. Furthermore, the results of this analysis also point out the need to do a more thorough analysis on the factors that affect the quality of port connectivity both to hinterland and maritime subsystems. Such investigations can shed light on the detailed impact mechanisms of changes in both subsystems on port connectivity. Eventually, this insight will be valuable to determine the appropriate policies to improve port connectivity. Our research questions are intended to create this insight and will be answered below.

2. How can we design a freight logistics model that can explore the effects of port-hinterland distribution networks on port-hinterland flows?

Apart from operational cost factors such as congestion and availability of mode of transport, a strategic factor that significantly determines hinterland transport routes and its associated costs is hinterland distribution structure. The way the ports, distribution centers and destination regions are connected determines the routing of the goods, shipment size, and eventually the cost associated with each of the routes.

However, estimating the structure of port-hinterland distribution networks is very challenging due to the number of factors that need to be taken into account in such a calculation. For this purpose, a computer model is needed where large scale computations can be done with the help of state-of-the-art models and solution algorithms. Unfortunately, there is no model that addresses the emergence of port-hinterland distribution networks resulting from the establishment of hinterland distribution centers (DC´s). Most of the available port-hinterland models are developed using purely a normative perspective where the focus is on the design of the efficient logistics and infrastructure network, rather than on describing the responses of the port-hinterland system to policy measures.

Therefore, to answer this research question, we developed a generic model of the aggregated port-hinterland logistics network for large regions/ continents. The model is specifically developed to fill the gap in port-hinterland logistics models for policy analysis. Furthermore, we integrated this model into a global network choice model for container transport, namely the World Container Model. The port-hinterland logistics model estimates the locations of distribution centers in continental Europe as well as the network structure which connects ports, DCs, and consumption regions. Based on this network structure, the WCM assigns the flows of containers from the origin countries to the destination(s) in Europe. Therefore, using this integrated model, we can analyze the door-to-door spatial pattern of container flows, including the ports and DCs that are chosen by the shippers. To the best of our knowledge, the integrated model we present here is the first descriptive model that describes the structure of port-hinterland distribution networks taking into account locations of distribution centers.

We demonstrated the use of the model by first estimating the European port-hinterland distribution network. Based on the estimated network structures, we obtained a performance metric that describes the connectivity of the ports to the hinterland destinations (particularly to the DCs). This metric includes total transport costs and times between ports and hinterland regions, lead times between DCs and hinterland regions, and the potential gateway throughput of each port in the Hamburg – Le Havre range. Through our experiments, it was shown that port-hinterland container trade flows influence the port-hinterland distribution network. Thus, this metric can be used to analyze the impact of different trade scenarios and policy actions on the connectivity of seaports to hinterland destinations.

We find that the efficiency of the current European Seaport's port-hinterland network can be improved by employing more centralized distribution structures. The current distribution structure is geared towards high service level with many local distribution centers serving regions within 50 km radius. Centralized distribution structures can potentially reduce the total logistics cost up to 12%, but also reduce the average service level of the system.

As the next step, we used the integrated model to analyze the impact of 2030 trade scenario on the volume of containers handled by ports in the Hamburg-Le Havre range. In this scenario, Eastern European and Northern African countries are expected to experience more growth than the rest of the European regions. The result of our experiment shows that Port of Rotterdam (PoR) and the other ports in the Hamburg-Le Havre range are foreseen to be negatively impacted by this trend, with the PoR experiencing the slightest impact in throughput. Through this experiment, we have demonstrated the efficacy of the model to estimate and explore the impact of port hinterland distribution networks on container throughput at the gateway ports in the Hamburg-Le Havre range.

3. How can we model plausible future structures of global maritime shipping networks to gain insight into the impact on port competitiveness?

The structure of the global shipping service network has a decisive influence on the competitive position of a port. Evidently, the global shipping network has a dynamic structure and continuously adapts itself to support changing world trade patterns. Predicting a certain future structure of the global shipping network is a challenging task. Rather than estimating a single structure, a more robust and promising approach is needed to estimate a range of plausible structures that determine port competitiveness.

Chapter 4 and 5 have presented novel models to explore alternative global shipping service networks. Specifically, in chapter 4 we developed a global maritime network model based on empirical observation and heuristics modeling the the emergence of direct shipping lines and its impact on port flows under global trade scenario in the year 2040. In chapter 5, we used a multi-level computation approach, modeling both shipping network structures and carrier choices to discover plausible structures for the global shipping service networks. This approach finds its roots in the 5-step aggregate freight modeling framework. Within this framework, we developed a service network design model and a worldwide container network choice model to represent supply and demand systems in global maritime container transport. Firstly, this approach computes the alternative structures for global shipping networks based on network design theories. Secondly, it describes the choice of the shippers to transport the containers over the network. These steps are iterated repeatedly until there is only a marginal improvement in the design objectives of the networks, namely total logistics cost and total network distance. A distinct feature of our approach is that it is computationally efficient. Computation results of a global scenario, involving more than 400 nodes can be obtained within one full day using a standard office machine.

By using the approach developed in chapter 5, we can demonstrate how alternative shipping network structures affect port competitiveness. Firstly, we apply the model to the Indonesian shipping network to demonstrate the ability of the model to find efficient network structures. Secondly, we scale up the application of the model to the global maritime shipping network. Special attention is given to investigate how these structures impact the total throughput and sea-sea transshipment flows of ports in the Hamburg-Le Havre range.

The results of the case study for global maritime networks show that the competitive position of the ports in the Hamburg-Le Havre range is strongly influenced by the structure of the global shipping service networks. Only in "continued globalization" scenario we see that port positions are relatively insensitive to network structure. Port positions are unstable in the

"local for local" and "regional production" scenario. This instability is volatile or unstructured in the "local for local" scenario and structured into two regimes in the "regional production" scenario.

We observe a general pattern where both throughput and transshipment of the ports share similar trends across different scenarios. That is, ports that are advantaged by the changing network structures normally show positive gain in both their throughput and transshipment and vice versa. In general, hub ports such as Rotterdam, Antwerp, Bremen, and Hamburg show relatively strong competitiveness across different scenarios. Only in certain scenarios, such as local for local and regional production scenarios, an interesting pattern emerged where smaller ports such as Le-Havre, Dunkirk, and Zeebrugge gain a significant rise in their transhipment or throughput volumes. These are scenarios where the network structure favors shorter transport distance over total transport cost, indicating a weaker presence of hub and spoke structures within the global shipping networks.

We conclude that plausible structures of the global shipping network and their impact on the competitive position of ports can be estimated using both a rule-based approach and a multi-level computation approach.

Finally, we revisit the main research question of this thesis:

What are designs of freight logistics network models that are suited to explore the impact of long-term changes in global container transport chains on the competitive position of the ports?

In this thesis, we address the absence of models for global container transport that take into account the changes in both the supply of service networks and the demand of freight transport. To answer the aforementioned research question and to fulfill the objective of this research, we have developed three different models (as presented in chapter 3,4, and 5) that explicitly take into account the supply and demand aspects of both the maritime and hinterland freight transport systems. Specifically, this thesis proposes a port-hinterland freight distribution network model in chapter 3; a global maritime network model for analzying the impact of the emergence of direct shipping lines in chapter 4; and a global shipping service network model for exploring efficient shipping networks and their impacts on the competitiveness of the ports in chapter 5.

In addition, we also find that the use of the currently available transport models is not such that it can lead to the development of robust policies for ports. Transport models are mostly used to analyse a limited number of scenarios. We argue that, to deal with uncertainties and complexity, these models should be used in an exploratory manner rather than a predictive manner. This also implies that the models need to be computationally efficient such that high number of experiments can be performed within reasonable amount of time.

To conclude, this thesis has shown that the use of exploratory modelling analysis, scenario discovery techniques, along with the development of policy analytic models for port-hinterland and global maritime shipping networks can offer a valuable support for port policy makers in formulating transport policies and planning. These models can be used

sequentially to provide better insights on the chained impact of uncertainties that propagate through the subsystems and to find policy answers for the relevant subsystems.

6.2   Policy implications

Drawing on the outcomes of this research, we formulate several policy implications for different stakeholders that are influential in creating transport policies and planning for port. However, it is noteworthy that since the investigations that are done with the detailed models are rather limited, the approach used in this research is not suitable to generate detailed policy measures and investment plans. The results presented in this research are mainly suited to give input to strategic discussions with regard to the development of measures to improve the competitiveness of ports in large economic regions such as European Union, the United States, China, India, ASEAN (Association of South East Asian Nation), UNASUR (The Union of South American Nations), AU (African Union), etc. Hence, our policy implications also take form in recommendations for further modelling exercises to identify more detailed policy measures.

Port Authorities

- *Develop measures to reduce the costs of port-hinterland access*
  Our analysis in chapter 2 on the key vulnerabilities of Rotterdam indicates that Rotterdam may lose throughput if it experiences an increase in hinterland travel times or a small reduction in costs for the ports in the Hamburg – Le Havre range. Factors that potentially contribute to the increase of travel times and costs are traffic congestion and peak loads caused by mega ships. To deal with this threat, Rotterdam should ensure sufficient capacity on access roads both within the port as on the wider national road network. Furthermore, adequate port gate planning could be established, such that truck traffic can be distributed across port operating hours, to avoid peaks.

  Regular patterns of cargo can also give better opportunities to consolidate containers using more economic transport modes such as train and inland waterways. To promote this modal shift, coordination with freight forwarders and logistic service providers is needed. The port can develop incentive schemes and efficient intermodal facilities that support the use of rail or inland waterways. Lastly, the national government also plays a leading role in investment projects in port-hinterland infrastructures such as rail and inland terminals. The model developed in chapter 3 can help to identify important economic regions that are connected to the port and explore how they are impacted by changes in global trade patterns.

- *Strengthen the position of Rotterdam as hub port by fostering cooperation with shipping alliances*
  The results of chapter 5 suggest that a substantial reduction in Rotterdam's container throughput can happen as shipping networks shift towards distance-led network rather than cost-led networks in the "local for local" scenario. In the real world, this can happen when the number of shipping alliances that call Rotterdam is reduced, causing Rotterdam to be less of a strong hub port in Europe. With the strong trend among shipping alliances to use mega ships, Rotterdam will lose substantial throughput when these mega ships decide not to call the port.

Therefore, to safeguard the role of Rotterdam as a hub port for these shipping alliances, Rotterdam can form a strategic cooperation with the alliances through different cooperation schemes. Examples of such cooperation might take form in prioritization on berth allocation to partner's ships, and port tariff reduction that is proportional to the call frequency and the total annual volume of containers loaded and unloaded by the ships. Moreover it is also important for Rotterdam to monitor the global trade scenarios that are currently happening together with their trends. In this way, the Port can adapt their strategies to the scenarios and be better prepared for the impacts of the foreseen changes in global trade patterns.

▪ *Assess the potential benefits of cooperation with hinterland distribution centres and inland terminals*

A measure that can be investigated further is to establish cooperation with distribution centers and inland terminals that connect the ports to their biggest hinterland market regions. These inland terminals and distribution centers can fulfill transhipment and storage functions for containers from and to the ports. A medium term cooperation can open up possibilities to provide unique services that can further increase the efficiency of the transport operations and the connectivity of the ports.

An example of this cooperation can take form in the synchronization of port gate scheduling systems with operation times of inland terminals or distribution centres. Information systems can be developed to inform inland terminals and DCs about the estimated arrival time of containers at the terminal, while the port can distribute the truck traffic going to the hinterlands more uniformly to avoid congestion. Furthermore, extending the operation time of DCs and inland terminals to off-peak hours in the evening would also help the port significantly to mitigate the effect of congestion. Eventually, this service can help strengthening the competitive position of Rotterdam so that it remains to be an attractive port for many liner shipping and freight forwarding companies.

Supranational government institutions

• *Establish further prioritization among ports within the Trans-European transport policy package (TEN-T)*

According to a report published by ITF/OECD in (OECD/ITF, 2015a), the way different national governments worldwide prioritize the development of certain national ports have indicated the employment of a national strategy to establish port hierarchy. The establishment of port hierarchy entails a strategic prioritization in the developments of all the ports of a country. Within this strategy, some ports can be designated to have a special role such as being gateway ports for international export/import activities while the others are merely secondary ports that function to facilitate transport flows of smaller local regions (OECD/ITF, 2015a). The hierarchy also determines which ports are of national importance or are of local/regional importance. The impact of this hierarchy can be significant if the ports that are of national importance also receive investment priority in national budget allocation. When successfully employed, port hierarchy can help to spend national budget on the most beneficial port infrastructure projects; to avoid having over or under investments on such projects, and to avoid negative competition between national ports.

The European Union has formulated a similar strategy in the Trans-European transport policy package (TEN-T) by designating no less than 104 core ports in the EU region. Although this policy has resulted in a comprehensive policy package for the core ports, it still lacks of focus in determining which ports should receive priorities. The increase of the number of the core ports from 83 to 104 has shown how the policy formulation process is also influenced by political interventions that are motivated by local interests rather than freight transport efficiency that is beneficial for broader public (OECD/ITF, 2015a).

The model presented in chapter 5 describes how changes in global trade patterns can impact global maritime shipping networks, and the flows at European ports. Hence, the model might offer technical support in determining further prioritization of port investments within the TEN-T policy package. Specifically, the model can be used to analyze the impact of different trade scenarios on port flows and to determine which ports and its corridors can be designated to form the core core port network in the EU.

- *Investigate the benefits and requirements of establishing shared European Distribution Centers and hinterland corridors*

    Chapter 3 shows that the use of more centralized distribution centers in Europe can lead to the considerable reduction of total logistics cost with a slight reduction in average service level. Furthermore, our model indicates that the current European port-distribution network is rather decentralized and fragmented, with different companies designing and operating their own distribution networks and facilities. While there are currently few incentives and many barriers to establish shared distribution centres, more research on the benefits and requirements to establish such a distribution system might be beneficial to enrich the perspective of different stakeholders and policy makers.

    The recent line of research on the Physical Internet (Montreuil, 2011) has offered a promising vision and solution to tackle the grand logistics sustainable challenge. Within the context of improving port-hinterland connectivity, the Physical Internet offers the notion of an open, connected, and shared port-hinterland distribution network which may significantly improve hinterland transport efficiency and sustainability. The section on future research provides more detailed recommendations relating to the development of models that apply the Physical Internet concept.

- *Foster discussion between relevant stakeholders that can create an organized and smooth progress in shared infrastructure developments*

    Although model-based analysis is valuable in understanding the impact of uncertainties faced by ports in an interdependent system, its contribution is still limited to the creation of insights about uncertainties. In order to treat uncertainties in the real world, a commitment from relevant stakeholders to cooperate with each other and implement adaptive measures is still needed. In fact, when the relevant stakeholders who are involved in the development of freight infrastructure systems can cooperate with one another, a considerable range of uncertainties can be reduced. For instance, when shipping companies can coordinate with the ports on the plan to use mega ships, the unknown negative impacts of such developments can be assessed prior to changes that take place. Such coordination can help to better prepare the

government, and port authoritiess to prepare and adapt the infrastructures smoothly such that negative effect such as congestion can be prevented.

6.3   Recommendations for further research

Recommendations for modelling port-hinterland freight distribution networks

1. Establish a database for port-hinterland international container flows and related storage activities

One of the main challenges we faced in this research was the limited availability of observed data related to international container traffic between ports and hinterland destinations, including storage activities of the transported goods. Such data is essential to calibrate more detailed port-hinterland distribution models. In light of this data shortage, we see the following data requirements, useful for future research:

- Volume of maritime containers handled at inland terminals and distribution centers, including their origin and destination.
- Employment data at the regions with distribution centers that is specifically related to containers that are transported between the ports and the distribution centers.

2. Investigate the benefits of the Physical Internet for port-hinterland distribution by extending current port-hinterland distribution models

The port-hinterland distribution network model proposed in this thesis can be further extended to create a model for an open, shared, and connected port-hinterland distribution network. Specifically, the neighborhood search algorithm within NSGAII routine can be modified to account for following structures:

- Each DC can be connected to any other DC(s)
- Each economic region can be connected to any open and shared DC(s)

The objective functions of the model may remain the same, that is minimizing the total logistics cost while maximizing the average service level of the whole port-hinterland distribution network. By comparing the total logistics cost of the currently observed port-hinterland network with one that applies the Physical Internet concept, we can gain an understanding of the values of such a distribution system. It is foreseeable that the complexity of the optimization problem will increase substantially due to the extended scope of the problem. In this case, the use of recently developed, state-of-the-art multi-objective evolutionary algorithms for large scale multi-objective optimization problems such as BORG (Hadka and Reed, 2015) or NSGA-III (Seada and Deb, 2015) can be investigated further. During the time when the port-hinterland distribution network model was developed, implementations of these algorithms were not yet widely available. Furthermore, we did not implement these algorithms because the optimization problem dealt in the model was in the scale that is solvable using our evolutionary algorithm which is based on NSGA-II.

Another valuable extension to the model is to take intra-European freight flows into account such as those from manufacturing plants to distribution centers, and eventually to the destinations. In this way, the design of the open distribution network will also be directed at serving intra-European freight flows. In order to do this, reliable data on exclusively intra-European Origin and Destination flows (i.e. non-maritime flows) would be needed.

Recommendations for modelling alternative configurations of global shipping networks
1. Modeling the formation of global shipping networks using agent based technology

A modelling technique that is increasingly being used in the transport domain is agent based modelling. Agent based models offer a modelling paradigm where real world logistics actors capable of devising their strategies individually are modeled as autonomous agents that can interact with each other. One of the main limitations of the network model developed in this thesis is that it simplifies the cooperation mechanism between liner shipping companies in estimating the emerging global shipping network structures.

ABM offers a promising way to address this limitation in a more rigorous and realistic manner by modelling each liner shipping company as an independent agent that can cooperate or compete with the others under a changing environment and over a certain time horizon. This is a unique approach that offers an alternative paradigm for simulating real world decision making processes. In this way, the emerging global shipping networks will be a result of dynamic interactions between the agents and their response to relevant transport policies. Moreover, behavioral models such as discrete choice models can be incorporated to ensure the use of established modeling theory.

2. Improving the reliability and efficiency of the current global shipping network models

In contrast to the first research direction, this direction moves along the lines of conventional transport modelling techniques which use static equation-based models. Unlike the dynamic, simulation-based approach, static models do not account for the changes in the behaviour of model elements in interacting with each other over time (Van Dyke Parunak et al., 1998). Nevertheless, static models offer the possibility to interpret the results of modelling exercises in a relatively straightforward manner. There are several promising directions for research that can be pursued to improve the reliability and the efficiency of the current model.

- *Modeling the emerging global shipping networks based on the predetermined plausible networks of the shipping alliances.*

An alternative way to model the aggregate global shipping network is by formulating it as a network optimization problem for all the major shipping alliances simultaneously. The shipping network of a shipping alliance is generally comprised of a set of port rotation schedules that is available publicly. Using this data, it is possible to enumerate a set of plausible ports that can potentially be called at in each of the schedules of the shipping alliance. This list of plausible ports can be determined by experts to include the most likely variations of the schedule. For instance, for a shipping alliance X, with 3 different routes, 3 lists of potential ports of call can be estimated. The decision to include a port in the list can be based on, for instance, the current trajectory of the route, the proximity of a candidate port to the route, the capacity, and the attractiveness of the port. Thus, when there are 5 major shipping alliances with 4 different routes for each alliance, 20 lists of potential ports can be enumerated. Next, a combinatorial optimization problem can be formulated where the objective is to find an efficient combination of shipping routes of all shipping alliances based on the total user transport costs and the total operational costs of the liner shipping

companies. Using this model, the impact of future global transport demand scenarios on the shipping routes and the port flows can be investigated

- *Calibrating the model based on observed global port to port container flows*
    As new global container flow data is becoming available through satellite-based monitoring technology, a better calibration of the choice model can be performed. Specifically, the model can be calibrated at the aggregate container flow level between ports rather than based on the throughput of the ports. This will increase the validity of the model.

- *Using parallel computation to overcome computation issues that arise from the scale of the model*
    Our experience with running the computation to estimate global shipping networks has shown the need to utilize parallel computing technology to reduce the total computation time. As stated in chapter 5, the network optimization involves more than 400 port nodes. Given the scale of the problem, even the most efficient algorithm will need more than 5 days to find satisfactory solutions when the computation is performed using a single processor. Implementing a parallel computation routine within the population-based search algorithm like genetic algorithms is technically feasible and useful to cut computation time substantially.

Recommendations for further research that require a multidisciplinary approach

1. *Applying Exploratory Modeling Analysis (EMA) and a Scenario Discovery Approach (SDA) for both maritime and landside models*
    Chapter 2 has demonstrated the value of applying the EMA and SDA on the World Container Model. Specifically, the quantitative proof for the key vulnerabilities of Rotterdam would not have been possible without this combination. A similar approach can be applied on the port-hinterland and shipping network model. In this way, we can gain a more detailed insight on the causes and impacts of unpredictable changes, within both hinterland and maritime subsystems, on port competitiveness.

2. *Integrating Spatial Computational General Equilibrium Models into the global freight transport model*
A valuable extension for the models developed in this research is the incorporation of an economic model such as a SCGE model into the freight transport model. This integrated model can be a powerful tool to estimate both transport and economical impacts of planned policy measures. Chapter 3 and 5 have shown how logistics aspects can be integrated into the freight transport modelling framework. However, we have not been able, within the scope of this thesis, to integrate the economic model that can describe and predict global trade patterns. This will require the implementation of interaction mechanisms between these models. Ideally, there is a dynamic feedback between the SCGE and the freight transport model, where the outcome of one model is used as an input for the other model and vice versa. Dedicated research is needed to implement a feedback mechanism, which is still functionally consistent with the 5–step modeling framework.

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Summary

The past couple of decades have seen a significant advancement in human's ability to cooperate and trade across the world. Between the year 2013-2015 alone, there are more than 130 million TEU of containers moved across worldwide shipping routes while ports handled more than 650 million TEU container movements. All of these developments are made possible through the advancement of information and communication technology, international standardization, trade liberation, and inter-continental shipping system. The result of this ongoing process is what we consider as globalization.

Unfortunately, globalization does not only bring positive impacts but it also creates new risks and challenges. The formation of long chained processes in global production and consumption activities has brought dependency in the economy and transportation system between countries to an unprecedented level. Changes in one element of the system due to unpredictable developments can cascade rapidly, affecting the other elements of the systems. Consequently, if one element in the chain fails to deliver its function, a disastrous consequence can impact other elements in the system pervasively.

A visible example can be seen in the impact of China's economic slowdown in the past couple of years on global container transport. The decline in China's imports combined with the current overcapacity of mega-ships has caused liner shipping companies to suffer from plunging freight rates, hitting its lowest level since the global economic crisis in 2009. This situation has forced shipping companies to be even more efficient in their operations. As a result, we see a continuing trend of the emergence of shipping alliances and the inevitable use of mega-ships to reduce operational costs further.

Impacted by these changes, major ports worldwide are faced with unprecedented challenges to handle higher volume of containers during the call of the mega-ships. Not only this has contributed to congestion problems in major ports in the west coast of the U.S., the high volume of cargo at peak times has also intensified congestions at port-hinterland connections. Another important issue that arises is the shift in bargaining power to the shipping alliances. A more coordinated network planning of the shipping alliances has created a situation where the ports are vulnerable to the changes in the network of these

alliances. Thus, it is evident that the chained effect of a change in global maritime shipping system eventually also impacts many landside logistic infrastructures such as ports, rails, roads, and terminals.

Among all strategic logistic infrastructures that face uncertainties, port is the most crucial logistic infrastructure which requires careful and comprehensive planning and policies. This is because port plays a central role as an interface between hinterland and maritime transport that facilitates global intercontinental trade. Consequently, it sustains economic growth of a country or even a region. Drawing insights from port development projects worldwide, it is not uncommon that the establishment and development of ports can impact the performance of national or regional economy. While under-investment in port infrastructure may lead to congestions and economic loss, over-investment is also undesirable to the economy. Specifically, over-investment may result in misallocation of public fund in less critical infrastructures and overcapacity in port infrastructure. This can be problematic as it can cause the port to be vulnerable to the decision of the liner shipping companies to call the port.

Therefore, given the strategic importance of port within the global freight transport system, this thesis is aimed at developing empirically grounded modelling approaches that can support the development of robust planning for ports and its connected infrastructures. As such, the main research question that is addressed in this thesis is:

What are designs of freight logistics network models that are suited to explore the impact of uncertainties in global container transport chain on the competitive position of the ports?

To answer this question, this research is comprised of several studies that address detailed research questions that can help answering the main research question. Specifically, we first studied how the impact of plausible uncertainties on ports can be systematically discovered and understood. This thesis shows there are many shortcomings that need to be addressed in the current method to analyze the impact of uncertainties on ports. To address this problem, we proposed scenario discovery approach to gain insight into the key vulnerabilities of ports in the Hamburg-Le Havre range. Next, the results of our studies pointed the need to study port-hinterland distribution system and global maritime shipping networks in greater depth. Unfortunately there are also gaps in freight models that can be used to analyze transport policies in large economic regions. As such, detailed models representing the maritime and hinterland sides of the ports are developed. Using these models we further study the impact of different scenarios on port competitiveness.

Discovering the impact of uncertainties in the global container transport system on European ports

The way many of the currently available models are used often do not lead to the development of robust policies for ports. Many of these models are used to analyze limited number of scenarios with extensive assumptions. We argue that, to deal with uncertainties and complexity, these models should be used in an exploratory manner rather than a predictive manner such that policies that are robust against unpredictable changes can be discovered and learned.

Chapter 2 addresses the question *How can we systematically identify the key vulnerabilities of ports that affect their competitive position*? In order to answer this question, we proposed a set of approach that combines exploratory modeling analysis, and scenario discovery study, to identify the key vulnerabilities of ports. As a proof of concept, we apply these approaches to Port of Rotterdam. It is found that the overall, the competitive position of Rotterdam is quite robust with respect to the various uncertain factors. The main vulnerability is the quality of the hinterland connections. A modest deterioration of the quality of the hinterland connections, resulting in increased travel time, will result in a loss of throughput for Rotterdam.

Modelling the Impact of hinterland distribution structure on port flows

An important insight obtained from scenario discovery study presented in chapter 2 is that hinterland connectivity of port of Rotterdam plays a crucial role in determining the competitive position of the port in the Hamburg-Le Havre range. This finding calls for a deeper study on the factors that influence transport cost in the hinterland link of the port and how they will, in turn, affect the volume of containers transported through the port. Apart from operational cost factors such as congestion, and availability of mode of transport, a strategic factor that significantly determines hinterland transport routes and its associated costs, is hinterland distribution structure. The way the ports, distribution centers and destination regions are connected, determines the routing of the goods, shipment size, and eventually the cost associated with each of the routes. In order to analyze the impact of port-hinterland distribution networks on port flows, a strategic port-hinterland distribution network model is needed. However, there is no freight logistics model available for analyzing port-hinterland distribution networks.

Therefore main question that is addressed in this chapter is How can we design a freight logistics model that can explore the effects of port-hinterland distribution networks on port-hinterland flows?. In order to answer this question, a strategic freight modeling approach which takes location of distribution centers into account is developed. The model consists of two sub-models. The first estimates the inland distribution structures including distribution centers; the second estimates the global routing of container flows through maritime ports and hinterland modes.

We demonstrated the use of the model by estimating the European port-hinterland distribution network. Based on the estimated network structures, we obtained a performance metric that describes the connectivity of the ports to the hinterland destinations (particularly to the DCs). Section 3.2.5 provides an overview of the performance metric for current port connectivity. Throughout our experiments, it has been proven that port-hinterland container trade flows influences the port-hinterland distribution network.

As the next step, we used the integrated model to analyze the impact of the 2030 trade scenario on the volume of containers handled by ports in the Hamburg-Le Havre range. In this scenario, Eastern European and Northern African countries are expected to experience more growth than the rest of the European regions. The result of our experiment shows that Port of Rotterdam (PoR) and the other ports in the Hamburg-Le Havre range are foreseen to be negatively impacted by this trend, with the PoR experiencing the slightest impact in throughput.

Modelling the Impact of the Emergence of Direct Shipping Lines on Port Flows

The result of the scenario discovery study in chapter 2 also indicated the need to investigate uncertainties caused by changing global shipping networks. A research gap that has not been addressed in the previous chapters is on the impact of changes in shipping network services on port flows. To amend this gap, chapter 4 presents a modelling approach that aims to investigate the impact of the emergence of direct shipping lines on global port flows. Specifically, the model developed in this chapter is aimed to answer research question: "*How can we model plausible future structures of global maritime shipping networks to gain insight into the impact of these structures on port competitiveness?*"

As a first step to answer this question, we apply a methodology that can give a preliminary picture of the aggregated responses of shipping lines to the foreseen trends of growth. Firstly, we examine how direct shipping lines between two ports can emerge as a response to the change in the demand for transport. Secondly, as a study case, we investigate the influence of the emergence of these direct lines to European ports, in terms of port throughput. Thirdly, utilizing the model capacity and scale, we also analyze how the direct lines affect container flows distribution worldwide and how the port choice of the shippers is affected by these lines, particularly for big ports in the US, and East Asia.

In this study we discovered that annual transport of 200.000 TEU containers is a threshold value for the scale of transport between two ports above which direct shipping service would likely to emerge. We use this empirical observation to model the emergence of direct shipping services in 2040, where there is a high growth in trade. The results show that the emergence of new shipping lines would have a significant negative impact on the transhipment of the Port of Rotterdam and an overall negative impact on the ports in the Bremen – Le Havre range. Furthermore, our experiment also shows that big transhipment ports in East Asia such as Singapore and Shanghai are also severely impacted by this trend. Similarly, big ports in the US such as Port of Los Angeles and Port of New York seem to be also negatively impacted by these direct lines.

Modeling the impact of alternative configurations of global shipping network on container flows

Chapter 4 has investigated the impact of the emergence of direct shipping lines on the ports in the Hamburg-Le Havre range and on the global port flows. However, the analysis assumed that the previously established shipping lines would remain the same even in the case where container transport demand changes in the future. This is a gap that needs to be addressed as it has been indicated that global shipping networks evolve dynamically due to changes in the global trade patterns.

In order to provide a complete answer on the research question, posed in chapter 4, Chapter 5, proposes a new approach that amends the gap. Specifically, the approach presented in chapter 5 combines models for freight demand and service network design, going beyond single-company networks. We specify the demand and supply subsystems of the global freight transport system and propose algorithms to model plausible future states of the global network. In our approach we avoid having to model individual carriers and their clients, which reduces data needs and decreases run times.

In an application we study the consequence of global network changes on the ports within the North-Western European port range. We observe, amongst others, that the competitive position of the ports in the Hamburg-Le Havre range is strongly influenced by the structure of the global shipping service networks. We observed a general pattern where port positions are relatively insensitive to network structure in the globalization scenario. They are unstable in the local and regional scenario. This instability is volatile or unstructured in the local scenario and structured into two regimes in the regional scenario. Furthermore, in scenarios, such as local for local and regional production scenarios, an interesting pattern emerged where smaller ports such as Le-Havre, Dunkirk, and Zeebrugge gain significant increase in their throughput. These are scenarios where the network structure favors shorter distances over total transport cost, indicating a weaker presence of hub and spoke structures within the global shipping networks.

Conclusions and Recommendations

In summary, this thesis has proposed modelling approaches to support the development of robust policies for ports. Specifically, we show that the use of scenario discovery approach together with strategic transport models that are consistent with the 5- steps modeling framework can offer valuable insights into the impact of uncertainties at global level. Given that ports are part of a global transport networks with interdependencies and uncertainties in its elements, a conventional approach to policy making using microscopic freight models in predictive manner will fail to account for the impact of changes in the broader components of global container transport system.

The models we proposed in this thesis are designed to analyse and support formulation of policies for large economic regions that often have connected infrastructures. Furthermore, these models are also designed and implemented such that large exploratory runs are possible to be performed to allow scenario discovery study. The applications of the models on case studies in ports in Hamburg -Le Havre range and some major ports worldwide have demonstrated the value of the models to derive insights that are useful to improve the efficiency of the global container transport system. Moreover, the models proposed also address a major gap in freight modeling literature by taking into account both the logistic aspects and freight demand behaviors in describing the spatial pattern of global container flows.

Based on this research several further research avenues can be formulated. Firstly, it is possible to expand port-hinterland distribution network model proposed in this thesis to study the potential solution for grand logistics challenges such as the physical internet. Secondly, parallel computing technology can be utilized to reduce the computation time of the model. Another exciting yet ambitious research direction would be to model the emergence of global shipping networks using agent based technology. Thirdly, the work with scenario discovery study presented in this thesis can be expanded for both maritime and port-hinterland networks, also taking into account the interaction between global transport and trade.

Finally, this thesis also formulated several policy implications for port policy makers, and especially for port of Rotterdam. It is evident that both the function of Rotterdam as a hub port and its hinterland access quality are strong determinants for its competitiveness in the Bremen – Le Havre range. Therefore, Port of Rotterdam needs to ensure that time and

cost related to their hinterland transport to remain at a desirable level. Furthermore, in order to retain their function as a hub port, Rotterdam needs to safeguard their cooperation with shipping alliances in a fair and sustainable manner. This may entail the development of cooperation schemes that are attractive for the shipping alliances yet consistent with the public values of the ports. Example of such scheme can be in the form of tariff reduction based on the frequency of calls of the ships.

At the supranational level, our research outcomes also indicate that there is a potential to improve the efficiency of port-hinterland transport in the Europe. However, much of this improvement requires trans-national cooperation and coordination to streamline the supply chain process for international container flows. Examples of such coordination may take form in the further prioritization for core port networks in Europe within the Trans-European Transport Network (TEN-T) policy package. Another form of coordination can be in the establishment of shared distribution centers across Europe that can help reducing the cost of hinterland transport further.

Samenvatting

In de afgelopen decennia zijn de mogelijkheden van de mens om samen te werken en te handelen over de hele wereld sterk toegenomen. Alleen al in de periode 2013-2015 is wereldwijd meer dan 130 miljoen TEU aan containers verscheept, terwijl havens meer dan 650 miljoen TEU aan containers hebben overgeslagen. Al deze ontwikkelingen zijn mogelijk gemaakt door de vooruitgang in informatie- en communicatietechnologie, internationale standaardisatie, vrije handel, en een intercontinentaal scheepvaartsysteem. Het resultaat van dit voortdurende proces is wat we globalisering noemen.

Globalisering brengt helaas niet alleen positieve resultaten, maar het schept ook nieuwe risico's en uitdagingen. De ontwikkeling van lange wereldwijde ketens van productie en consumptie heeft de onderlinge afhankelijkheid van nationale transportsystemen vergroot tot een niet eerder vertoond niveau. Het falen van één element van het systeem door onvoorspelbare ontwikkelingen kan indirect alle elementen van het systeem beïnvloeden.

Een zichtbaar voorbeeld is de impact van China's economische stagnatie in de afgelopen jaren op het wereldwijde transport van containers. De afname van de wereldhandel gecombineerd met de huidige overcapaciteit in de maritieme transportmarkt heeft gezorgd voor scherp dalende vrachtprijzen. Deze situatie heeft scheepvaartmaatschappijen gedwongen om nog efficiënter te worden in hun uitvoering. Hierdoor blijven we een trend zien van opkomende consolidatie van reders in allianties en een verdere schaalvergroting via mega-schepen, om operationele kosten verder terug te brengen.

Grote havens worden vanwege deze schaalvergroting geconfronteerd met de uitdaging om steeds grotere aantallen containers tegelijk te verwerken. Dit leidt niet alleen tot congestieproblemen, maar ook tot een toenemend aantal opstoppingen op achterlandverbindingen. Een ander belangrijk issue is de verschuiving van onderhandelingsmacht van havens en overheden naar scheepvaartallianties. Een verandering in het maritieme scheepvaartsysteem heeft zo een domino-effect op veel logistieke infrastructuur zoals havens, spoorwegen, wegen en terminals.

Onder alle strategische logistieke infrastructuur die onderhevig is aan onzekerheden, is een haven de meest cruciale logistieke infrastructuur die zorgvuldige beleidsontwikkeling

vereist. Een haven speelt een centrale rol als interface tussen achterland en maritiem transport, en ondersteunt daarmee de economische groei van meerdere landen. Zowel een te hoog als een te laag investeringsniveau kan problematisch zijn. Terwijl een te laag investeringsniveau kan leiden tot opstoppingen en economisch verlies, kan overinvestering resulteren in misallocatie van publieke middelen in minder kritieke infrastructuur en overcapaciteit in haven-infrastructuur. Beide kunnen problematisch zijn, omdat het een haven kwetsbaar maakt voor de beslissing van reders om de haven wel of niet aan te doen.

Gegeven het strategisch belang van een haven binnen wereldwijde goederenvervoernetwerken, is dit proefschrift daarom gericht op het ontwikkelen van empirisch gegronde modellen die het robuust plannen van havens en de daarmee verbonden infrastructuur kan ondersteunen. De hoofdvraag van dit proefschrift is:

Wat zijn ontwerpen van goederenvervoermodellen die geschikt zijn om de gevolgen van onzekerheden in het containertransport op de concurrentiepositie van zeehavens te verkennen?

Dit onderzoek is samengesteld uit deelonderzoeken die ieder ingaan op gedetailleerdere onderzoeksvragen, die ons helpen bij het beantwoorden van de hoofdvraag. Wij hebben allereerst onderzocht hoe de impact van onzekerheden op havens systematisch geanalyseerd kan worden. Dit proefschrift toont aan dat er veel tekortkomingen zijn die aangepakt moeten worden in de huidige methoden. Concreet hebben wij een *scenario discovery* benadering ontwikkeld om inzicht te verkrijgen in de voornaamste kwetsbaarheden van havens in het gebied tussen Hamburg en Le Havre. De resultaten van ons onderzoek wezen ons vervolgens op de behoefte om de relaties tussen het distributiesysteem in het achterland en het maritieme scheepvaartnetwerk diepgaander te bestuderen. Helaas zijn er ook tekortkomingen in goederenvervoermodellen die gebruikt kunnen worden om transportbeleid in grote economische regio's te analyseren. Daarom hebben we enkele gedetailleerde modellen ontwikkeld die het maritieme systeem en het achterlandsysteem zowel apart als gezamenlijk weergeven. Gebruikmakend van deze modellen hebben we de impact van verschillende scenario's op de concurrentiepositie van havens onderzocht. Hieronder bespreken wij de verschillende deelstudies en de corresponderende hoofdstukken van het proefschrift in meer detail.

De impact van onzekerheden in het wereldwijde containervervoer op Europese havens

De manier de huidige goederenvervoermodellen gebruikt worden leidt niet tot de ontwikkeling van robuust beleid voor havens. Ze worden gebruikt om een beperkt aantal scenario's te analyseren met een omvangrijk aantal aannames. We betogen dat, om om te gaan met onzekerheden en complexiteit, deze modellen op een verkennende wijze gebruikt zouden moeten worden en niet op een voorspellende wijze zodat beleid dat robuust is tegen onvoorspelbare veranderingen geïdentificeerd kan worden.

Hoofdstuk 2 gaat in op de vraag: '*Hoe kunnen we op systematische wijze de voornaamste kwetsbaarheden van havens identificeren, die hun concurrentiepositie beïnvloeden?*'. Om deze vraag te beantwoorden, hebben we een benadering voorgesteld die *exploratory modeling* en *scenario discovery* combineren. Om de praktische haalbaarheid aan te tonen, hebben we deze benaderingen toegepast op de haven van Rotterdam. Onze belangrijkste bevinding was dat de algehele concurrentiepositie van Rotterdam robuust is met

betrekking tot de verschillende onzekerheidsfactoren. De voornaamste kwetsbaarheid is de kwaliteit van de verbindingen met het achterland. Een gematigde verslechtering van deze kwaliteit, gemeten in reistijd, zal resulteren is een verlies van overslag in Rotterdam.

Modelleren van de impact van achterland distributienetwerken op overslag

De bevinding dat de haven vooral kwetsbaar is voor haar bereikbaarheid vanuit het achterland vraagt om een diepere studie van verschillende aspecten van het achterlandtransport. Behalve aspecten zoals congestie en beschikbaarheid van transportmodaliteiten zijn distributiestructuren een strategische factor die de transportroutes en de daaraan verbonden kosten bepalen. De manier waarop havens verbonden zijn met distributiecentra en bestemmingsregio's, bepaalt de routes, de transportvolumes en uiteindelijk de kosten verbonden aan elk van de routes. Om in staat te zijn de impact van achterland distributienetwerken op havenoverslag te analyseren, dient een model ontwikkeld te worden die deze relaties kan leggen.

De hoofdvraag van dit hoofdstuk is daarom *'Hoe kunnen we een goederenvervoermodel ontwerpen die de impact van haven-achterland distributienetwerken op de overslag voor het achterland in kaart kan brengen?'*. Om deze vraag te kunnen beantwoorden is een strategisch vrachtvervoer-model ontwikkeld die het gebruik van distributiecentra als hubs in deze netwerken beschrijft. Het model bestaat uit twee sub-modellen. Het eerste model maakt een inschatting van de mogelijke distributienetwerken; het tweede model maakt een inschatting van de vervoersstromen tussen zeehavens en deze netwerken.

We hebben de bruikbaarheid van het model aangetoond door het toe te passen op het Europese haven-achterland distributienetwerk. Gebaseerd op geschatte netwerkstructuren, hebben we een prestatie-indicator verkregen die de connectiviteit tussen havens en regio's in het achterland beschrijft. In onze experimenten is aangetoond dat de ruimtelijke oriëntatie van handelsstromen de lay-out van de distributienetwerken beïnvloedt.

Als een volgende stap hebben we het geïntegreerde model gebruikt om de impact te analyseren van een economisch scenario voor handel in 2030 op het overslagvolume van de havens in de Le Havre-Hamburg range. Oost-Europese en Noord-Afrikaanse landen zullen in dit scenario naar verwachting meer groei ondervinden dan andere Europese regio's. Het resultaat van ons experiment laat zien dat de haven van Rotterdam en andere havens in het gebied van Hamburg tot Le Havre negatief beïnvloed zullen worden door deze trend, echter met de minste impact voor de overslag in de haven van Rotterdam.

Modelleren van de impact van de opkomst van directe verbindingen tussen havens op overslag

Het resultaat van de 'scenario discovery' studie in hoofdstuk 2 onderstreepte ook de noodzaak om nader onderzoek te doen naar veranderende wereldwijde scheepvaartnetwerken. Een hiaat in het onderzoek tot zover is de impact van systematische veranderingen in wereldwijde scheepvaartdiensten op de overslag. Om dit hiaat ten delen op te vullen, presenteert hoofdstuk 4 een eenvoudig empirisch model om de impact te berekenen op overslag van de opkomst van directe lijndiensten. Het model is ontwikkeld om de volgende onderzoeksvraag te beantwoorden: *'Hoe kunnen we aannemelijke toekomstige structuren van*

wereldwijde scheepvaartnetwerken modelleren en inzicht verkrijgen in de impact van deze structuren op de concurrentiepositie van havens?'.

Als een eerste stap om deze vraag te beantwoorden, richten wij ons op de geaggregeerde reacties van lijnvaartmaatschappijen op de verwachte verdere groei van handelsstromen. Ten eerste onderzoeken wij wanneer directe diensten tussen twee havens opkomen in relatie tot de verandering in de vraag naar transport. Ten tweede onderzoeken wij als 'case study' de invloed van de opkomst van directe diensten op relaties wereldwijd. Ten derde analyseren wij hoe deze diensten de keuze voor een bepaalde haven bepalen in het bijzonder voor grote havens in de V.S. en in Oost-Azië.

Uit ons onderzoek blijkt een de jaarlijkse volume van 200.000 TEU een drempelwaarde te zijn voor de schaal van transport waarbij het waarschijnlijk is dat rechtstreekse diensten gaan ontstaan. We gebruiken deze empirische waarneming om het ontstaan van rechtstreekse diensten te modelleren in 2040, afhankelijk van de toename in de handel. De resultaten laten zien dat er een significante negatieve impact is op de overslag van de haven van Rotterdam en een algehele negatieve impact op de havens in het gebied tussen Bremen en Le Havre. Verder laat ons experiment ook zien dat grote overslaghavens in Oost-Azië zoals Singapore en Shanghai de gevolgen van deze trend ondergaan. Grote havens in de V.S. zoals de haven van Los Angeles en de haven van New York lijken op soortgelijke wijze negatief geraakt te worden door deze directe diensten.

Modelleren van de impact van alternatieve configuraties van het globale scheepvaart netwerk op containerstromen

De analyse in Hoofdstuk 4 ging uit van de veronderstelling dat de eerder opgerichte diensten hetzelfde zouden blijven, zelfs in het geval dat de vraag naar containervervoer verandert in de toekomst. Het is echter waarschijnlijker dat wereldwijde scheepvaartnetwerken mee-evolueren met de handelsontwikkelingen.

Om een vollediger antwoord te kunnen geven op de onderzoeksvraag die gesteld is in hoofdstuk 4, vult hoofdstuk 5 de analyse aan met een bredere benadering. Deze benadering combineert modellen voor vraag naar goederenvervoer en het ontwerp van servicenetwerken en gaat verder dan de netwerken van één bedrijf of één herkomst-bestemmingsrelatie. Wij specificeren vraag en aanbod subsystemen van het wereldwijde goederenvervoersysteem en stellen algoritmes voor om aannemelijke toekomstige toestanden van het netwerk te modelleren. In onze benadering vermijden wij het modelleren van individuele bedrijven en hun klanten, hetgeen de hoeveelheid data reduceert en de benodigde simulatietijd vermindert.

Als toepassing onderzoeken we de consequenties van de meest belangrijke netwerkveranderingen op de havens in Noordwest Europa in verschillende geografische scenario's. Wij nemen onder andere waar dat de concurrentiepositie van havens in de Le Havre-Hamburg havenrange sterk beïnvloed wordt door de structuur van de scheepvaartdiensten. Wij zien een algemeen patroon waar de posities van havens relatief ongevoelig zijn voor de netwerkstructuur in een scenario van voortdurende globalisering. Ze zijn echter minder stabiel in het geval van een toename van de lokale of regionale handel. Deze instabiliteit is veranderlijk en ongestructureerd in het lokale scenario en gestructureerd in twee regimes in het regionale scenario. Verder kwam er een interessant patroon naar boven in deze scenario's waarbij kleinere havens zoals Le Havre, Duinkerken en Zeebrugge een

significante toename zien in hun overslag. Dit zijn scenario's waar de netwerkstructuur ten gunste komt aan havens die relatief korte afstanden bedienen.

Conclusies en aanbevelingen

Samenvattend stelt dit proefschrift modellen voor om de ontwikkeling van robuust beleid voor havens te ondersteunen. Meer specifiek laten we zien dat het gebruik van technieken voor *exploratory modelling* en *scenario discovery* samen met strategische transportmodellen waardevolle inzichten kan verschaffen over de toekomstige havenoverslag. Gegeven de vele afhankelijkheden en onzekerheden in wereldwijde handels- en transportnetwerken, waar havens een onderdeel van zijn, kunnen de conventionele, trendmatig voorspellende benaderingen onvoldoende rekening houden met grote veranderingen in containernetwerken in voor- en achterland. Via *scenario discovery* laten we zien dat deze veranderingen van groot belang zijn voor de toekomstige havenoverslag.

De modellen die we voorstellen in dit proefschrift zijn ontworpen voor de analyse en ondersteuning van de formulering van beleid voor grote economische regio's. Verder zijn deze modellen zodanig ontworpen en geïmplementeerd dat uitgebreide verkennende simulaties kunnen worden uitgevoerd. De toepassingen van de modellen op cases in de Le Havre-Hamburg range, alsmede enkele grote havens wereldwijd, hebben tot doel de waarde van de modellen te laten zien om inzichten te verkrijgen die nuttig zijn voor het verbeteren van de efficiëntie van het wereldwijde containervervoerssysteem. De modellen adresseren een groot hiaat in de literatuur van de wereldwijde goederenvervoermodellen, door de vraag naar goederenvervoer te koppelen aan zowel maritieme als logistieke achterlandnetwerken.

Gebaseerd op dit onderzoek kunnen verscheidene verdere onderzoeksrichtingen geformuleerd worden. Ten eerste is het mogelijk om het ontwikkelde haven-achterland distributienetwerkmodel verder uit te breiden, om onderzoek te doen naar grote logistieke uitdagingen zoals het fysieke internet. Een tweede, spannende en ambitieuze onderzoeksrichting is het modelleren van wereldwijde scheepvaartnetwerken, door gebruik te maken van *agent based* technologie. Ten derde kan het werk met *exploratory modelling* en *scenario discovery* worden uitgebreid voor zowel maritieme als achterlandnetwerken, daarbij ook rekening houdend met de interactie tussen wereldwijd transport en handel. Hierbij zal *parallel computing* technologie nuttig zijn om de rekentijd van het model verder te reduceren.

Ten slotte formuleert dit proefschrift een aantal implicaties voor de beleidsmakers van havens en voor de haven van Rotterdam in het bijzonder. Het is evident dat zowel de functie van Rotterdam als maritieme hub als de goede bereikbaarheid vanuit haar achterland sterke determinanten zijn voor haar concurrentiepositie in het gebied van Bremen tot Le Havre. De Rotterdamse haven moet daarom zekerstellen dat transporttijd en -kosten op een gewenst laag niveau blijven. Verder moet Rotterdam haar samenwerking met de scheepvaartallianties veiligstellen om haar functie als hub te behouden.

Op supranationaal niveau geven de uitkomsten van ons onderzoek aan dat er mogelijkheden zijn om de efficiëntie van het vervoer te verbeteren. Veel van deze verbeteringen vereisen echter internationale samenwerking. Voorbeelden hiervan kunnen zijn een gezamenlijke prioritering binnen het Trans-European Transport Network (TEN-T) beleid of het opzetten van gedeelde distributienetwerken door heel Europa, die de kosten van vervoer naar het achterland verder reduceren.

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