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Assessment of Capacity and Risk
A Framework for Vessel Traffic in Ports

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TRAIL THESIS SERIES

Xavier Bellsolà Olba

Assessment of Capacity and Risk: A Framework for Vessel Traffic in Ports

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A Framework for Vessel Traffic in Ports

Xavier Bellsolà Olba

Delft University of Technology, 2018

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A Framework for Vessel Traffic in Ports

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”Tot està per fer i tot és possible”
Miquel Martí i Pol

Summary

World globalization trends have led to a tremendous increase in vessel traffic over the last years with a direct impact on port traffic. The increasing vessel sizes combined with the restricted nautical infrastructure imply more difficult vessel manoeuvrability and higher vessel flows in ports. Despite the importance of these factors, there is no existent research addressing their impacts in port traffic. Hence, the assessment of vessel traffic is a key issue for the future in ports when designing new infrastructures, expansions or changes in the traffic strategies.

This research focuses on vessel traffic efficiency evaluation in ports with the motivation to contribute to the development of a methodology that combines capacity and risk. In order to achieve this objective, better understanding of vessel traffic was gained through the review and assessment of existing port simulation models, in-depth vessel traffic data analysis in ports and plenty of discussions with risk and navigation experts. Capacity and risk for ports are addressed through individual research first, which led to a variety of new methods to evaluate these topics. This research brings together both topics while providing a methodology for vessel traffic port assessment.

The state-of-the-art of port simulation models helped to identify the most relevant infrastructure design and navigational processes, which might condition the research on risk and capacity. This review revealed that detailed infrastructure, detailed traffic rules, encountering effects between vessels and navigational behaviour should be considered when modelling ports. The existing models are not suitable for both capacity and risk assessment. Thus, other models might be consider for that purposes. Future models should consider these features for a more realistic vessel traffic representation.

In relation to capacity, a new estimation methodology presents an approach to estimate the capacity of a port network. The use of several port traffic indicators reveals their relations. The proposed method considers the total number of trips and the ratio waiting time to service time as indicators. By developing variety of scenarios using a simulation model, trade-offs between these indicators were found from the results. The capacity was identified when the number of trips remain stable while the ratio waiting time to service time kept increasing. Further, the step-by-step process to estimate the nautical capacity of a port network was developed.

The local capacity of certain locations, such as intersections, might become a bottleneck for the overall traffic in a port. Because of this importance, research on this topic was developed and a new capacity estimation method for waterway intersections was proposed. This method identifies the conflicting interactions between different vessel directions, based on an analogy with the conflict technique for road intersection capacity estimation. As a result, the maximum amount of vessels that a certain intersection can hold, given a certain Origin-Destination (OD) table and traffic characteristics, is estimated by using any data, real or simulated. Two case studies in the Port of Rotterdam were developed using historical data. The method revealed that the traffic shares for different directions have a considerable impact on the final result, and the estimated value can be used for the assessment of waterway intersections.

In order to assess nautical risks in ports, a generic risk index was developed to quantify the risks over different port areas. The methodology developed considers aggregated and not individual vessel traffic risks as done before. The risk is defined by combining risk perception from nautical experts and their consequences. Based on expert risk knowledge and the definition of the relevant risk criteria in ports, experts were interviewed to derive the risk perception weights for each criteria. Given a time period, a scale of consequences is defined for each criteria, and the nautical risk index for every port area is obtained. Based on historical data, the risks in the Port of Rotterdam were quantified. This new risk quantification provides a methodology for analysing navigational risks in ports, including environmental, traffic, infrastructure and port control information. As an advantage, the method is not only based on historical data, and it can be used for forecasting risks for any port design and time period. Its application goes from the assessment of existing ports to the planning of port expansions or new ports.

The combination of vessel traffic capacity and navigational risks in ports is done with an multi-criteria decision making methodology. The methodology first identifies the main efficiency criteria. To generate a variety of scenarios a simulation model is used, which input and output is defined in relation to the criteria. The outputs from the simulation are used in a multi-criteria decision making method, considering unknown preferences from decision makers and the use of an attribute weighting method. This method provides different sets of weights that represents the unknown decision makers preferences. The method has been applied to the Port of Rotterdam, using a generic port traffic model from the company *Systems Navigator*. The methodology results in a wide range of different solutions to decision makers, who can use this results to support their choices when strategic and operational vessel traffic decisions should be taken. Decision makers can use these results for changes in traffic management strategies or changes in the port infrastructure.

In sum, this thesis gives new insights into the evaluation of vessel traffic in ports and provides methodologies to assess capacity and risk independently, and jointly. The use of both historical and simulated data enriches the different research steps performed and its applicability is proven through real case studies.

Samenvatting

Wereldwijde globalisatie heeft de laatste jaren geleid tot een enorme toename in het scheepvaartverkeer met een directe impact op verkeer in havens. De toenemende omvang van de schepen gecombineerd met de beperkte nautische infrastructuur impliceert verminderde wendbaarheid en hogere vaartuigstromen in havens. Ondanks het belang van deze factoren is er geen bestaand onderzoek naar de impact van deze factoren op het scheepvaartverkeer in havens. De beoordeling van het scheepvaartverkeer is dan ook een belangrijke kwestie voor de toekomst van havens wanneer nieuwe infrastructuur moet worden ontworpen, of wanneer uitbreidingen of veranderingen aan de verkeersstrategieën moeten worden gemaakt.

Dit onderzoek focust op de evaluatie van de efficiëntie van scheepvaartverkeer in havens met het doel om bij te dragen aan de ontwikkeling van een methodologie die capaciteit en risico′s combineert. Om dit doel te kunnen bereiken, is eerst een beter begrip van scheepvaartverkeer gecreëerd, middels de beoordeling van bestaande haven simulatiemodellen, een diepgaande analyse van data betreffende scheepvaartverkeer in havens en vele discussies met risico- en navigatie experts. Capaciteit en risico in havens zijn eerst apart onderzocht. Dit heeft geleid tot een variëteit aan nieuwe methoden om deze onderwerpen te evalueren. Dit onderzoek brengt beide onderwerpen samen, waarbij een methodologie is ontwikkeld waarmee scheepvaartverkeer in havens kan worden beoordeeld.

Het maken van een overzicht van bestaande simulatiemodellen voor havenscheepvaartverkeer heeft tevens geleid tot de identificatie van de meest relevante infrastructuur ontwerpen en navigatieprocessen, welke het onderzoek naar risico en capaciteit kunnen conditioneren. Dit overzicht onthulde bovendien dat bij het modelleren van havens aandacht moet worden besteed aan de gedetailleerde infrastructuur en verkeersregels, schepen die met elkaar interacteren en navigatiegedrag. De bestaande modellen zijn niet geschikt voor de beoordeling van zowel capaciteit als risico. Andere modellen zullen dan ook moeten worden ontwikkeld voor dat doel, waarbij de eerdergenoemde aspecten zeker moeten worden meegenomen voor een realistischere representatie van scheepvaartverkeer.

Een nieuwe methode is ontwikkeld om de capaciteit van een havennetwerk te schatten. Het gebruik van meerdere indicatoren die het havenverkeer beschrijven onthult hun relaties. De voorgestelde methode gebruikt het aantal ritten en de ratio tussen

wachttijd en tijd voor laden en lossen als indicatoren. Door een variëteit aan scenario′s te ontwikkelen en door te rekenen met een simulatiemodel zijn de relaties tussen de indicatoren in kaart gebracht. De capaciteit is geïdentificeerd als de situatie waarin het aantal ritten stabiel is, terwijl de ratio tussen de wachttijd en de laad- en lostijd toeneemt. Daarnaast is een stapsgewijze procedure ontwikkeld om de nautische capaciteit van het havennetwerk te berekenen.

De lokale capaciteit van specifieke locaties, zoals kruispunten, kan een knelpunt worden voor het verkeer in de haven. Daardoor is onderzoek omtrent dit onderwerp uitgevoerd waarbij een nieuwe methode om de capaciteit van kruispunten van vaarwegen te schatten is voorgesteld. Deze methode identificeert de conflicterende interacties tussen verschillende vaarrichtingen, gebaseerd op een analogie met de conflict-techniek voor de berekening van de capaciteit van kruispunten voor wegverkeer. Het resultaat is dat het maximum aantal schepen dat een kruispunt kan afwikkelen wordt berekend door gebruik te maken van data, historisch of gesimuleerd, gegeven een bepaalde herkomst-bestemming (HB) matrix en verkeerskarakteristieken. Twee casestudies in de haven van Rotterdam zijn uitgevoerd met historische data. De methode toonde aan dat de verkeersaandelen voor de verschillende richtingen een aanzienlijke impact hebben op het eindresultaat en dat de berekende waarde kan worden gebruikt voor de beoordeling van vaarwegkruispunten.

Om de nautische risico′s in (delen van) havens te kwantificeren is een generieke risico-index ontwikkeld. De ontwikkelde methode beschouwd geaggregeerde, niet individuele, scheepvaartverkeer risico′s zoals al eerder is gedaan. Het risico is gedefinieerd door het combineren van de risico perceptie van nautische experts met de gevolgen van deze risico′s. Op basis van de risicokennis en de definitie van de relevante risico criteria in havens zijn experts geïnterviewd om gewichten voor elk risico-perceptiecriterium te vinden. Op basis van een vooraf bepaalde tijdsperiode wordt een schaal gedefinieerd voor de gevolgen voor elk criterium. De combinatie van beide vormt de nautische risico index voor elk havengebied. Gebaseerd op historische data zijn de risico′s voor de haven van Rotterdam gekwantificeerd. Deze nieuwe manier van kwantificeren van risico′s vormt de basis voor het analyseren van navigatie risico′s in havens op basis van informatie over milieu, verkeer, infrastructuur, en havenmanagement. Een voordeel van de methode is dat deze niet alleen gebaseerd is op historische data. De toepassing van de methode reikt dan ook van de beoordeling van bestaande havens tot de planning van havenuitbreidingen en nieuwe havens.

De beoordelingscriteria capaciteit van scheepvaartverkeer en navigatierisico′s in havens worden, samen met eventuele andere factoren, gecombineerd middels een multi criteria beslissingsmethodologie. De methode identificeert eerst de belangrijkste efficiëntie criteria. Om een variëteit aan scenario′s te genereren wordt simulatiemodel gebruikt. De simulatieresultaten worden gebruikt in de multi criteria beslissingsmethodologie, waarin onbekende voorkeuren van beslissers worden meegenomen en waar gebruik wordt gemaakt van een attribuut-weging methode. Deze methode geeft verschillende sets van gewichten die de voorkeuren van de onbekende beslissers representeert. De methode is toegepast op de haven van Rotterdam, door gebruik te maken van een generiek havenverkeersmodel van het bedrijf *Systems Navigator*. De methode resulteert in een breed scala aan oplossingen voor beslissers, die de resultaten kunnen gebruiken om hun strategische en operationele keuzes betreffende het scheepvaartverkeer te onderbouwen. Beslissers kunnen deze resultaten gebruiken voor veranderingen in verkeersmanagementstrategieën of veranderingen in de haven infrastructuur.

Kort samengevat geeft deze thesis nieuwe inzichten in de evaluatie van scheepvaartverkeer in havens en voorziet in methoden om capaciteit en risico zowel onafhankelijk als gezamenlijk te beoordelen. Het gebruik van zowel historische als gesimuleerde data verrijkt de verschillende onderzoek stappen. De toepasbaarheid van de methode is bewezen middels echte casestudies.

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Chapter 1

Introduction

Growth in maritime transportation is linked to the globalization process. Some maritime trade routes exist since old times, such as the Silk Road or Arab Sea Routes. At the end of the 15th century the Turks disrupted the land trade route connecting Europe and Asia, and emerging European powers, such as Spain and Portugal, were forced to find alternative trade routes. Cristopher Columbus' expedition sailed to the west where he discovered America (1492), and Vasco da Gama's expedition sailed to the east through the Cape of Good Hope where a new trade route to India was discovered (1497). Britain, France and the Netherlands followed these alternative routes too, and with the improvement of sailing ships, getting larger and more efficient, the international trade and colonization lasted for a couple of centuries (Rodrigue et al., 2016).

The industrial revolution by late 18th century, with the first propelled maritime vessels, was a turning point for the growth of maritime transportation, and the first regular maritime routes connecting harbours worldwide were created during early 19th century. The construction of canals reduced international distances, such as the Suez (1869) and Panama (1914) canals, and the maritime circulation around the globe improved dramatically, with more trading routes and an increase in maritime traffic, as well as the development of new ports. From then on, vessels have kept growing in size and tonnage, economies of scale have reduced transportation costs, and containerization has contributed to the globalization of trade with huge positive economic impacts. Hence, ports have become hub locations with large transfers and processing of cargo from water to land and the other way around.

These maritime globalization trends have led waterborne transportation to a tremendous increase in vessel traffic over the last years with a direct impact on port traffic (see figure 1.1). The increasing vessel sizes, combined with the restricted nautical infrastructure which, in most of the cases, was not designed to accommodate these large vessels, imply that vessel manoeuvring in ports and waterways becomes more difficult and, at the same time, larger vessel flows bring higher navigational risks and larger waiting times for vessels in ports. Port infrastructures are complex to design and expand and they are not flexible to improvements mostly due to elevated construction costs and spatial limitations, such as natural protection or land already used for other purposes. Hence, the assessment of vessel traffic is a key issue for current and future ports when designing new infrastructures, expansions or changes in traffic strategies, and to predict whether and how future demands can be handled.

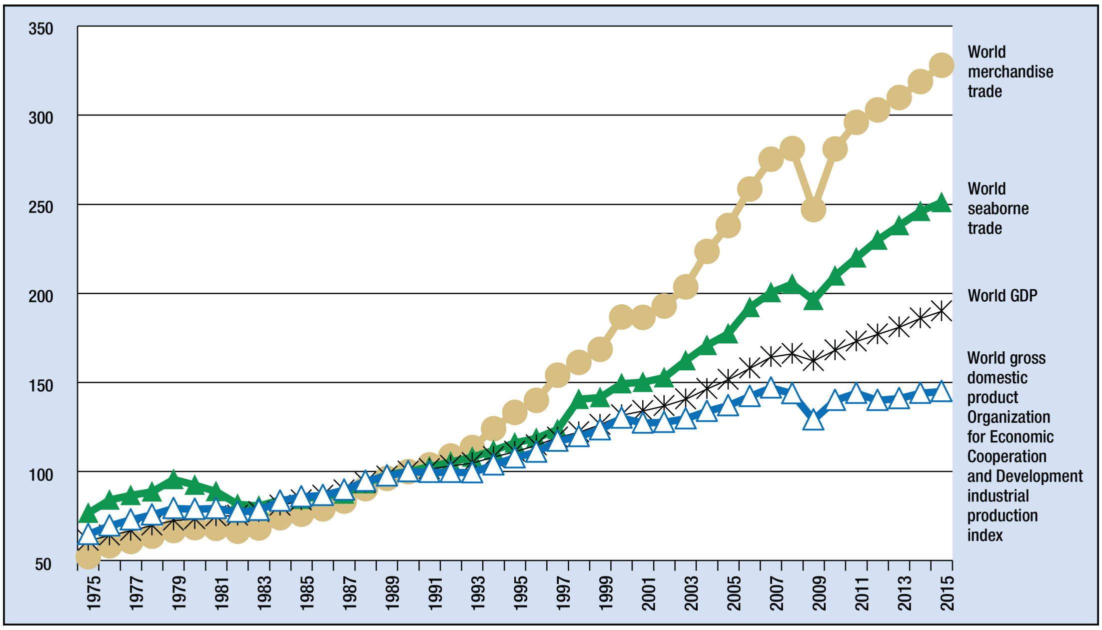

Figure 1.1: Organization for Economic Cooperation and Development industrial production index and indices for world gross domestic product, seaborne trade and merchandise trade, 1975–2015. Source: UNCTAD (2016)

Note: 1990=100. Indices calculated based on GDP and merchandise trade in dollars and seaborne trade in metric tons.

There are many disciplines to be considered when assessing ports in general, such as terminal performance, hydrology, geology and natural environment (Ligteringen and Velsink, 2012). The choice of relevant performance and assessment criteria, such as nautical risks, capacity or vessel emissions, are considered for the evaluation of current or future ports and their expansions. The combination of all these criteria for a joint use in a single methodology is complex and it has not been yet addressed. The development of new methodologies to help and support the corresponding decision makers or port designers in assessing port nautical traffic would be beneficial to evaluate different situation.

So far, research on vessel traffic in ports has mostly focused on the analysis of port risks and safety assessment (Pak et al., 2015; Yip, 2008), while other approaches considered vessel emissions (Chang et al., 2013) or terminal capacity (Daganzo, 1989; Stahlbock and Voß, 2007). However, the assessment of vessel traffic in ports based on the combination of several criteria and not only a single one has not been addressed yet. We live in a fast-paced technological era where innovations have contributed to the nautical field, as well as to port traffic. Since more than ten years, a tracking system needs to be installed on almost all sea-going vessels, the Automatic Identification System (AIS), that records their location, speed and characteristics. Thus, more nautical traffic related data becomes available for its in-depth analysis, which provides rich information about traffic patterns or risk of collision (Silveira et al., 2013), as well as vast information of individual sailing vessel behaviour (Shu et al., 2017). In depth analysis of AIS data is necessary for better understanding vessel navigation and operations within a port and how these data can be better used in the future. This data analysis should also reveal the necessary data to develop, calibrate and validate simulation tools or for the development and application of assessment methodologies.

Regarding the simulation tools, they have been extensively used in research for the simplified representation of complex processes. In relation to nautical traffic, several simulation models have been developed in the past with specific purposes such as risk assessment (Li et al., 2012). The choice of a model needs to be assessed for fitting the purpose of the research by including the adequate level of detail and the desired outcomes. The use of simulation models can help to the development of this research to test different scenarios.

The purpose of this research is to develop a generic assessment methodology of the nautical traffic in ports. By combining research on risk and capacity assessment approaches, two of the most relevant indicators for port decision makers, and the analysis of the information provided by AIS data contributes in revealing the important processes and criteria that can be derived from the data for the assessment of nautical port traffic. Capacity is chosen due to its relation to port performance, because all ports want to attract the maximum number of vessels. On the other hand, there is an increasing concern in keeping nautical risks below a certain threshold value by port stakeholders, with an increasing importance of a proper assessment of the nautical risks.

The methodology resulting from this research can help and guide port stakeholders or designers to assess ports when applying new traffic management strategies, and during the planning phase of new ports or when assessing different port expansions from existing ones. Moreover, its application can be adapted to also accommodate autonomous ships when these will become part of the traffic in ports.

1.1 Research objectives

As introduced in the previous section, the main objective of this thesis is the development of a methodology to assess nautical port safety and capacity that supports port decision makers either to make operational changes in traffic management with the current port designs due to changes in the vessel demand, or to better plan any new port or port expansion.

In order to fulfil the main objective of the research, several challenges should be addressed and the following research questions are formulated:

1. What are the characteristics of current port simulation models to represent the processes involved in vessel navigation? Are these models applicable to predict port risk and capacity? (Chapter 2)
   The relevant port processes and indicators to reproduce and assess vessel traffic in ports are reviewed and, based on them, the current simulation models are assessed. The review supports the choice of indicators related to nautical traffic, methods in different disciplines and the needs for the development of future models, and it is the starting point for developing new approaches and methodologies for risk and capacity assessment of vessel traffic in ports.

2. What is the definition of capacity for a port as a network of waterways? Which indicators and method are used to estimate the vessel traffic capacity of a port waterway network? (Chapter 3)
   In order to answer this question, we looked into previous literature in maritime traffic as well as other fields, such as road or rail traffic, to find an adequate capacity definition at an infrastructure network level. Moreover, the most suitable indicators for capacity estimation are identified, and relations between these indicators from simulation results are used for capacity estimation. From the outcomes of the previous steps, a method to estimate the capacity of a port network is developed.

3. Which method determines the capacity of an intersection of waterways? (Chapter 4)
   The local capacity of an intersection, which represents a small part of the network, might affect the capacity of a whole network. A formulation for this capacity exists for other transport modes, but not for nautical traffic. The review of existing capacity methodologies in other fields, combined with the analysis of vessel traffic data in intersections, is used to develop a new method to determine the capacity of an intersection of waterways.

4. Which criteria describe the navigational risks in a port? Which methodology quantifies nautical risks for port assessment? (Chapter 5)
   Since there are different criteria related to risk, the identification of the most relevant criteria is a key factor for port risk assessment. Based on these criteria, a critical review of risk assessment methodologies in relation to the requirements of vessel traffic helps to identify the features of the assessment method. Based on the definition of the desired outcomes, a suitable methodology for the assessment of nautical risks in ports is developed.

5. Which methodology combines multiple indicators to assess vessel traffic in ports with practical applicability? (Chapter 6)
   On the basis of the answers to the previous questions, a methodology to assess vessel traffic in ports combining risk and capacity indicators can be properly developed. The review of multi-criteria decision making methods helps to identify a suitable methodology for vessel traffic evaluation in ports. The methodology,

which includes the indicators previously identified, is used as a framework to test and assess several scenarios developed using simulation. Finally, the application of the methodology into a case study in the Port of Rotterdam shows its contribution to the decision making process and its applicability into the real world.

1.2 Research approach

The development of an assessment methodology of vessel traffic in ports that integrates capacity and risk indicators needs the use of different research methods. The research approach followed in this research is described in figure 1.2.

To answer research question 1, the port processes involved in navigation have been identified. These processes have been used to review existent simulation models with focus on which of these processes are included and how current models represent vessel navigation. An overview of port characteristics and a better understanding of vessel traffic has been gained to be applied in the rest of the research.

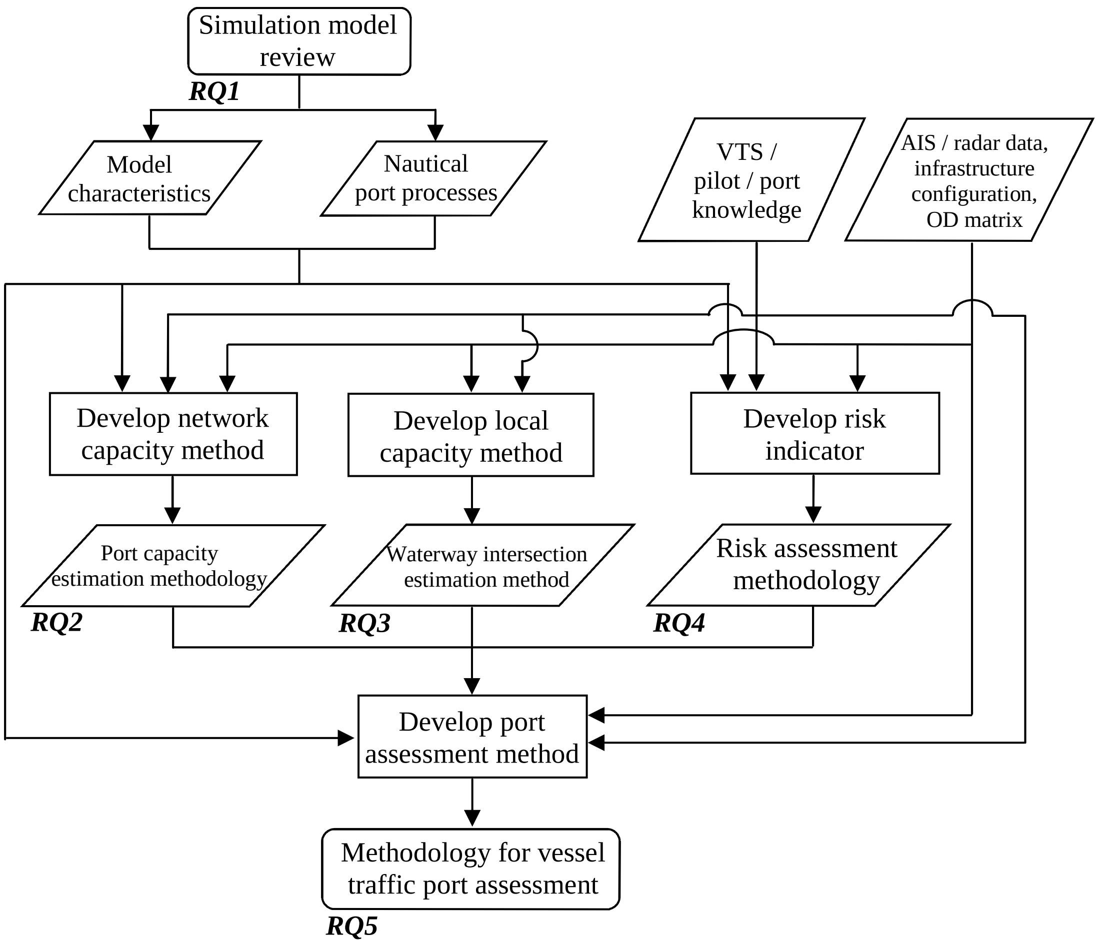

Figure 1.2: Research approach.

Another part of this research is the study of port capacity, which has been divided into network and local capacity of ports (research questions 2 and 3). Theoretical research into the foundations of the definitions of capacity of networks and intersections is used to define the scope of the research. To answer research question 2, the relations between the main indicators related to network traffic are combined to derive trade-offs between them. A structured method to estimate the capacity of a whole port is developed based on the relations between indicators and the identification of the limiting capacity of the port network. To answer research question 3, due to the similarity between road and waterway intersections, an analogy from the conflict technique method for road intersection is used. An in-depth AIS data analysis helps to identify similarities and differences between the two fields to derive and validate the method.

Research question 4 requires a review into the maritime risk assessment field to identify the risk criteria previously used. For developing a risk assessment methodology without dependency on historical data, expert knowledge is used. Through expert interviews the most relevant criteria are used to develop a new risk assessment methodology for ports. To develop this methodology, questionnaires are facilitated to VTS operators and pilots to gather their risk perception through in person or on-line questionnaires. Moreover, interviews with risk experts are used to define the consequences of these risks. The combination of the risk perception and consequence values is used to define and calculate the risk indicator and to develop the risk assessment method.

The last research question is approached by combining the previous research steps into an overall multi-criteria method. Multi-criteria decision making (MCDM) methods are extensively used to provide support in the decision process. The method considers the indicators previously identified for risk and capacity as assessment criteria of vessel traffic in ports. By defining the necessary input to represent properly vessel traffic in a port and to obtain the output criteria desired, a port simulation model is used to generate scenarios. The model is validated using real data and its robustness is verified. When decision makers' preferences are unknown, the use of an attribute weighting method provides different sets of weights for decision makers that can be used to compare the effect of different preferences. The use of these sets of preferences into a MCDM method provides the results for each scenario, which have been applied into a case study to analyse and evaluate the decision-making method.

1.3 Thesis contributions

This section presents the main contributions of the thesis. As outlined in the previous section, the research focused on gaining a better understanding and providing new approaches for the two main aspects in the assessment of port vessel traffic, which are risk and capacity. The research resulted in a method that includes both fields into a port assessment methodology. The achievements of the thesis are split into scientific and practical contributions.

1.3.1 Scientific contributions

A state-of-the-art overview of the existing port simulation models and their capabilities to simulate realistic vessel navigation and their application to port risk and capacity assessment. Through an in-depth literature review, the main port processes linked to nautical layout, such as anchoring or berthing, and the navigational behaviour characteristics, such as vessel navigation or fleet composition, are identified and categorized based on their relation to the realistic simulation of vessel traffic in ports. Furthermore, these processes are used for a qualitative assessment of the existent port models, which provides an overview of the characteristics in relation to realistic vessel navigation and their possible application for risk and capacity assessment purposes. (Chapter 2)

A new method to estimate the vessel traffic capacity of a port network. A definition of network capacity of nautical traffic is developed. Based on this definition, the method considers the most relevant indicators related to the capacity of a network of waterways. A wide variety of scenarios were simulated, which allow the analysis of trade-offs and relations between the indicators, and port capacity can be estimated. Based on the previous analysis, a methodology describes the steps to be followed to find the Port Network Traffic Capacity (PNTC) value of any port design for existent or new ports, given certain design of the nautical infrastructure and origin-destination trip matrix. (Chapter 3)

A new method to estimate the capacity of an intersection of waterways. The capacity of an intersection of waterways has been defined. Using the analogy between road and waterway traffic, a theoretical method based on the conflict technique used in road traffic has been developed. This approach combines the vessel flows shares per direction with a conflict matrix between directions, resulting in the capacity value of any intersection. The method can be applied to any intersection of waterways using real or simulated data, and case studies showed its applicability. The method was validated with a detailed data analysis of two intersections in the Port of Rotterdam. (Chapter 4)

A risk assessment methodology for vessel traffic in ports. A quantitative assessment methodology that provides a Nautical Port Risk Index (NPRI) has been developed, which can be used to assess nautical risks in different port areas for the desired time period. The methodology identifies the main navigational risk criteria according to pilots, who are experienced navigators. The NPRI is defined as a combination of all criteria, which includes the navigational risk perception from VTS operators and pilots to derive a risk perception value, and the knowledge from port risk experts to quantify the consequences of the risks. This index provides a quantification of risk over certain time periods and it allows the assessment of nautical risks in different areas over time. (Chapter 5)

A multi-criteria decision-making methodology to evaluate vessel traffic for port assessment. A methodology that combines multiple criteria to evaluate vessel traffic in ports was developed. The methodology uses the main assessment criteria for risk and capacity of vessel traffic in ports. These criteria are used to define the input required by a simulation model to create a variety of scenarios. The model provides the indicators to apply to a multi-criteria decision-making method and its further analysis. The method considers different preferences of decision makers and provides the results for the assessment criteria of the desired scenarios to be assessed. This methodology combines risk and capacity and reduces the complex decision process when multiple criteria are considered and they are dependent on each other. (Chapter 6)

1.3.2 Practical contributions

The structured multi-criteria methodology, combining capacity and risk indicators, helps decision makers to justify their choices based on their preferences without knowing in detail all complexity of the vessel traffic. This methodology can be used for strategic and operational decisions in relation to vessel traffic in ports. The results can be used to assess future changes in traffic management strategies or changes in the port infrastructure, such as port expansions or new traffic scenarios with autonomous ships.

The methodology developed includes different parts that can also be individually applied in studies with specific interests as described in the following paragraphs.

The PNTC methodology allows the estimation of the capacity of a port network from any simulation model. Port designers can use it in the planning and design phases of new ports or port expansions to assess different infrastructure layouts or changing terminal locations.

The capacity of an intersection of waterways can be derived from traffic-shares within different directions, which can be applied by port authorities or port designers to evaluate the future performance of intersections, given changes in demand, fleet or changes in destinations. Thus, different traffic management strategies can be assessed for any port intersection.

The developed nautical port risk index (NPRI) allows the risk quantification for each port area. The NPRI is based on expert judgement, both navigational and risk experts, which provides meaningful insight into the navigational risks. Due to its objective value, the index is suitable for comparison between different situations. Decision makers can use it as a support tool to assess their future decisions, either for changes in the current traffic management strategies or for new port designs or port expansions.

1.4 Thesis outline

This thesis consists of seven chapters (including this introduction). Figure 1.3 presents the outline of the thesis and the relations between the chapters. Chapter 2 presents an overview of port simulation models evaluating their ability to represent realistic vessel navigation. Port capacity is studied in chapters 3 and 4. In chapter 3, the most relevant capacity indicators are chosen to develop the Port Network Traffic Capacity estimation method, by analysing their trade-offs from simulation results. Chapter 4 develops a generic method to estimate the capacity of an intersection of waterways in ports, based on an analogy to the conflict technique for road intersections. The study of risk in ports is performed in chapter 5. The nautical port risk index (NPRI) is developed to assess the risk in port navigation over any period of time. Chapter 6 focuses on the combination of risk and capacity indicators and provides an approach to compare and assess them as a whole. Chapter 7 summarizes the main contributions, discusses the potential applications and provides recommendations for research directions in the field of nautical port assessment.

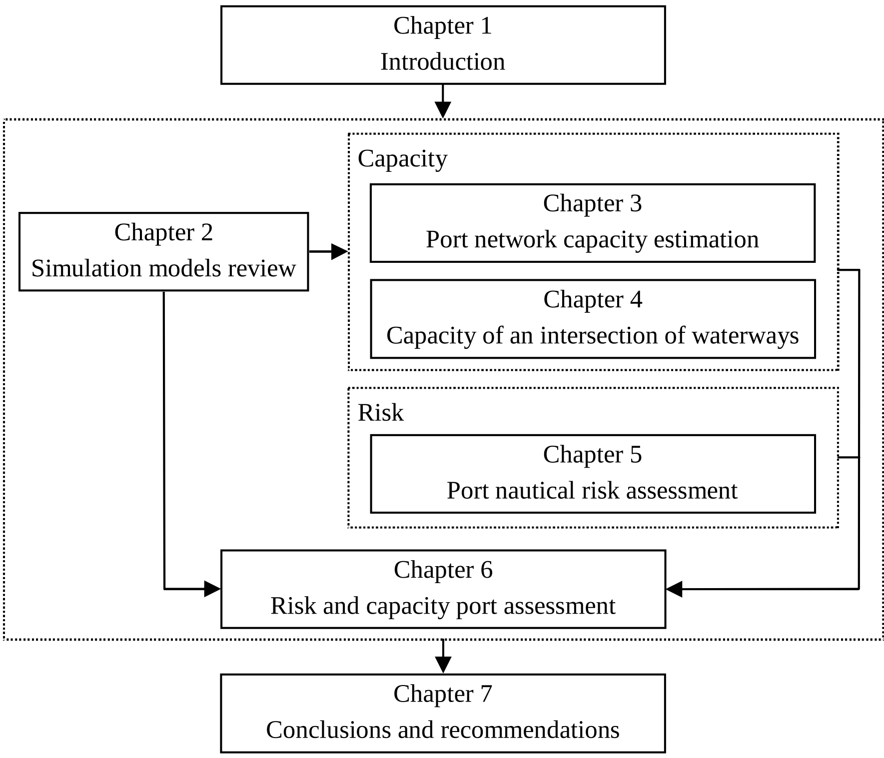

Figure 1.3: Outline of the thesis

Chapter 2

State-of-the-Art of Port Simulation Models

This chapter identifies the main navigational processes related to the port nautical infrastructure and provides a state-of-the-art of the current port simulation models for risk and capacity assessment. The models are qualified based on how operations are covered by each model and how they represent realistic vessel navigation. Future port simulation models should consider detailed infrastructure and explicit tug and pilot assistance, as well as detailed traffic rules.

This chapter is an edited version of the article:

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2018). State-of-the-Art of Port Simulation Models for Risk and Capacity Assessment based on the Vessel Navigational Behaviour through the Nautical Infrastructure. *Journal of Traffic and Transportation Engineering (English Edition).*

Abstract

Ports play an increasingly important role in the freight transportation chain due to containerization. High vessel flows and higher densities increase the relevance of the non-terminal related processes. Several simulation models have been developed in the recent decades with different goals, but their abilities to represent realistic vessel traffic in ports differ. In this paper, we identify the main navigational processes and operations related to the port nautical infrastructure, and review and assess the current port simulation models. This survey represents an exhaustive review of the state-of-the-art of simulation models for port assessment purposes focusing on safety and capacity. The model assessment focuses on the identification of the relevant criteria to represent vessel navigation, based on which processes are covered by each model and how they

have been considered in each model. The assessment covers the nautical infrastructure representation and the navigational behaviour. The outcome of this review will be used for the development of a simulation based port assessment methodology. Future port simulation models should include the suitable criteria for a more realistic traffic representation that allows a proper safety and capacity port analysis and assessment.

2.1 Introduction

Globalization is leading to a rapid growth in maritime transport, both in size and number of vessels. The world seaborne trade has increased substantially in the past two decades ((United Nations Conference on Trade and Development, 2013)). As shown by Ducruet and Notteboom (2012), the total port throughput has exponentially increased during the last 50 years, and it has been more than doubled just in the last 20 years. The increase in throughput is linked to more vessel movements. Since ports are quite inflexible infrastructures and difficult to expand, the situation has led to higher traffic densities and eventual congestions in some areas. Ports accommodate a higher traffic demand without a waterway infrastructure expansion that implies, in many cases, longer waiting times for vessels, which reduces the efficiency of the system. Because of this increasing demand and the limited nautical infrastructure (berths and sailing areas), vessel navigation related processes in the port become decisive for port performance. Existing ports might need be optimized or expanded and new ports have to be planned considering these limitations. In both cases, their safety and capacity, among other factors, should be guaranteed and tools to assess them in different designs are required.

Maritime transportation simulation models have been proven to be useful tools to represent port operations and processes to assess port performance. Several models have been developed during the last decades with many different purposes, such as strait or waterway performance or maritime risk assessment. Regarding traffic simulation in straits, several models represent navigation systems as queueing systems, with first in first out (FIFO) sequences (Golkar et al., 1998; Köse et al., 2003). Waterway traffic representation has been another subject of interest (Almaz and Altiok, 2012; Hasegawa et al., 2001; Xiao et al., 2013,1; Xu et al., 2015). In relation to risk assessment, a risk index-based model for vessels was developed, the SAMSON model (Safety Assessment Model for Shipping and Offshore on the North Sea), by MARIN (Maritime Research Institute Netherlands) (2015). Furthermore, a simulation model for vessel traffic based on ship collision probability has been developed (Goerlandt and Kujala, 2011). Moreover, there are models for detailed port representation and performance analysis (Bellsolà Olba et al., 2017; Groenveld, 1983; Scott et al., 2016; Thiers and Gerrit, 1998).

As described in the previous paragraph, there is a wide range of maritime simulation models with different purposes. In this paper, we present a state-of-the-art of port models and we assess their applicability to port risk and capacity assessment, as a base for the future development of a port assessment methodology based on a suitable simulation model. This research includes some models recently reviewed (Bellsolà Olba et al., 2015b) and models that have been developed since then. It includes, to the best of our knowledge, all the current non commercial port simulation models, which features are described in detail in scientific publications. The commercial models are excluded because their details and features are not available. In previous work, the most relevant processes involved in port navigation were identified a more comprehensive description is presented in section 2.2. Moreover, this paper reviews and assesses the models already developed on these processes in a more detailed level. The calibration of the models is an important step to ensure that they properly simulate real traffic. Hence, all the models have been assessed based on if they have been calibrated or not.

The outline of this paper is as follows. Section 2.2 describes the nautical processes in a port. Section 2.3 identifies all the required criteria for port traffic simulation. Section 2.4 describes the characteristics of the criteria identified. Based on these, the assessment of simulation models will be discussed in two parts, layout and navigational behaviour, in section 2.5. This paper concludes with a discussion of the results with an overall model assessment in section 2.6, and conclusions and remarks for future model development in section 2.7.

2.2 Port nautical processes

Ports are complex networks, both from an infrastructure and navigation point of view. This section describes the main processes linked to the nautical infrastructure necessary to represent the vessel traffic in a port and its evaluation (see figure 2.1).

Traffic processes in a port start when a vessel arrives and requests access. The Vessel Traffic Service (VTS) provides information about the berth availability and other conditions, such as weather or tide. If it is feasible to enter the port, the traffic situation is checked. Vessels with permission from the port authorities can enter the port and sail towards their destination. Otherwise, they wait outside the port in the anchorage until permission is given. Vessels with specific navigation requirements or limitations will need pilot and/or tug assistance.

Once a vessel is allowed to enter the port, it sails to a specific berth through the approach channel or entrance waterway. Until its arrival at the berthing area, each vessel will sail through different parts of the port, such as turning basins, crossings or inner basins. Each of these areas has specific requirements in sailing and manoeuvring, also depending on the vessel characteristics. Vessels can usually sail in any position inside each section of the port, but, to avoid groundings, there are some fixed corridors or paths for vessels with the deepest draughts.

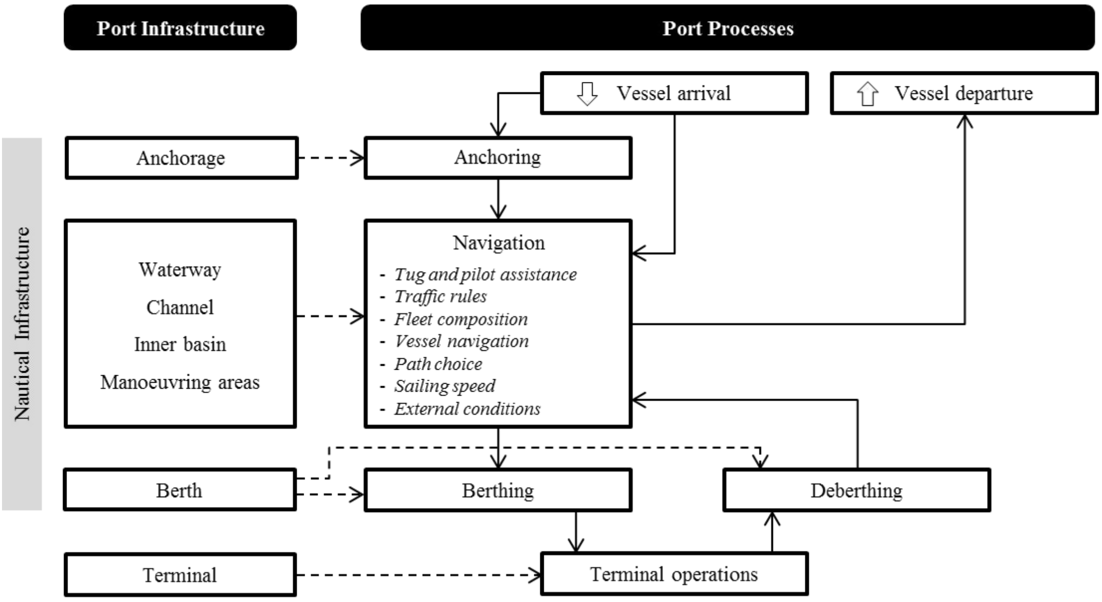

Figure 2.1: Diagram of port nautical infrastructure and processes.

After the vessel has performed all these steps, the berthing process is performed and loading/unloading operations start. These operations aim to control the movement and storage of cargo within the terminal and stacking area, entry/exit gates and rail or road connections. When the loading/unloading operations are completed, vessels are ready to depart; they are required to ask for new permission to leave the port or sail towards another berth. The reverse navigation process occurs when they are allowed to sail towards their exit.

2.3 Assessment methodology

Port simulation models have specific requirements to likely represent the overall vessel navigational behaviour. Hence, existing port simulation models (non commercial) are compared with respect to their current ability to represent the different traffic demands in a port and its associated processes. Figure 2.1 shows the representative port infrastructure parts and the main processes. The basis of comparison within this review is to assess each of the characteristics of port processes and vessel navigation that an ideal model should be able to replicate for capacity and risk analysis of a port. This study compares the capabilities of existing models, developed with different purposes, to provide a realistic representation of vessel traffic in ports. In the following paragraphs a description of the relevance of the attributes introduced in figure 2.1 is presented.

Since manoeuvring areas (where vessels make complex turns) or inner basins can become a key element in the performance of a busy port and their analysis should be possible, the inclusion of all nautical infrastructure parts is necessary. They can lead to substantial variations in the sailing process of a vessel and thus imply variations in sailing times. Detailed research in the anchoring process has already been performed and could be implemented to make this process more realistic (Huang et al., 2011). At least anchoring should not be considered as a simple queue process, where the influence of anchorage dimensions and vessel distribution does not affect its performance. In the same line, berthing processes are relevant and should be included as an independent parameter, from terminal operations in simulation models that aim to assess the vessel traffic performance. The rest of the terminal operations could be considered together.

The inclusion of tugs and pilots is necessary for any port simulation model. However, the best way to do that is not clear. Including their position at any time could make it more realistic but more time consuming, so it could be implemented with their dwell or idle times. Moreover, the number of tugs and pilots available should not be assumed to be infinite.

Explicit and detailed traffic rules can allow their assessment individually. A control and traffic verification agent has been shown to be relevant and should be considered (Xiao et al., 2013). A detailed implementation of these rules allows a more accurate analysis of the results. It might also help to identify hidden traffic management problems behind simulation results and new traffic management strategies could be implemented.

Vessel arrivals have been extensively discussed in previous research (Fararoui, 1989; Groenveld, 2001; Nicolaou, 1967; Noritake and Kimura, 1983; Pachakis and Kiremidjian, 2003; Thiers and Gerrit, 1998). It can be agreed that the most suitable distributions for new ports are negative exponential distribution (or Poisson and Erlang-1 as discrete distributions), with the desired and expected parameters. For existing ports, and thanks to AIS data availability, historical data analysis shows to be the best option to adjust the most suitable vessel demand. For new port vessel arrival estimation, AIS data from similar ports could be extrapolated to the new scenario, which would make the estimation closer to reality. Specific idiosyncrasies in vessel arrival process for each port should be taken into account, such as seasonality, because they could cause relevant differences in the final performance.

In terms of fleet composition, making clear groupings of vessels can lead to a more precise simulation model. The classification should be accurate and the different groups should be chosen based on their similarities in navigational behaviour. Although vessel speeds do not change instantaneously, the possibility of a model to include free speed choices and changing with time, fits better an accurate representation of vessel navigation in a port. In addition, the influence on vessel navigation of the infrastructure and encounters between vessels should be included. Free course choice and the influence of the infrastructure or other vessels on vessel navigation is really relevant to assess different situations and specific behaviours that might affect the safety of the port. The inclusion of human factors, such as bridge team behaviour, in the sailing path should be considered (Hoogendoorn et al., 2013). Moreover, there is an extensive research on vessel behaviour based on AIS data that should be used for new model implementation (Shu et al., 2012; Xiao et al., 2012). These features reassemble vessel navigation close to reality and consider all the specificities given certain infrastructure design and fleet compositions.

External conditions should be evaluated in each case, but a port model should have the possibility of including any option inside their structure. Tidal windows have an important effect on port processes and performance as an operational time limitation. Weather conditions, such as wind speed and direction, can also have relevant weight in vessel traffic navigation, depending on the location of the current study (Thiers and Gerrit, 1998). These conditions should be considered as behavioural effects on vessel behaviour and some correlations can be obtained based on AIS data analysis with different weather scenarios. Another important condition that can be crucial for navigation is current.

Based on the different relevant criteria described, the assessment is divided into two parts: the first part considers the nautical infrastructure representation according to which criteria can be modelled and how detailed is each of the processes according to our purposes, plus the assistance and the traffic rules that applied in the navigation; the second part is related to how navigational characteristics are modelled and how close the simulation resembles to reality. All port infrastructure parts, and the corresponding processes, which are summarized in figure 2.1, should be included in a model, which are: 1) nautical infrastructure, 2) anchoring, 3) berthing and 4) terminal(s) operations, 5) pilot/tug assistance and 6) traffic rules. Moreover, the main criteria that affect navigation depending on each type of vessel are: 1) vessel arrival process, 2) fleet composition, 3) influence of infrastructure design or vessel encounter on the navigation, 4) course choice possibility, 5) speed variation, 6) external effects and 7) model calibration. Thus, these criteria are used as a basis for the assessment criteria in the next section, and below are explained.

The information about each of the simulation models used in this review is obtained from the published papers describing them. Since the authors of this paper do not have the models available, we assume that the description of the simulation models presented in the papers agrees with their real implementation.

2.4 Assessment criteria for port simulation models

A detailed description of all criteria, both related to port infrastructure or navigation, identified in the previous section are presented in this section. Their influence on port nautical infrastructure processes and traffic is described and a rating system is chosen for each element in order to compare the different models.

2.4.1 Nautical layout assessment

This section describes the criteria used for the assessment of the infrastructure design in the simulation model. These are the nautical infrastructure, the anchorage, the berths, the terminal operations, the tug and/or pilot assistance and the traffic rules considered.

Nautical infrastructure

The nautical infrastructure in ports is divided into channels (the main waterway for this type of models), inner basins and crossings or manoeuvring areas. Each of these areas has specific navigational characteristics and traffic rules that, in reality, lead to differences in navigation. Due to these differences through each part of the infrastructure, the model capability to simulate realistic port traffic highly depends on the parts which are considered. Hence, the simulation model is expected to represent them too.

Models will be classified in this part depending on the inclusion of the infrastructure for modelling vessel traffic behaviour in the different parts of the infrastructure realistically, therefore the following scheme is used:

A	Anchorage	M	Manoeuvring areas
W	Waterway / Channel	B	Berth
I	Inner basin		

Anchorage

As the competition between ports increases, all processes should be optimized and vessel arrival processes, such as the anchorage allocation or the entrance to the port, become crucial and these processes need to be minimized. However, few research into anchorage capacity, definition or assessment, has been done. Literature shows only a couple of recent studies were addressing this topic (Huang et al., 2011; Verstichel and Berghe, 2009).

In order to improve the current situation and give the importance that anchoring spots have, from captains and ship masters experience, Huang et al. (2011) concluded that vessels usually tend to stay close to each other. In addition, due to anchorage complexities, they adapted disc-packing algorithms to optimize the specific vessel allocation in an anchorage, based on the ship lock optimization problem. The captains decision in choosing an anchoring position was included in order to make the algorithm more realistic.

Each model will be classified with a rating system as follows, and which level of detail should be required for this process, for a suitable port risk assessment, will be discussed in section 2.5.

✓ ✓	Anchorage allocation algorithm, detailed infrastructure and manoeuvring
✓	Anchorage with dimensions and vessel sailing
✓ / χ	Anchorage with dimensions and vessel time allocation within the model
$\sim$	Queueing system without dimensions within the model
χ	No anchorage within the model

Berth

As the previous section introduced, the importance of each process in port performance is crucial for minimizing costs and dwell times. For this reason, vessel berthing has been an important process studied in detail by several researchers. A topic of interest has been berth allocation (Alvarez et al., 2010; Arango et al., 2011; Fararoui, 1989). However, this is a process more related to vessel arrival optimization than analysing the vessel berthing process and its dwell time, depending on its characteristics.

There are different levels of detail to describe the berthing process, since it can be seen as one process with a dwell time associated (Bellsolà Olba et al., 2017; Scott et al., 2016; Yeo et al., 2007) or, on the contrary, the different steps of the berthing process and their related manoeuvring can be included, such as speed reduction, tug assistance and mooring ropes (Okazaki et al., 2009). The details for this process can be relevant when considering busy basins or waterways. At certain locations, due to specific traffic situations, berthing manoeuvring can become a bottleneck for port processes or can have higher risk than expected. Although, from a higher level of analysis, berthing can be less relevant, a complete implementation of the different processes involved would give a more realistic performance of the system.

The aim of the comparison of the berthing processes is to identify how berthing time and manoeuvring is simulated for each of the models. The rating scheme used to classify it is as follows:

✓	Berthing manoeuvring process
✓ / χ	Berthing process simplified (no manoeuvring modelled)
χ	No berthing

Terminal operations

There is extensive literature related to terminal operations, its optimization and improvement. An extensive review on crane and terminal optimisation was developed by Stahlbock and Voß (2007). Related to terminals, researchers have also focused on terminal simulation modelling (Hassan, 1993; Kia et al., 2002). Terminal operations analysis and simulation comparison are out of the scope of this paper. However, since the berthing process can be included as part of the terminal operations, it is important to know how these operations has been considered in different models. Thus, even though the simulation is not detailed, there is a need to include all the different tasks separated to not forget any characteristic of the port. In order to classify them, the following scheme is proposed:

✓	Detailed terminal operations
✓ / χ	Joint terminal operations
$\sim$	Joint terminal and berth operations
χ	No terminal operations

Tug and pilot assistance

Ports often have restrictions on navigation for several types of vessels because of their dangerous cargo or difficult manoeuvring characteristics, that require assistance by tugs or a pilot to assure safe navigation inside the area. Although each port usually has a certain number of tugs and pilots, some models consider an unlimited number of them as a simplification. The level of detail of the assistance cannot be assessed from the descriptions. Hence, models are rated depending on the following considerations:

✓	Limited number of tugs and pilots
∼	Unlimited number of tugs and pilots
χ	No tug and pilot assistance

Traffic rules

Traffic rules in ports usually follow the rules of the International Maritime Organization (IMO) plus their own specific rules due to their specific design characteristics. As mentioned before, VTS centres control if vessels follow these rules and that they do not initiate dangerous situations. These rules are directly related to risk and safety levels, and the more detailed they are, the better the risk assessment can be carried out.

The inclusion of the traffic rules in the models can be at different levels of detail and they have been classified according to the parameters considered below.

H	Minimum headway with predecessors
E	Encountering priority rules
S	Speed reduction during encounters
O	Overtaking possible when right traffic conditions
C	Crossing priorities
?	Unknown / Not specified

2.4.2 Navigational behavior assessment

The second group of assessment criteria focuses on attributes that has influence in the vessel navigational behaviour. The attributes considered are the vessel arrival process, the fleet composition, the vessel navigation itself, the course choice for vessels, the sailing speed, the external conditions affecting navigation and the model calibration.

Vessel arrival process

The first process in a port is the vessel arrival, which will condition the berth allocation and terminal planning. This is a complicated dynamic process that compromises waiting times and vessel queues. There is not an extensive amount of research publications focused on the arrival process itself, since it is a difficult process to evaluate.

The arrival process is dependent on the shipping lines in a port which can determine, more or less, scheduled arrivals. However, external factors as weather conditions or engine failures can affect this regularity. Due to the variety of operators in a port and these external factors, the most common situation is a random arrival process. A negative exponential distribution (N.E.D.) has been statistically proven to reasonably correspond with this kind of arrival, as a continuous distribution (Fararoui, 1989; Groenveld, 2001; Noritake and Kimura, 1983; Pachakis and Kiremidjian, 2003), or with its discrete derivation as a Poisson distribution (Nicolaou, 1967; Thiers and Gerrit, 1998). Different vessel arrival patterns for individual shipping lines were analysed by Van Asperen et al. (2003). Equidistant arrivals, stock-controlled arrivals already scheduled and Poisson distributed arrivals were compared to evaluate their effects on port performance.

The correlation between vessel arrivals and approximations for queueing systems were developed in the specific case of marine bulk cargo ports (Jagerman and Altiok, 2003), and it was proven that there is a negative correlation of the arrival instant between two consecutive vessels. Hence, when two consecutive vessels arrive in a short time interval, the following vessel is expected to arrive in a longer time interval. When a shipping line has a regular service, vessel inter-arrival time distribution mainly follows the Erlang-k Distribution (Kuo et al., 2006). In these cases, contrary to assumptions in other studies, arrivals are not independent.

For the simulation of processes in ports, vessel arrival becomes a relevant parameter that has to be properly considered since it can condition the design of a new port or the expansion of an existing one. For existing ports, a good representation of vessel arrival patterns, based on historical data, can help to improve traffic scheduling or traffic management.

The most suitable choice would be to base the vessel arrival on a prediction from historical data, considering the stochasticity of the arrival process. However, in case of not having historical data, the most appropriate choice is a N.E.D. as explained before.

Each model will be classified depending on the way that vessel arrival is performed:

N	Negative exponential distribution (NED)
P	Poisson distribution (discrete NED distribution)
E	Erlang-1 distribution
H	Historical data

Fleet composition

In navigation, the behaviour of each vessel is different. Their different sizes and weights influence their movements and speeds, as well as braking times or rudder angles. Fleet composition in the models has been rated depending on their ability to simulate different type of vessels.

✓	Different types of vessels
χ	Unique vessel type

Vessel navigation

Vessel navigation can be affected by the nautical infrastructure design or encounters with other vessels. Models will be classified in this part considering the simulated behaviour, if the vessel interaction with both infrastructure and other ships have been included to resemble real situations, just the interaction in encountering situations, or none of them.

✓	Vessel navigation influence in encounters and due to the infrastructure design
∼	Vessel navigation influence in encounters
χ	No vessel navigation influence

Course choice

Vessel course choice, or path change, during navigation between two points is a complex element to simulate. This path depends on several parameters, such as bridge team behaviour or external conditions. The precision of the models according to real vessel sailing behaviour is related to their manoeuvring behaviour during this process. Previous research showed that ship dynamic manoeuvring can be modelled (Sutulo et al., 2001). Moreover, the human behaviour in vessel manoeuvring can also be modelled and it makes more realistic the vessel navigation (Hoogendoorn et al., 2013).

The assessment of their ability to dynamically choose a random course or modify their course due to human behaviour is rated as follows:

✓ ✓	Dynamic freedom of movement, course choice and crew behaviour at each time step
✓	Dynamic freedom of movement and course choice per time step
∼	Movement fixed, but path generated at the beginning for each vessel
χ	Fixed movement and course with same path for all vessels

Sailing speed

During the navigation process, vessels change their speeds and their maximum and minimum speeds are different from other types of vessels due to their physical characteristics. In the simulation models, due to the computational complexity of representing these accelerations or decelerations, different algorithms have been adopted. There are different possibilities that can be applied, as free speed choice and variation during sailing, the use of several specific fixed speeds according to each specific situation or port area, or sail with a unique speed. According to this speed choice, each model has been classified with the following scheme:

✓	Free speed choice
∼	Several fix speed choices
χ	Unique speed

External conditions affecting navigation

External conditions are a constraint parameter on daily port performance. Each simulation model has its own specifics and researchers have considered different criteria. The vessel navigation specifications of the models might change due to the effect of different conditions. The different external conditions are listed below and their inclusion in the models will be assessed in the comparison tables.

V	Visibility
S	Storm
W	Wind
T	Tidal conditions
C	Current
χ	No external conditions

Model calibration

Model calibration is an important part of any simulation model to be able to reassemble to reality. A realistic port simulation model should fit real vessel routes. Hence, the use any kind of data, such as AIS, for calibration and validation of the models is assessed.

✓	Model calibration
χ	No model calibration

2.5 Port simulation models review and assessment

Port navigational processes are difficult to describe analytically. For this reason simulation models have been developed in maritime transportation. Most of them do not represent the whole infrastructure and/or processes. Moreover, each of the models have a specific application, such as port/terminal operations and logistics, vessel traffic, risk simulation or hydrodynamics. Simulation models developed with other purposes are also considered in this assessment because, even with a different application, there is not an extensive amount of port simulation models and these ones can be used for comparison of their navigational approach.

In this section, to the best of our knowledge, the existing port related simulation models (non commercial) are compared in relation to the criteria described in section 2.4. A brief assessment of each model is presented below. Table 2.1 summarizes the ratings of infrastructure related criteria from models developed specially for ports, while the ratings of the navigation related criteria are presented in table 2.2. All simulation models are micro-simulation models simulating single vessel units and their microscopic properties such as position or velocity.

Table 2.1: Nautical infrastructure layout assessment.

Nr.	Model	Nautical infrastruct.	A	B	TO	TPA	Traffic rules
1	Harboursim (Groenveld, 1983)	A W I M B	~	✓/χ	✓/χ	✓	H E S O C
2	(Park and Noh, 1987)	A W I M B	✓/χ	✓/χ	✓	✓	?
3	(Hassan, 1993)	A W I M B	~	✓/χ	✓	✓	H E S
4	(Thiers and Gerrit, 1998)	A W I M B	✓	χ	✓	✓	H E S O C
5	(Demirci, 2003)	A W I M B	χ	✓/χ	✓/χ	~	?
6	(Yeo et al., 2007)	A W I M B	~	χ	~	χ	H E S O C
7	(Almaz and Altiok, 2012)*	W	✓	χ	~	χ	?
8	(Piccoli, 2014)	A W I M B	~	χ	~	~	H E
9	(Ugurlu et al., 2014)	A W I M B	~	✓/χ	✓/χ	✓	?
10	(Bellsolà Olba et al., 2017)	A W I M B	~	χ	~	χ	H
11	(Scott et al., 2016)	A W I M B	~	χ	~	χ	?

* Waterway model

Abbreviations: Title: A = Anchorage, B = Berth, TO = Terminal operations, TPA = Tug and pilot assistance

Nautical Infrastructure: A=Anchorage, C = Channel, I = Inner basin, M = Manoeuvring areas, B = Berth.

Traffic rules: H = Minimum headway with predecessors, E = Encountering priority rules, S = Speed reduction during encounters, O = Overtaking, C = Crossing priorities.

Since each model has different characteristics, the ratings for each model are discussed in the following paragraphs. From the whole simulation models assessed, five of them have other applications than port simulation, such as a bay (Hasegawa et al., 2001), a gulf (Goerlandt and Kujala, 2011), a waterway network (Huang et al., 2013), a waterway channel (Rayo, 2013; Shu et al., 2015; Xiao, 2014) or a multi-bridge waterway (Xu et al., 2015). Since literature in port simulation models is rather limited, these non-port related models are included in the analysis. Because of their application to different locations rather than a port, the models are not able to cover the port infrastructure, and thus the nautical infrastructure layout assessment is not possible for them. However, these models have been assessed in relation to the navigational behaviour.

2.5.1 Model 1 - *Harboursim (Groenveld, 1983)*

The first model assessed is Harboursim (Groenveld, 1983), which is one of the earliest existent port simulation models. The model is detailed and quite complete in relation to the infrastructure. All infrastructure parts are included in the model, though the anchorage is just considered as queuing system. Moreover, a complete range of weather conditions and different types of vessels, without different behaviours, are modelled. On the other hand, vessel navigational characteristics are simplified, such as fixed speeds, no vessel interaction and course choice. The vessel arrival distribution is NED and includes seasonality. This simulation model has been extensively used for port planning and extension, e.g. the Port of Rotterdam extension case (Groenveld, 2006).

Table 2.2: Navigational behaviour assessment.

Nr.	Model	VAP	FC	VN	CC	SCC	EC	C	Goal
1	Harboursim (Groenveld, 1983)	N	✓	χ	χ	∼	V W T C S	χ	Port planning and expansion.
2	(Park and Noh, 1987)	N	χ	χ	χ	χ	χ	χ	Port planning, expansion and economic analysis.
3	(Hassan, 1993)	H	✓	χ	χ	χ	T	χ	Port planning, expansion and economic studies.
4	(Thiers and Gerrit, 1998)	P	✓	∼	χ	✓	T	χ	Port planning and expansion.
5	(Demirci, 2003)	N	✓	χ	χ	χ	χ	χ	Investment planning.
6	(Yeo et al., 2007)	P	χ	χ	χ	χ	χ	χ	Evaluate port traffic congestion.
7	(Almaz and Altiok, 2012)	H	✓	χ	∼	χ	T	χ	Delaware River simulation.
8	(Piccoli, 2014)	E	✓	χ	χ	χ	T	χ	New port simulation assessment.
9	(Ugurlu et al., 2014)	D	✓	χ	χ	χ	S	χ	Port handling capacity, efficiency and queues.
10	(Scott et al., 2016)	H	✓	χ	χ	χ	V W T	χ	Hidrodynamic impact on port economics.
11	(Bellsolà Olba et al., 2017)	D	✓	χ	χ	∼	χ	χ	Port capacity estimation.
12	(Hasegawa et al., 2001)	H	✓	✓	✓	✓	χ	χ	Vessel traffic in a bay.
13	(Goerlandt and Kujala, 2011)	P	✓	χ	∼	χ	χ	χ	Assess risk in vessel navigation.
14	(Huang et al., 2013)	H	✓	∼	∼	χ	χ	✓	Waterway network simulation.
15	(Rayo, 2013)	N	✓	χ	χ	∼	V W T	χ	Approach channel assessment.
16	(Xiao et al., 2013)	χ	χ	✓	✓	✓	W T C	✓	Assess risk in vessel navigation.
17	(Shu et al., 2015)	χ	χ	✓	✓	✓	χ	✓	Realistic vessel sailing behaviour.
18	(Xu et al., 2015)	H	✓	✓	∼	∼	V W C	χ	Multi-bridge waterway assessment.

Abbreviations: VAP = Vessel arrival process, FC = Fleet composition, VN = Vessel navigation, CC = Course choice, SSC = Sailing speed choice, EC = External conditions, C = Calibration.

2.5.2 Model 2 - *(Park and Noh, 1987)*

The bulk port operations model, developed by Park and Noh (1987), shows a complete layout structure, with detailed terminal operations but excluding manoeuvring areas. Also the traffic rules are not specified. However, the navigational behaviour is non-existent. Other modules, such as economic analysis, or inland transport mode inside the model, show that the focus of this model is more extensive than the previous one, but the external conditions are not included. As in the previous model, the arrival distribution is NED.

2.5.3 Model 3 - *(Hassan, 1993)*

Hassan (1993) developed a complete simulation model for ports, including the nautical infrastructure, cargo-handling operations, warehouse operations and inland transport. Although, the infrastructure design is not as detailed as in the Harboursim model, it has the main parts as well as explicit availability of pilot and tug assistance, and simplified traffic rules such as minimum headway, encountering priority or speed reduction during encounters. Course choice, vessel influence or weather conditions are not included. Only tide is included as external condition. Vessel arrival distribution is obtained based on available historical data. As the previous model, this model has a broad scope, shown by the level of detail of the navigational module.

2.5.4 Model 4 - *(Thiers and Gerrit, 1998)*

This model, developed for the Port of Antwerp by Thiers and Gerrit (1998), has a detailed layout configuration that allows the representation of all infrastructure parts except the berthing, which is included as a dwell time. However, interaction between vessels is simplified using speed reduction, based on collision avoidance and safety rules. The navigation is not realistic, with linear course not influenced by encounters. Vessel arrival follows a Poisson distribution and detailed traffic rules are specified. In addition, the model was validated based on observations from pilots on whether waiting times occur in a new infrastructure which had been previously simulated.

2.5.5 Model 5 - *(Demirci, 2003)*

Demirci (2003) developed an overly simplified model in order to cover all processes in the whole port and supply chain, including nautical, cargo (loading/unloading), terminal and hinterland operations. Since the purpose is to analyse the port processes for investment planning, the model does not reproduce real traffic processes.

2.5.6 Model 6 - *(Yeo et al., 2007)*

A model for marine traffic congestion evaluation of the port of Busan was developed by Yeo et al. (2007). The model includes the main infrastructure, such as channel, manoeuvring areas and anchorage, together with simplified traffic rules. No terminal operations are included. In this model, the Poisson distribution is used to generate the vessel inter-arrival times. Behavioural navigation factors are not considered, just different priorities are given for ships.

2.5.7 Model 7 - *(Almaz and Altiok, 2012)*

A more recent model to simulate vessel traffic in Delaware River (U.S.A.) was developed by Almaz and Altiok (2012). The goal of this model is to represent traffic in the river with several anchorages and berths. Although the infrastructure is not like a port, it is close enough to assess it. Berthing processes are not specified; they are assumed to be with the terminal operations. One relevant improvement in this model, in comparison with the previous models, is a specific course generated for each vessel based on AIS data analysis. This improvement leads to a more realistic model, though a change in the vessel course, influenced by the waterway or other vessels. Thus, the differences in encounters according to the paths can be used for risk assessment. Vessel arrival is obtained from historical AIS, including seasonality. Weather conditions are not included due to the low influence expected by the authors.

2.5.8 Model 8 - *(Piccoli, 2014)*

Another port specific model reviewed in this paper was developed to assess the port nautical infrastructure processes (Piccoli, 2014). The infrastructure is described in a simplified way, considering the berthing process and terminal operations as a joint process. The anchorage is considered to be a single queue, which does not represent the real manoeuvring time. There are traffic rules inside the model and the number of pilots and tugs are assumed to be unlimited, which can lead to an unexpected higher vessel traffic than if just considering a real amount of them and their required times for changing from one vessel to another. With respect to navigational behaviour, there are no weather conditions or influence between vessels or infrastructure that affects course choice.

2.5.9 Model 9 - *(Ugurlu et al., 2014)*

Recently, a queueing simulation model for ports was developed to compare the queues generated for different scenarios in a port with four terminals with loading arms (Ugurlu et al., 2014). The navigation processes for vessels are considered as a sequence of queues to reach their berths and to get served. The main goal of this model is to determine the handling capacity and usability of a port terminal. There is no vessel interaction, speed variation or course choice. One relevant issue considered in this model is the limited number of tugs and pilots. Regarding the weather conditions, just two possible conditions are considered, good weather or storm. In the second case, some limitations are applied in tug and pilots services.

2.5.10 Model 10 - *(Scott et al., 2016)*

The most recent port simulation model existing in literature is a discrete event simulation model of port processes, which is used for the cost-benefit analysis of various long wave mitigation approaches (Scott et al., 2016). The vessel arrival process includes anchorage, inbound transit and berthing, ship loading, unberthing and departure, and the vessel generation has been determined from historical data. All the sailing process are reduced to a time for the whole process, which is influenced by wind and wave conditions.

2.5.11 Model 11 - *(Bellsolà Olba et al., 2017)*

In addition, a simulation model to represent a port network in order to estimate the capacity of the waterway network from a port has been developed (Bellsolà Olba et al., 2017). The model simplifies the port infrastructure considering a main channel, several inner basins, maneuvering basins and different number of berths, depending on different scenarios. The anchorage, berthing maneuvering, terminal operations are not modelled. Moreover, in relation to the sailing characteristics, as the two previous models, no vessel interaction, speed variation or course choice are considered in this model.

2.5.12 Model 12 - *(Hasegawa et al., 2001)*

Currently, there is more data available in relation to vessel behaviour in navigation thanks to Automatic Identification System (AIS) data recording from most of the commercial vessels, which has lead researchers to calibrate and/or validate their models. One of the pioneers on that were Hasegawa et al. (2001), who developed a free navigational model in Osaka Bay. Although the model does not include external conditions, it is the only existing models that reproduces vessel behaviour and allows free course choice, steering and speed are updated at each time step. Moreover, vessel traffic arrival is based on historical data and influence from other vessels and bay boundaries is implemented.

2.5.13 Model 13 - *(Goerlandt and Kujala, 2011)*

Goerlandt and Kujala (2011) developed a model to determine the vessel collision probability. Based on extensive AIS data analysis, multiple trajectories are set into paths for each type of vessel. The simulation model creates a series of waypoints for each vessel without deviation from the course. The simulation results show a detailed risk assessment. Even being a simplified model, the results prove the relevance of an AIS data analysis and model calibration.

2.5.14 Model 14 - *(Huang et al., 2013)*

Another recent model, that includes vessel behaviour from AIS data, was developed for waterway networks (Huang et al., 2013). As the previous one, this model allows several course generation without deviation from the path. External conditions and speed variation are not considered while simplified influence is included in the model.

2.5.15 Model 15 - *(Rayo, 2013)*

In addition to the previous models, a model to assess the port approach channels was developed (Rayo, 2013). It is not as realistic as the previous ones, since it is not based on real AIS data. On the other hand, this model includes weather conditions and speed variations while vessels are navigating.

2.5.16 Model 16 - *(Xiao et al., 2013)*

A traffic simulation model with multi-agent system was developed to simulate dynamic ship manoeuvring to assess maritime safety (Xiao et al., 2013). This is a new approach for maritime simulation where vessels behave as autonomous agents. The model includes waterway infrastructure and encounter influence, as well as wind and current effects. Although the innovative approach, the model does not consider different fleet compositions and crew behaviour is not sufficiently implemented. The model is also calibrated with AIS data.

2.5.17 Model 17 - *(Shu et al., 2015)*

Shu et al. (2015) have recently developed a simulation model to predict vessel sailing behaviour in ports and waterways. The model is calibrated with AIS data, without considering interaction with other vessels during encounters or the influence of external conditions in the navigation. Although the model needs to be extended to become a whole port simulation model, this research presents an innovative approach to generate vessel route choice, according to the minimized bridge team utility cost. This route choice behaviour is based on the approach presented by Hoogendoorn et al. (2013), where they formulated and modelled the behaviour in the decision-making process of the bridge team.

2.5.18 Model 18 - *(Xu et al., 2015)*

The last model reviewed simulates vessel traffic flows in inland multi-bridge waterways (Xu et al., 2015). The model structure is divided in three parts: a vessel generating model, a route model and a vessel behaviour model. The first model generates the vessel distributions based on historical AIS data using a Monte Carlo method, and it considers different distributions for vessel types, vessel sizes, vessel arrivals and vessel velocities. The route model generates the position of the waypoints for each vessel route. In this last model, the vessel behaviour model, considers different sailing restrictions for specific traffic situations as free flow, overtaking or following.

2.6 Discussion

The models presented above have different characteristics and their implementation has considered more or less in detail the different important criteria for a realistic vessel traffic representation in ports. Therefore, a discussion on how the existing models include the different criteria for a realistic vessel traffic representation in ports are discussed.

The assessment of the nautical infrastructure shows that even though most of the models include detailed nautical infrastructure layout (detailed in figure2.1), only two of them consider all the infrastructure parts (Groenveld, 1983; Thiers and Gerrit, 1998). Anchoring processes have not been extensively implemented until now and specific algorithms, introduced in the anchorage subsection from section 2.4.1, have not been implemented yet. The models developed by Thiers and Gerrit (1998) and Almaz and Altiok (2012) have an adequate implementation of the anchorage area. The level of detail of these anchorages is sufficient for a port model, but if desired it could still be improved including the anchoring allocation algorithm. Berthing processes have been considered as dwell times in two ways, independent from terminal operations or together, without modelling the manoeuvring. Since the influence of these processes in the overall performance of a port is relevant, they should be properly implemented, considering uncertainty in their modelling. In the reviewed models, tugs and pilots are included with idle times and dwell times, which proves its importance, and should always be considered with this level of detail. Even though some models include several traffic rules, and all models include a control and traffic verification agent that checks rules application, most of them are not complete. This implies that not all the possible traffic situations are covered by these models.

In relation to the navigational behaviour assessment, the vessel arrival process has been considered according to several distributions or historical data and it will be discussed in the next section. As shown by the existing models, different fleet composition is relevant for port traffic performance. This diversity of vessels makes models more realistic. Influence on vessel navigation should be included as was done in some of the latest models (Hasegawa et al., 2001; Shu et al., 2015; Xiao et al., 2013; Xu et al., 2015). The other models just considered this as a simplified crossing, omitting the importance of the distance between vessels regarding safety issues. This implementation can show the effects of different designs or encountering situations and can help to choose a better port design.

Free course choice has not been implemented in any of the port simulation models. Regarding the rest of the models, three of them models developed a model with free and variable course choice, for each time step (Hasegawa et al., 2001; Xiao et al., 2013; Xu et al., 2015). Few of the latest models can simulate different fixed course choice, without freedom of movement (Goerlandt and Kujala, 2011; Hasegawa et al., 2001; Huang et al., 2013). While free sailing speed choice has been modelled in four models (Hasegawa et al., 2001; Shu et al., 2015; Thiers and Gerrit, 1998; Xiao et al., 2013) and others consider several fix speeds (Groenveld, 1983; Rayo, 2013), the rest modelled vessel speeds as fixed. The external conditions have not been extensively implemented. The assessment shows that some of the external conditions, such as tidal windows, as well as wind and current, have been previously implemented. However, the other conditions have not been considered. Current effects have been included just in the models developed by Rayo (2013) and Xu et al. (2015). Future models should include them in order to compare and assess the effects of them on the navigation and port performance.

Finally, recent models (Huang et al., 2013; Shu et al., 2015; Xiao et al., 2013) have been calibrated with AIS data, which gives results that would fit a real situation. Any future model should be calibrated with existing data according to the different behaviour of the vessels.

2.7 Conclusion

This review and assessment of several port nautical infrastructure simulation models leads to a better understanding of the ability of them to represent and simulate port navigation as close as possible to reality.

The overall assessment is based on the capabilities of the models to simulate vessel traffic in ports for capacity and risk assessment purposes. Therefore, the models are classified according to their application to capacity and risk assessments as follows:

✓	The model can be used for a suitable assessment
$\sim$	The model can be used for a partially suitable assessment
χ	The model should be improved for the assessment

In table 2.3, the assessment shows that none of the models previously developed are able to properly represent the vessel navigation in ports to correctly assess the capacity and the corresponding risk. Each of the models reviewed was developed for a specific purpose and their content and output was adequate for each specific purpose, and the focus of this assessment is to check if they could be also used for capacity and risk assessment purposes.

In relation to capacity assessment, four of the models have the sufficient criteria to be used for a suitable risk assessment (Groenveld, 1983; Hassan, 1993; Park and Noh, 1987; Thiers and Gerrit, 1998), and there are three other models, with another application than a port, that would satisfy the assessment of an approach channel (Rayo, 2013) or a waterway network (Huang et al., 2013; Xu et al., 2015). The rest of the models that simulate a port have some of the required characteristics, but they miss other important as can be some of the parts of the nautical infrastructure, the inclusion of tug and pilot assistance or traffic rules (Almaz and Altiok, 2012; Bellsolà Olba et al., 2017; Demirci, 2003; Piccoli, 2014; Scott et al., 2016; Ugurlu et al., 2014; Yeo et al., 2007).

Regarding the risk assessment, the models simulating a port are simplified and do not include properly the navigation process for a suitable risk assessment. Two of the models have some simplifications and can be used for risk assessment although the results are more on an aggregated level (Almaz and Altiok, 2012; Goerlandt and Kujala, 2011). The influence on vessel navigation due to infrastructure design or encountering situations, and, free course choice has not been included in any of the port models. The addition of these features would lead to more realistic results and would reproduce encounters as they happen in reality and the risk assessment would result more reliable. Recent models developed by Xiao et al. (2013) and Shu et al. (2015) already include these features, but have not been extended to simulate a whole port network. External conditions are also relevant for vessel navigation and have been omitted in most of the models. We would recommend to consider them, adding the current effects, and model all them in future research since they affect directly to the vessel manoeuvring. Hence, the risk changes due to current effects.

Table 2.3: Overall model assessment.

Nr.	Model	Goal	CA	RA
1	Harboursim (Groenveld, 1983)	Port planning and expansion.	✓	χ
2	(Park and Noh, 1987)	Port planning,expansion and economic analysis.	✓	χ
3	(Hassan, 1993)	Port planning, expansion and economic studies.	✓	χ
4	(Thiers and Gerrit, 1998)	Port planning and expansion.	✓	χ
5	(Demirci, 2003)	Investment planning.	∼	χ
6	(Yeo et al., 2007)	Evaluate port traffic congestion.	∼	χ
7	(Almaz and Altiok, 2012)*	Delaware River simulation (waterway).	∼	∼
8	(Piccoli, 2014)	New port simulation assessment.	∼	χ
9	(Ugurlu et al., 2014)	Port handling capacity, efficiency and queues.	∼	χ
10	(Scott et al., 2016)	Hidrodynamic impact on port economics.	∼	χ
11	(Bellsolà Olba et al., 2017)	Port capacity estimation.	∼	χ
12	(Hasegawa et al., 2001)	Vessel traffic in a bay.	χ	χ
13	(Goerlandt and Kujala, 2011)	Assess risk in vessel navigation.	χ	∼
14	(Huang et al., 2013)	Waterway network simulation.	✓	χ
15	(Rayo, 2013)	Approach channel assessment.	✓	χ
16	(Xiao et al., 2013)	Assess risk in vessel navigation.	χ	∼
17	(Shu et al., 2015)	Realistic vessel sailing behaviour.	χ	∼
18	(Xu et al., 2015)	Multi-bridge waterway assessment.	✓	χ

Abbreviations: CA = Capacity assessment, RA = Risk assessment.

Future port simulations models should consider detailed infrastructure and explicit tug and pilot assistance, as well as detailed traffic rules. Navigational behaviour should be implemented, thanks to extensive AIS data research already performed, which should allow the validation and calibration of detailed models, as it has been developed in the models developed by Huang et al. (2013), Rayo (2013) and Xiao et al. (2013). Moreover, the application of a method to reproduce human behaviour while navigating has been proven to be possible and should be used in future model developments (Hoogendoorn et al., 2013).

Considering the different criteria previously discussed, new port models should be developed with the highlighted characteristics described in this research to better fit real port performance and processes. Port stakeholders would extremely benefit from improved port simulation models that can be used for risk and capacity assessment purposes.

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Chapter 3

Network Capacity Estimation of Vessel Traffic

In this chapter a methodology to estimate the capacity of any port network is developed. First, the capacity for a port network is formulated and a review of capacity indicators, allows the identification of the main indicators to be used. A variety of scenarios is generated with a simulation model. The analysis of the results shows trade-offs between several indicators, and the point where capacity is reached can be estimated. The application of the methodology is useful for port-planning phases or new port designs.

This chapter is an edited version of the article:

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2017). Network capacity estimation of vessel traffic: an approach for port planning. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, 143(5), 1-9*.

Abstract

Port capacity is an essential parameter for the assessment of port performance. In the literature, there is no unanimous capacity definition, which depends on each research goal. Vessel traffic in ports and the corresponding port performance indicators have been analyzed with different simulation models, but they generally do not include a method for determining a ports capacity. Guidelines or other studies using empirical data also have not addressed this important topic. The method developed in this paper estimates the port network traffic capacity (PNTC) by using vessel traffic data. The analysis and comparison of several indicators are used to identify meaningful relationships for estimating port capacity with generic applicability to any port design. The

relation between the total number of trips in the port and the ratio of waiting time to service time seems to be the most suitable for identifying when the port reaches unstable flowsituations, that is, when it reaches capacity. The method has been applied successfully in six scenarioswith various berths, layouts, service times, vessel fleet types, and maneuvering times. Application of the method is useful during the port-planning phase, because with a few simulations, an indicative PNTC value for each design can be inferred, and thus, different scenarios can be compared.

3.1 Introduction

World globalization and containerization have led to a significant increase in vessel traffic in most of the commercial ports around the world. Therefore, ports face growing demand for vessels and cargo handling that might lead to traffic congestion. The evaluation of port performance becomes more relevant for the efficient development of the whole maritime supply chain. Because of the growth in the numbers and sizes of vessels, traffic congestion can occur in some ports such that the ports capacity is a key indicator for identifying loss times or delays. Although port productivity is usually determined by terminal operations, port efficiency can be reduced by vessel traffic congestion.

Previous research focused on specific activities in a port, such as the ship arrival (Van Asperen et al., 2003), the shipberth interaction Dragović et al. (2006), and the anchorage (Huang et al., 2011). Moreover, extensive research on terminal operations assessment and optimization has been conducted (Daganzo, 1989; Stahlbock and Voß, 2007), and specific research has studied the individual sailing behavior of ships in ports (Shu et al., 2013).

Port network capacity is a valuable indicator for port planning during the design of new ports or terminals and during the expansion of existing ones. Recently, a new method for estimating capacity of a port network was developed by (Bellsolà Olba et al., 2015a), called the port network traffic capacity (PNTC). The goal of this paper was to develop the PNTC estimation method on the basis of previous research that introduced this method (Bellsolà Olba et al., 2015a) but did not present an accurate method for clearly identifying the PNTC value. Therefore, the PNTC value estimated was subjective, and this paper provides a detailed explanation of the way the method was developed and is applied in a generic way. By using a simulation model, a variety of scenarios, including extreme situations, are generated, and the results of each simulation provide a single representative value for a specific configuration (fleet composition, port infrastructure layout, etc.), while the underlying computation method provides insight into the critical port processes for estimating the PNTC. Any simulation model, or real vessel traffic data, could be used with the indicators introduced in the following sections to estimate the PNTC. This method allows the estimation of the capacity in any port network design, and the estimated value is useful for port planning because it can be used to compare the results of different designs or measures in relation to the maximum vessel flow.

This paper is divided into six sections. In the next section, port performance indicators from literature are presented. The third section describes the methodology used in this paper, including the indicators, the development of the PNTC estimation method, and the conceptual network-capacity model. The experimental setup is presented in the fourth section. The fifth section describes the setup, model, and results of the simulation. The last section presents conclusions and suggestions for future research.

3.2 Literature overview

The literature reveals an extensive variety of definitions for port capacity according to the way the definitions are used, such as terminal capacity (Ligteringen and Velsink, 2012) and bottleneck approach (Fan and Cao, 2000). In addition, many of the proposed indicators are not generic and have severe limitations in terms of their applicability. For example, the bottleneck approach defines port capacity on the basis of the most critical element of the network. However, there can be specific port networks that do not reach capacity despite having a critical bottleneck.

Despite the existence of these definitions, the port capacity definition considered in this research for a port network was recently proposed as the maximum average vessel flow that can be handled by a port, with its specific infrastructure layout, vessel fleet, traffic composition and demand, satisfying the required safety and service level (Bellsolà Olba et al., 2015a).

Past literature has not addressed the capacity of a port. However, there is research on how to evaluate port performance. Hence, the most relevant indicators related to port performance and some background information is summarized in this section.

Port performance and efficiency can be measured with financial and operational indicators, which have been extensively used for many years. For research purposes, like the previous research developed by Bellsol Olba et al. (2015), the focus is on the operational level, and the most relevant indicators are presented in this section.

An early study assessed port performance based on traffic engineering with the following indicators: degree of occupancy (percentage of time that the total number of berths is occupied, recently called berth occupancy) and the degree of congestion (percentage of time that the number of ships exceeds the number of berths available)(Nicolaou, 1967). The use of these indicators has some drawbacks. The degree of occupancy does not indicate how the occupancy is split; for example, the results would be the same whether one-half the berths were occupied during a certain period or all of them were occupied for one-half the time during the same period. Hence, this indicator alone does not provide enough information. Because the degree of congestion is dependent on the length of the port infrastructure, ports with longer waterways require more sailing time, and this indicator becomes higher without having a higher flow.

There are other indicators used for port efficiency. Researchers recently approached this topic by using the average turnaround time (Ducruet et al., 2014), which is the time spent by each vessel when performing all the operations inside the port (entering, berthing, loading and unloading, and departing). Although this indicator is a proper indicator for port performance, it will not be applied in this research because its main variations are caused by the terminal service time (the larger time). For the purposes of this study, the turnaround time would not be sufficiently representative because the sailing time is a small part of the total turnaround time.

Other research presented several operational indicators directly related to productivity and to the operational performance of a port, such as the previous turnaround time, and others, such as waiting and service times (UNCTAD, 1985). One of the most appropriate measures of the level of service of the port, quality of traffic service, is the ratio of waiting time of vessels to the total service time at the terminal, which has been shown to be below 30% (UNCTAD, 1985). In reality, this factor will be conditional on the basis of specific rules and costs assigned to the waiting time, and according to port experts, the value should be below 20% (UNCTAD, 2012). The information that this indicator alone provides can lead to an incorrect interpretation, because an increase in the terminal service time results in a lower ratio without any performance improvement.

Many other indicators related to port throughput could be considered, such as tons per gang hour. However, their application is useful for assessing the terminal performance, and they do not contribute to the assessment of the vessel traffic performance in a port. Because none of the existingmetrics are satisfactory, in this study, a new metric was developed and tested for robustness using simulation.

Port networks have not been analyzed from an aggregate point of view in terms of traffic. There is extensive research for road networks, and because there are similarities between port and road networks, similar approaches could be applied to create the new metric. Recent work on roads developed the concept of macroscopic or network fundamental diagram (MFD and NFD, respectively)(Geroliminis and Daganzo, 2008; Keyvan-Ekbatani et al., 2012), where the relation between the total flow and the average density allows for identification of different traffic states. In the case of a traffic jam, the flow decreases with the density increase; however, this would not happen in a port because traffic regulations at the entrance prevent vessels from being queued inside the port. According to a concept similar to perimeter control in roads, the load on the waterway network is reduced, such that it will not exceed the capacity, so no congestion will occur in the port. However, the uncongested regime of the NFD could be related to unsaturated port operations. On the basis of the successful results in road traffic, analogous relations between port performance indicators were analyzed in this paper, exploring the possibilities for building and improving the previous PNTC estimation method (Bellsolà Olba et al., 2015a).

3.3 Methodology

This section presents the indicators chosen to develop the method, describes the steps of the PNTC estimation method, and explains the conceptual network-capacity model.

3.3.1 Indicators

The indicators considered relevant to combine for estimating capacity on the basis of literature overview presented are:

- Waiting time to service time ratio (WT/ST), considering the entire port including sailing time, describes the degree of port efficiency;
- Total trips (TTs), the average number of trips that vessels complete within a time interval, gives a reference for the vessel flow (entering or exiting the port is considered as one trip each, while each trip between terminals is considered another trip); and
- Berth occupancy (BO), the percentage of time that the total number of berths is occupied.

3.3.2 PNTC estimation method

A generic method to estimate PNTC was recently presented by (Bellsolà Olba et al., 2015a) and has proven applicable in different port setups and sailing characteristics with similar outcomes. As previously introduced, the previous research addressing this topic (Bellsolà Olba et al., 2015a) did not define a PNTC value, which was subjective to the user interpretation. In this section, a comprehensive and detailed explanation of the PNTC estimation method is presented. The application of the method depends on the availability of a port simulation model or a data set from a port with traffic congestion that allows the calculation of the desired indicators. The different steps of the method are presented as follows:

- Calculate the indicators WT/ST, total trips (vessels per day), and berth occupancy.
- Set the values to define the desired port design and characteristics, such as infrastructure layout, terminals, service times, safety measures, and traffic rules.
- Estimate a demand interval to come up with a range of values for WT/ST and berth occupancy. To obtain values between 0 and (at least) 1.5 for the first indicator and between 0.25 and (at least) 0.80 for the second one, the authors recommend that the capacity from the relation between the two indicators be clearly defined.

- Run a sufficient number of simulations with different demands until values with stable and unstable conditions are obtained. These values are used as minimum and maximum demands.
- Find the average value of the maximum total trips, based on the WT/ST values greater than 1, to determine the PNTC value.
- The graphical representation of total trips versus WT/ST, and the exponential fitting, should lead to the graphical representation of the estimated curve, for which the limit value is the PNTC.
- Applying a reduction coefficient of 0.9 to the PNTC value, an acceptable flow for a specific port design can be obtained, and it can be used for the evaluation of port performance and for comparisons to other designs.

3.3.3 Conceptual network capacity model

A conceptual capacity model is presented in figure 3.1. The capacity influencing factors are directly linked to capacity and to each other. The macroscopic vessel flow is determined by the microscopic vessel behavior, which in turn, is determined by the different factors influencing the microscopic behavior.

As shown in figure 3.1, the indicators depend on the specific setup in each case, such as infrastructure design, fleet composition, and so forth, and on specific demand. The total number of trips (vessels/day) has a close relationship with capacity, and it is one of the outputs from the simulation model. Although the outflow of the port was used in previous research (Bellsol Olba et al. 2015), when trips between terminals are considered, the outflow indicator misses the effects of having interterminal trips; thus, it loses meaningfulness. The berth occupancy factor does not allow the identification of the location of the occupancy. Although it is not useful for drawing conclusions about certain problems in a port network, together with WT/ST this indicator is useful for an aggregate analysis of a network or for comparing different scenarios.

From the combination of indicators and network capacity, some relationships are expected.An increase in demandmight lead to different variations in the indicators. For example, this increase can lead to higher TT and BO values with the same or slightly higher WT/ST. This means that TTs and BO are improving, and the port was operating below capacity under the previous demand-level scenario. In an alternative situation, an increase in demand leads to a small increase in TTs and a moderate increase in WT/ST while BO decreases or remains the same. This situation might be the consequence of traffic congestion caused by limited wet infrastructure capacity. Because they find restrictions in the waterways, vessels are not able to reach the berths as expected and the BO decreases. Another possible scenario would emerge in which there is a limitation in the terminals. An increase in demand would not affect the BO(itwould remain close to the maximum value for this configuration) while WT/ST would increase moderately and the TTs would not have a remarkable difference.

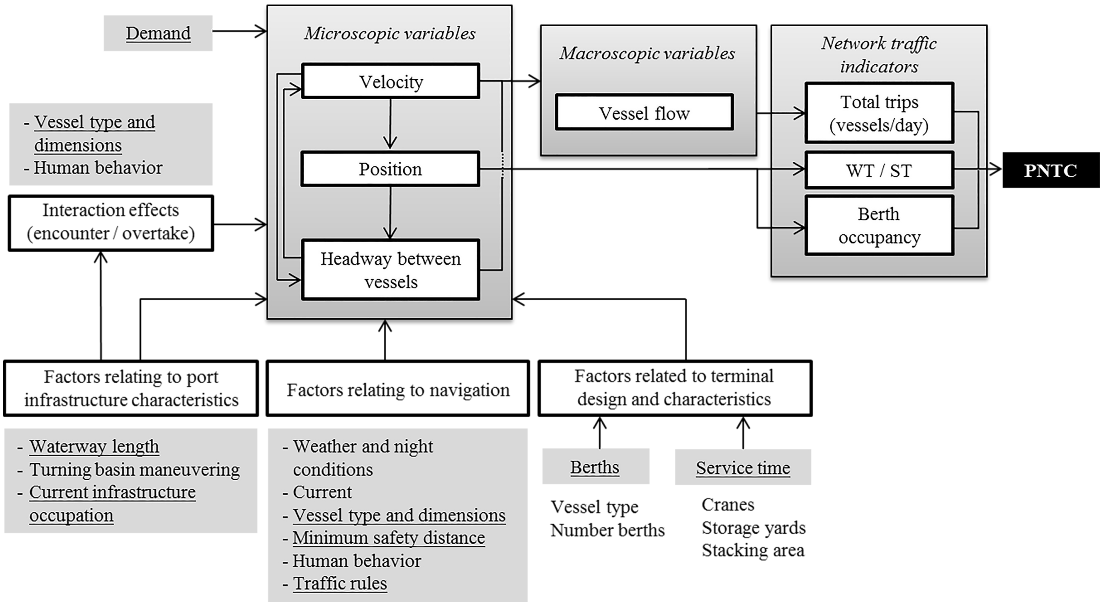

Figure 3.1: PNTC conceptual model (Note: Factors underlined are included in the model) (adapted from Bellsolà Olba et al. (2015a)).

In this research, changes in the terminals and some parts of the wet infrastructure (layout) will help in identifying and assessing the effects on the network-traffic indicators and the applicability of the PNTC-estimation method in any port design. Because of their main influence in vessel traffic inside a port, several control variables were used in this research. In relation to the terminals, the service times and number of berths were changed for different scenarios. With respect to the wet infrastructure, the lengths of the waterways and the maneuvering times in the turning basins were changed. The simulation setup presents all these possibilities.

3.4 Experimental setup

This section describes the experimental setup used to validate the method. The first subsection presents the conceptual capacity model and indicators considered in the PNTC-estimation method. The subsequent two subsections present an overview of the port infrastructure layout considered and the data used for setting up each scenario.

3.4.1 Layout

The schematic of the port layout defined in the model used to simulate the different scenarios is presented in figure 3.2. It is the same one previously used by Bellsolà Olba et al. (2015a). The infrastructure layout chosen includes the main parts of all port designs. There are several waterways and terminals as well as some turning basins and terminals. Any of these might become the bottleneck or otherwise influence vessel flows. The layout represents a complete port network infrastructure.

The port wet infrastructure is made up of an approach channel (L4) with a turning basin (B1), where vessels are separated. The vessels destined for Terminal 1 use the waterway L1, and the others continue through waterway L5. At the end of this waterway, there is a second turning basin (B2) that connects with two waterways. Vessels destined for Terminal 2 will sail through waterway L2 while vessels going to Terminal 3 sail through waterway L3.

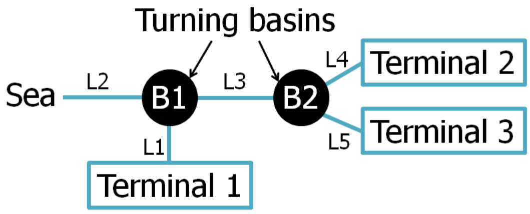

Figure 3.2: Port network model layout (adapted from Bellsolà Olba et al. (2015a))

3.4.2 Scenario setup

To evaluate the relationships between the indicators, different scenarios were implemented with different control variables. The different setups allowed for the creation and comparison of different port designs, identification of the level of congestion in each case, and determination of port capacity.

The data used to build different scenarios are shown in figure 3.3. The control variables changed for the different scenarios are demand, layout, terminal service time, vessel fleet types, number of berths per terminal, and maneuvering time in turning basins. The changes in these parameters affected the traffic flow and port capacity, and they were used to apply and validate the method. Two layouts of different lengths were implemented (table 3.1). As for the other parameters, changes in the lengths of different approach channels and basins will affect traffic because of different sailing times and, thus, have direct effects on the port performance and the resulting capacity. The authors chose demands according to each port configuration with the purpose of reaching congested traffic states in the port and estimating the PNTC.

Table 3.1: Layout

	Waterway length (m)				
Layout design	L1	L2	L3	L4	L5
1	1200	500	700	1000	2000
2	1200	1500	1500	2000	2500

			Scenarios					
			S1	S2	S3	S4	S5	S6
Expected demand [h]	Min.	10				x		
		30	x	x			x	x
		60			x			
	Max.	40				x		
		70	x	x			x	x
		90			x			
Layout	Design 1		x		x	x	x	x
	Design 2			x				
Service Time [h]	μ	5			x			
		10	x	x		x	x	x
	σ	0.5			x			
		1	x	x		x	x	x
Vessel fleet types		1	x	x	x	x		x
		2					x	
Berths per terminal		5				x		
		10	x	x	x		x	x
Maneuvering turning basin time [min]		10	x	x	x	x	x	
		20						x

Figure 3.3: Simulation setups

3.5 Simulation

Simulation brings the possibility of building different scenarios for analyzing and comparing results as necessary to implement the estimation method previously described. In this section the developed simulation model is first described. Then, the simulation setup with the characteristics of the scenarios implemented is presented, and finally, the results are presented and analyzed according to the PNTC-estimation method.

3.5.1 Simulation model

To apply the PNTC estimation method, different data sets are needed for the different scenarios. The method is independent of the simulation model used but depends on the indicators. Any existing simulation could be used for this purpose, but the outcome would not provide the indicators required for the purposes of this study. Hence, a simulation model that provides the indicators required for applying the method is needed. In this research, the simulation model previously used by Bellsolà Olba et al. (2015a) was enhanced. To represent reality as closely as possible, the vessel trips between terminals are implemented in the model, which allows for analysis of their effects. The port network traffic has been analyzed using a dedicated event-oriented simulation model developed in *MATLAB*. This microscopic model describes individual vessel dynamics within a port in a simplified way with time-step calculations. The basis of the simulation model is described.

When the simulation is started, a vessel generation module creates vessels according to the prespecified interarrival time toward each destination (terminal). Ships can sail directly to the destination and then leave the model, or ships can make a chain of trips with intermediate destinations at different locations (terminals) in the port. The interarrival time was Poisson distributed, and each vessel gets a random speed. The considered speed is between a maximum and minimum range related to vessel length. After all vessels are generated, the vessel module, including three submodules (sailing, turning basins, and terminals), does the required computational calculations. The sailing submodule is built for each stretch of the port and stores and updates vessel positions for each of the waterways and basins. The turning basins submodule includes all basins from the port infrastructure and stores and updates the time spent by each vessel in them. Finally, the terminals submodule includes all the berths and terminals available and stores the service time of each vessel moored in each of the berths. Each of the submodules elements store and update each vessel position at every time step. When a vessel has completed the trip in one of the submodules, the vessel will wait in the current submodule until the next submodule has space to allocate more vessels. Once the simulation time, defined by the user, is reached, the vessel module stops and all data are stored.

Although ports usually have an anchorage, which provides vessel queuing and reordering possibilities, the port layout considered in the simulation model does not explicitly includes it. The model considers the port entrance as the location where vessels can reorder in cases of different terminal destinations and current availabilities as if anchorage was used.

The model implementation includes several assumptions to simplify the complex port network and the sailing behavior of vessels, and thus, to build and compare different scenarios in a reasonable time. Built on the assumptions presented by Bellsolà Olba et al. (2015a), those considered for this study were:

- Sailing characteristics:
  - Vessels sail in a one-dimensional movement with no interactions between vessels in head-on and no overtaking situations;
  - Random vessel speeds are generated between 4.5 and 10 knots ($\sim$ 3.1 - 5.1 m/s) with speed range varying according to vessel length; and
  - Each vessel speed assigned is a constant unless the safety distance with the predecessor reaches a minimum in which case the vessel sails at the predecessors speed.
- Vessel destinations:
  - Vessel destinations and trips between terminals are predetermined when vessels are generated; and
  - Vessel entrance to the port is contingent on berth availability within sailing time such that once a vessel visits different terminals, a berth is reserved in the next terminal while the vessel is served in the current one, but if no berth is available, vessels have to wait outside.

- Maneuvering and operations:
  - The turning-basin maneuvering is defined as a fixed time period equal for all vessels; and
  - Neither berthing operations nor loading and unloading processes are detailed in the model, but these operations are included in the service time, which is described by a normal distribution.
- External conditions:
  - No weather conditions, tidal windows, or night effects are included.

None of these assumptions has a severe effect on the indicators considered in the capacity-estimation method, and they are considered reasonable for the purpose of this research. However, the authors acknowledge that for a more advanced model that considers, for example, two-dimensional vessel movements, the influence in speed and path while encountering other vessels moving in the opposite direction and the availability of tugs to help large vessels maneuver in turning basins would provide an estimated capacity closer to reality. Moreover, the model could also relate vessel speed to vessel size and the effects of the infrastructure over a dynamic path, as developed in recent research for a unique vessel (Shu et al., 2015). Hence, for the application of this method in a real port, an advanced model would provide more realistic results. However, the research purpose is to develop the PNTC method, and the model is used only to validate the capacity-estimation method.

3.5.2 Simulation setup

The different simulation setups for each scenario are summarized in figure 3.3. Each demand is gradually increased within a range between minimum and maximum values to gradually overload the system, and each simulation includes 30 different demands equally distributed between the two extreme values. Gradually increasing demand provides increasing values of each indicator when reaching capacity. Once demand is over capacity, indicators should reveal that the operations in the port network are unstable.

The model includes the possibility for vessels to make a trip chain within the port. For this research, 20% of the entering vessels will make interterminal trips, and the rest of the vessels will just visit one terminal.

Because the model is stochastic, 10 runs for each scenario were carried out, resulting in a total of 300 values per scenario. To make the scenarios comparable, an average value over the 10 runs was considered. The simulation time was 5 days with a warming-up period of 1 day.

3.6 Results and analyses

The simulation results for the different scenarios are analyzed in this section. Because the results from all scenarios follow the same trends, figure 3.4 shows only the results for the different capacity indicators for scenarios S1 and S4.

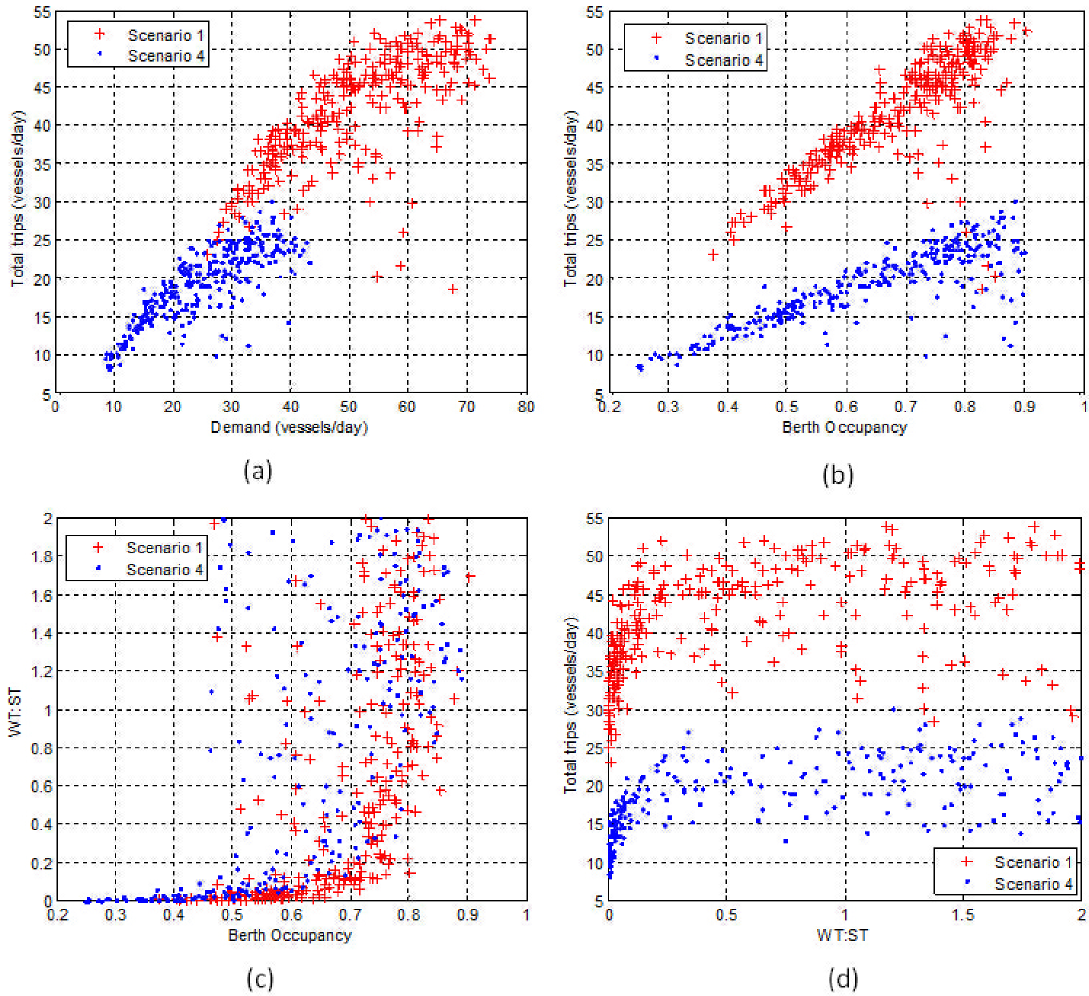

Figure 3.4: Simulation results for S1 and S4 (total of 10 different simulations each scenario): (a) TT versus D; (b) WT/ST versus BO; (c) TT versus BO; (d) TT versus WT/ST

Figure 3.4(a) shows the relationships between each demand and TTs each day. S1 and S4 show a parabolic relationship between the demand and TTs, which flattens at higher demand levels. The initial linear relationship for lower demands disappears at a specific demand value, approximately 40 vessels/day for S1 and approximately 18 vessels/day for S4, and there is a dispersion of results. Previous research showed that, not considering internal trips, the outflow reached a maximum with a stable value (Bellsolà Olba et al., 2015a). However, in this case, allowing vessels to make trips between terminals created unstable situations exceeding the capacity level. This is reflected by some points with high demands resulting in fewer TTs because of congestion. This pattern does not clearly reflect the situation when the capacity of the port is reached.

Figure 3.4(b) shows the relationship between BO and TTs, and it can be seen that above 0.7 of BO, there are some drops in TTs, which can be related to the excess demand over capacity and the congestion level of the port. When the congestion in some areas of the port is high, there might be situations where the port network cannot process as much traffic as it did before. Figure 3.4(b) also shows a high density in the right part of S4, and some TT values were lower at the same BO, which means that, increasing demand even further, BO reached its limit and TTs could not be higher. Hence, we can see that number of berths and the distribution among different terminals can be limiting factors in planning the port waterway network. However, for S1 between 0.7 and 0.9 BO, there is a high point density, which implies that if there is congestion, the limiting factor is partly the result of the wet infrastructure design and not only the number of berths.

The relationship between WT/ST and BO (figure 3.4(c)) shows that WT/ST increases following an exponential distribution with respect to BO with a high dispersion above a value between 0.6 and 0.75 of WT/ST. This comparison proves that above a certain BO value, any increase in demand will produce only an increase in waiting times while the service time remains the same. Therefore, the port might be crowded with increasing levels of congestion and the efficiency may decrease. It should be mentioned that previous research using queueing theory proved that this relationship follows a similar trend (Groenveld, 2001); thus, the model output fits realistic trends previously studied. In addition, the scatter results above a certain WT/ST show the influence of congestion on the stability of the network. In this case, even with increasing demand, the resulting BO is lower than it is under lower demands when the situation is stable.

Figure 3.4(d) presents the relationship between TTs and WT/ST. Both scenarios follow the same trend: They have a linear increase up to a certain point where the WT/ST keeps increasing with a large fluctuation of TTs. This finding proves that the port has reached capacity (maximum number of TTs) for a certain port configuration.

As the TT value becomes unstable above a specific demand level, the maximum traffic is reached for the port, and the value of TT between stable and unstable situations is considered the PNTC. The estimation of the PNTC can be obtained as the average value for WT/ST above 1 (PNTC = c; table 3.2). In addition, because all scenarios have a similar pattern for the relationship between TTs and WT/ST, a best fit of functions was performed (figure 3.5), revealing that this pattern follows an exponential distribution, shown in Eq.(1) as follows:

$$f(x) = a \cdot e^{bx} + c \tag{3.1}$$

Table 3.2: Exponential Fit and Capacity Estimation

	Scenario					
Parameter	S1	S2	S3	S4	S5	S6
a	14.23	14.78	24.73	10.29	15.39	14.05
b	14.69	16.21	25.87	10.74	17.33	13.38
c=PNTC (vessels/day)	44.75	44.81	69.72	21.64	44.95	43.68
R^2	0.38	0.45	0.42	0.51	0.45	0.53

Note: PNTC = port network traffic capacity.

Using the PNTC obtained for each scenario as c in equation 3.1, the parameters *a* and *b* of the exponential distributions are obtained as shown in table 3.2. All scenarios had moderate correlations to the data on the basis of the R-squared value obtained for each of them, and figure 3.5 shows the graphs of the exponential fittings for each scenario. The dispersion of results above a certain value is attributable to the stochasticity of vessel arrivals and trips between terminals. Although for each scenario a higher TT than PNTC value can be observed, these values are mostly in the unstable situation, in which increasing demands lead to higher increased WT/ST than TTs, and the situation is unstable.

Figure 3.5 shows that although the resulting limits are different for each scenario, all scenarios show the same trend, with a limit at capacity (PNTC). When the TT value reaches PNTC, relating it to road traffic concepts, this would be the congested state. A port cannot operate at that state of high demand for a long period because the waiting times are unacceptable. Hence, the threshold value that determines an efficient port operation has to be below the PNTC.

In addition, the PNTC is different for each scenario because of their different setups. Assuming S1 as the basic case for comparison (figure 3.5(a)), figure 3.5(b) shows that S2 has almost the same TT values without much influence from the longer sailing distances through the port. S3 (figure 3.5(c)) considers a service time of 5 h, one-half that of S1. In this case, the PNTC results are almost twice as high as the one estimated for S1, which shows that the port infrastructure, the inclusion of internal trips, and the sailing time influence the TTs. In figure 3.5(d), S4 has one-half the berths of S1, and the PNTC estimation is below one-half that of S1. S5 (figure 3.5(e)) considers two vessel fleet types, and the final result is almost the same as the previous scenarios, which means that this is not an influential parameter in this analysis. On the basis of the traffic point of view, this finding shows that the only factors that change among ship types are lengths and speeds and, as a consequence, so do safety distances. Further research should examine the influence of different maneuvering times. Finally, in figure 3.5(f), S6 was implemented with double maneuvering time in turning basins (20 minutes), and therefore, the result shows that the PNTC values are slightly lower than for S1, although the influence is really limited.

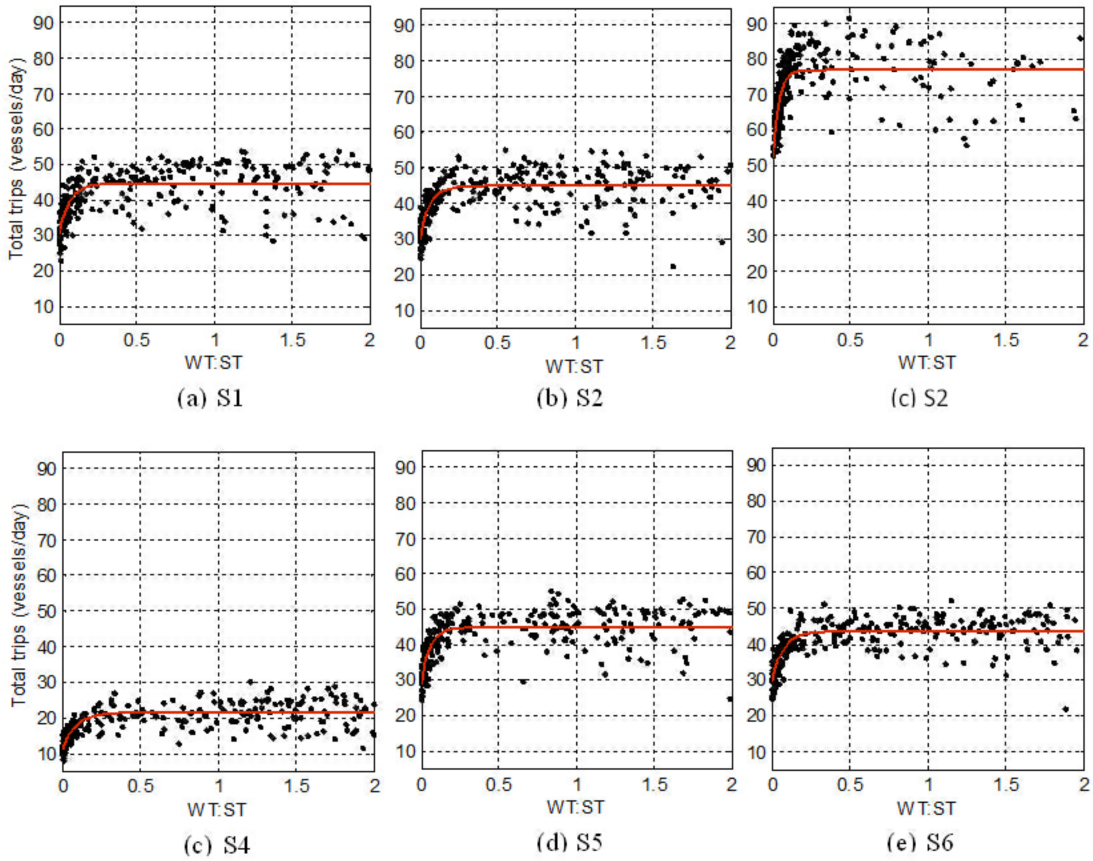

Figure 3.5: Exponential fit to data for each scenario: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6

When comparing the results for different port designs, we can conclude that the control variables with strong effects on the PNTC were the service time and the number of berths in each terminal. The rest of the control variables had small effects.

The comparison between scenarios showed that, despite the different configurations, the indicators for estimating PNTC follow the same trends, and the PNTC can be estimated for any scenario. To guarantee acceptable congestion and WT/ST values, the point that determines the threshold of an acceptable operation with a specific port design should be below the PNTC. By following a similar approach used for road traffic, as described in the *Highway Capacity Manual* (2010), in which different levels of service have been related to the traffic situation, a value of 0.92 volume/capacity is found for the level D threshold, which approaches unstable flow, corresponding to a maximum delay for freeway designs. The next level in this scale, E, corresponds to unstable flow. Figure 3.6 shows the relationship between the demand/capacity ratio with respect to the WT/ST. Setting a demand/capacity ratio of 0.92 as the upper limit of stable flow (see line in figure 3.6), as happens in vehicular traffic, congestion leads to more dispersed results than does stable flow. Furthermore, WT/ST is below 0.2, which is, as mentioned already, the maximum acceptable value for ports. Hence, after estimating PNTC, this value could be used as a reference value to assess new port designs or extensions.

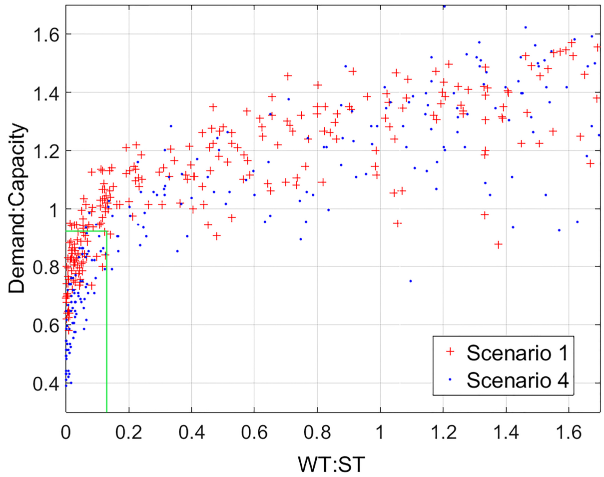

Figure 3.6: Demand/capacity ratio versus WT/ST

Figure 3.7(a) shows the boxplots for Scenario 1 and figure 3.7(b) shows them for Scenario 4. The results of both scenarios, and the others, follow the same pattern, and it can be seen that the demand/capacity ratio reaches 1 at approximately 0.15 of WT/ST for Scenario 1 and approximately 0.20 of WT/ST for Scenario 4. Moreover, the average values show that the demand/capacity ratio increases slightly more than the WT/ST ratio for high demands because of the capacity limitations of the port designs assessed.

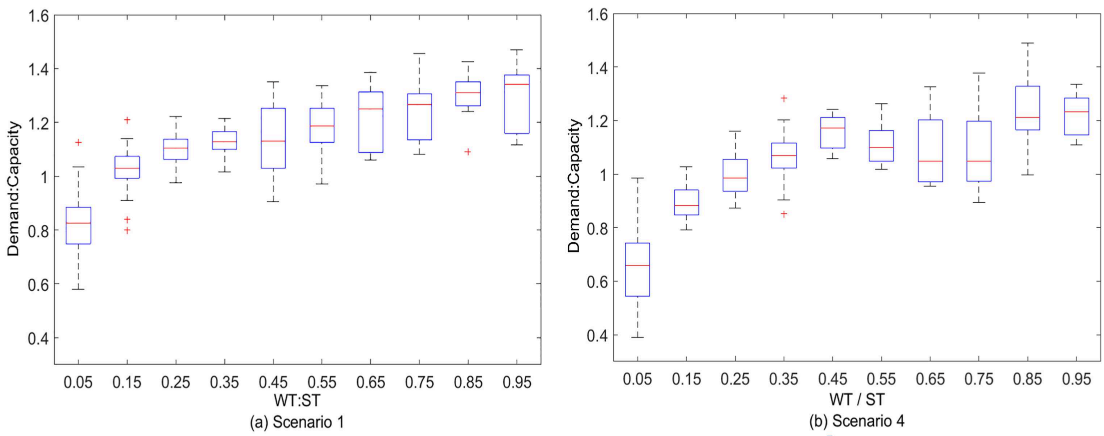

Figure 3.7: Boxplot representation of demand/capacity ratio versus WT/ST: (a) Scenario 1; (b) Scenario 4

3.7 Conclusions

This paper presented the PNTC estimation method, which provides the capacity value that can be sustained by a port network (Bellsolà Olba et al., 2015a). The method allows for the identification of trends and relationships between indicators in a port from aggregated data for estimating its capacity. These indicators can be obtained from any simulation model with the required output. To show the applicability of the approach, vessel trips were implemented between terminals in a simplified simulation model, generated data for a range of situations and also through which extreme situations can be compared. The results revealed a trend that relates TTs with WT/WS. At a particular point, PNTC, the system becomes unstable and the results become more dispersed. The capacity can be reached because of berth limitation or traffic congestion.

This methodology focuses on the traffic assessment of the port network and does not consider costs or restrictions with respect to waiting times. It can be applied during the port-planning phases to identify the optimum design in relation to vessel traffic. The application of this method allows port planners to estimate the capacity of different port designs while they are comparing feasible scenarios.

On the basis of these results, planners can evaluate and compare the respective PNTC values, and use them as reference values for choosing between the options. The approach presented is part of a methodology for making an assessment of a complete port while taking into account other indicators, such as risk and costs. In an additional step, other indicators will be included to improve this estimation method. Moreover, the implementation of different port configurations and extra functionalities can show the influence of other limiting factors, such as pilot and tug availability, the infrastructure design on capacity, among others. The results of the estimation method presented for real port networks directly depend on the level of simplification of vessel navigation and port infrastructure. The more a model accurately represents the most relevant factors in navigation, the closer to reality the results will be. On the basis of this method, further research might lead to defined levels of service in ports.

Acknowledgments

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Chapter 4

Capacity Estimation Method of an Intersection of Waterways in Ports

In this chapter a new method to estimate the capacity of an intersection of waterways in ports is presented. The analogy between road and maritime traffic allows the development of the method based on a road intersection capacity estimation method. Case studies for two intersections from the Port of Rotterdam are performed by using real data. A sensitivity analysis is used to assess the robustness of the method. Finally, this method proves to be useful as a proxy to assess current or future traffic situations and to help improve current traffic management strategies making waterway intersections more traffic efficient.

This chapter is an edited version of the article:

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. A Method to Estimate the Capacity of an Intersection of Waterways in Ports. *Transportmetrica A: Transport Science*, under review.

Abstract

The maritime transportation growth leads to more intensively used waterways, especially in ports. Since the capacity of an intersection of waterways becomes more important, this research presents a new method to estimate this capacity. Based on an analogy between roads and waterways, the conflict technique is applied to an intersection of waterways. The vessel flows in each direction and their conflicting movements are input for the capacity calculation. The generic method can be applied to any intersection, considering the conflicts between the different streams in the intersection and the flows inferred from empirical data or from predictions. The applicability of the method is shown with two case studies, based on data from the Port of Rotterdam.

After using the proposed method, we compare the real flows with the estimated ones to assess the capacity estimates. This method can improve traffic management strategies, traffic rules in waterway intersections or port designs.

4.1 Introduction

Maritime transportation is continuously growing and waterways have to handle higher traffic flows. As a result, waterway intersections are more intensively used and more crowded for navigation. Since port authorities are concerned about the maximum vessel flow that intersections can accommodate, the main question in this research is: How can we determine the capacity of an intersection of waterways?.

Capacity has been a subject of interest in maritime transportation research, but usually more focused on the terminal level rather than on the wet infrastructure level. Recent research has focused on the effects of high vessel flows in ports with different purposes. A recent practical study presented the application of domain analysis to a port area to assess navigational risks (Rawson et al., 2013). Similar research was developed for seaport fairway capacity by Wang et al. (2015), while analysing different port safety and service levels. Another application of ship domain was done to analyse the free flow efficiency of vessel traffic between two pilons while including a Traffic Separation Scheme (TSS) (Jensen et al., 2013). Liu et al. (2016) developed a ship domain model, based on trigonometrical relations for capacity analysis of waterways. Their approach includes crossings in navigations, but the different turning directions within an intersection are not included. At an aggregate level, a method to estimate the capacity of a port network, using a simulation model, has been recently presented (Bellsolà Olba et al., 2017). Even though the capacity of waterways and fairways or port networks has been already extensively addressed, an method to estimate the capacity value of an intersection of waterways in ports have not been specifically developed. The previous methods allow the calculation of the current capacity and it can be compared to a service level, but how to determine objectively a maximum value has not been performed. Because of this, we aim to fulfil this gap with this research.

The definition of capacity of a waterway intersection has not been previously formulated. The definition may be similar to the definition for approach channels (PIANC, 2014): the maximum traffic volume to be handled by the approach system satisfying the required service level and safety level. This definition considers an approach system instead of a waterway intersection, and the vessel composition and traffic shares (OD matrix) are not included. The vessel composition and the traffic shares have a direct effect on capacity, and it will be lower with larger vessels or when vessels have specific encountering safety requirements. Correspondingly, we propose that the capacity of a waterway intersection may be defined as: the maximum traffic volume to be handled by an intersection of waterways satisfying the required safety level, and conditional on the traffic composition and traffic shares over different directions. The utilization of the intersection can be considered as the number of vessels passing the intersection through cross sections in each direction during a certain time interval. Thus, the difference between the estimated capacity and the utilization is a proxy for assessing the current traffic situation, as it allows to find out if there is still space for the port to grow or if new port designs or other traffic management strategies should be implemented to avoid a bottleneck in a specific intersection.

The capacity estimation of vessel traffic in intersections of waterways is difficult due to the uncertainty in vessel arrivals, which has been proven to be random (Fararoui, 1989; Pachakis and Kiremidjian, 2003), and the different traffic shares, which vary over time. A good estimate of the capacity of an intersection of waterways could be obtained using a port simulation model, but, when there is no model available, there is not any method that allows its estimation. The objective of this research is to develop a generic method to estimate the capacity of any waterway intersection on a high level. The method is suitable for and applicable by any stakeholder to compare the current situation with the estimated capacity. Since a similar method has not been previously developed, research in other fields is considered. This paper continues with the review of existing capacity estimation methods for roads and their characteristics (section 4.2). Based on the literature review, an analogy between waterways and unsignalised intersections in roads can be drawn because of their similarities. Based on this analogy, a capacity estimation method for waterway intersections is developed (section 4.3). Section 4.4 presents two case studies where a data analysis is performed and the method is applied to two different intersections. This case study describes the data used, which leads to the input for the method, followed by the capacity calculations and a sensitivity analysis. The last section presents the summary and future research (section 4.5).

4.2 Background

Waterway intersections have many similarities with unsignalised road intersections, such as certain headway between vessels and different choice of directions, but also important differences, such as communication among vessels and between vessels and the port, with the Vessel Traffic Services (VTS), exist. Moreover, there are no queues at intersections, to indicate that the capacity has been reached.

Though a method to estimate the capacity of waterway intersections does not exist, the concept of estimating intersection capacity has been extensively studied for road traffic. Previous research on unsignalised road intersections presented two methods to estimate capacity: the gap-acceptance theory (among others, Brilon et al. (1999); Amin and Maurya (2015), and the conflict technique (Brilon and Miltner, 2005).

The first method is based on the idea of estimating the minimum critical gap, which is the minimum headway during which each individual driver will accept to enter the intersection. This critical gap is different for each individual, resulting in a critical gap distribution. In unsignalised crossings, the driver of the vehicle without priority will accept a gap between vehicles in the main stream to enter the intersection if the offered gap is larger than his critical gap. This critical gap can be estimated with different methodologies, such as the maximum likelihood or Hewitts method (Brilon et al., 1999). The value or distribution for the critical gap, estimated with any of the existing methods, can be used to determine the capacity of the intersection. However, the critical gap estimation method has some drawbacks, as stated by Brilon and Wu (2001). For example, the critical gap estimated is different depending on the direction of the vehicle, and requires a clear definition of traffic rules, which hampers its use for the estimation of a single capacity value for other transport modes. There are many rules in waterways which are according to the sailors code of conduct, and it is not possible to define.

The second method, the conflict technique, simplifies the movements and operations of an intersection representing the intersection as a queuing system Brilon and Miltner (2005). For the intersection capacity calculation, they consider the flows in each stream and the interactions between them. Road users, from both traffic streams, will occupy the conflict area. This area is the space in the intersection that cannot be used simultaneously by vehicles from different streams. Road users from the major stream can pass the intersection, while the ones from the minor stream must wait when the conflict area is occupied. The probability that the intersection is blocked can be calculated for each stream by multiplying the traffic flow and the time that a vehicle occupies the intersection. As a road user could enter the intersection when the conflicting streams are free of traffic, the capacity for each movement is calculated as the probability that the conflict area is not occupied times the probability that no other vehicle is coming during a specific time interval. A total of 28 movements are allowed at a 4-way intersection with two-way traffic, including the movements of cyclists, pedestrians and vehicles. However, in case of just considering the cars, a total of 12 movements would be allowed (see figure 4.1). The more streams in an intersection, the more conflicts will occur between the different streams.

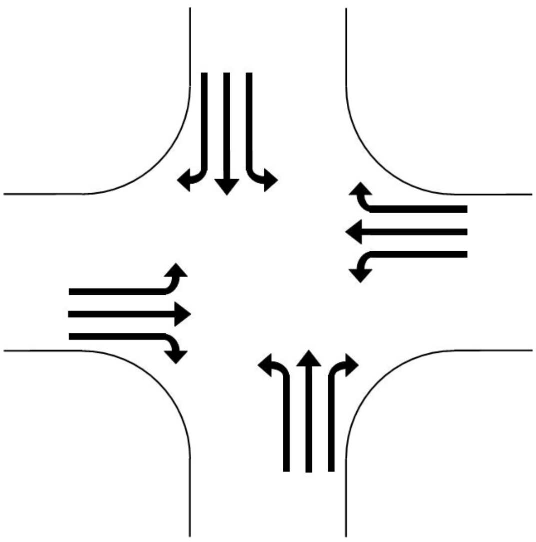

Figure 4.1: Definition of traffic movements at an intersection of waterways.

4.3 Capacity estimation method for waterway intersections

The gap-acceptance theory is not suitable for our purposes because vessel traffic flows are not constant and do not have high densities for long periods of time. In addition, since vessel communication and decision making are different from road traffic when approaching an intersection, the gaps could not be estimated using a similar method.

As a starting point to develop a capacity estimation method for waterway intersections, we therefore consider the conflict technique. This technique considers the intersection as a queueing system with probabilities of conflict between different streams from the traffic flow shares in each stream. This method has the drawback of simplifying the intersection into a queuing system which does not respect the complexity of reality. However, a generic method which includes all the specificities of waterway intersections is not feasible, and it might not provide great differences compared to a simplified one on an aggregated level. The advantage of the method presented is that it allows the estimation of the capacity with the consideration of traffic shares and the time vehicles are blocking the intersection. Hence, we consider that a capacity estimation method for waterway intersections can be derived from the conflict technique method.

There are similarities and differences between roads and waterways, and the relevant ones need to be described. The total number of possible vessel movements in a waterway is 12, as shown in figure 4.1. These movements are the same as for vehicles on roads, excluding cyclists and pedestrians. With respect to priorities, waterways do not have right-of-way priority, vessels communicate amongst each other and the VTS provides information and navigational advice to support their navigation, always under navigators responsibility. Apart from this, each crossing may have specific priorities according to some vessel types or sizes, the waterway design and dedicated port regulations, such as Traffic Separation Schemes (TSS), where vessels have independent sailing lanes. Otherwise, vessels navigators behaviour should satisfy to COLREGs (COLREG, 1972) and common practices. For example, LNG tankers might not be allowed to cross with other vessels, so the intersection should be completely blocked for other vessels while these tankers are crossing. One more difference is related to the flow. During the peak times, the stochastic vehicle arrival at a road intersection might have less variation than the vessel arrival in waterways.

The input required by the conflict technique is the total vehicle flow, the occupation duration of the intersection and the traffic share for each direction. Based on the specificities in waterways, as done in road traffic, some assumptions are made in order to turn the conflict technique into an applicable method for waterways. First, although a large variety of vessel types exists, no difference in vessel types and sailing speeds are considered. There are faster and slower vessels, as cars and other vehicles on roads, but they can be represented with an average value when looking into an aggregated level. As explained before, the navigation is assisted by VTS and there might be specific priorities for some vessel types that limit the traffic because dangerous encounters, which might lead to a reduced capacity. In this research, we aim to find a maximum value, so the assumption is useful for high level calculations where the value is used for strategic or tactical assessment of navigational or infrastructure changes. Second, the occupation time of the intersection will be averaged according to the speed used, as previously used in the method for unsignalised road intersections (Brilon and Wu, 2001). Last, we consider that, with a high traffic flow, VTS control might have stronger influence which leads to dependent arrivals. Hence, the vessel arrival is assumed to be uniform over time. Since the waterways are usually not sufficiently congested, it is difficult to estimate a minimum headway between vessels. This minimum headway could be estimated from data when having reliable data available. In this research, we use a theoretical minimum safe time clearance kept by each vessel with respect to its predecessor, and we name it as safe headway (h^{safe} [s]). Previous studies considered the safe vessel braking distance (d_n [m]) in confined waters as 3 times the vessel length (Fujii and Tanaka, 1971; Pietrzykowski, 2008), independent of vessel speed and load of the vessel. More recent studies, based on AIS data, have shown that a longitudinal space in front of a vessel suits the comfort zone of ship navigators in open waters (Hansen et al., 2013). Thus, for confined waters, we define the individual safe vessel braking distance (d_n) as 3 times the vessel length. Hence, the safe headway for each individual vessel (h_n^{safe}) can be calculated as d_n divided by its speed over ground (v_n [m/s]) in the direction towards the intersection (speed measured on surface, while the vessel might navigate at a higher or lower speed depending on the current in the water), as shown in the following equation:

$$h_n^{safe} = d_n/v_n \tag{4.1}$$

In vehicular traffic, it is assumed that while a vehicle is occupying the intersection, no other vehicle can enter until the first vehicle goes out. For waterways, due to the larger distance to cover and the low sailing speed, two conflicting vessels could be allowed simultaneously at the intersection. Hence, we consider that when the vessel inside the intersection has travelled more than half of the length of her path through the intersection to her specific direction, the next vessel can safely enter the intersection area, always respecting d_n.

The mean safe headway ($\overline{h}^{safe}$) can be calculated as the mean of h_n^{safe}. Since this is dependent on data availability, in case of not having this individual speed data, an educated guess of the mean speed, for example, in relation to waterway limits (width and water depth), can be made by expert consultation.

Equation 4.2 introduces the maximum flow in any stream without any conflict (q_{1D} [vessels/hour]), which can be calculated with the inverse of $\overline{h}^{safe}$ ([h]). As a result, the calculated flow is the total number of vessels that is able to cross the intersection within an hour in any direction without any conflict with other directions.

$$q_{1D} = 1/\overline{h}^{safe} \tag{4.2}$$

The probability that a vessel from stream i occupies the intersection (P_i) can be obtained by multiplying three factors (see equation 4.3). The first factor (α_i) is the percentage of traffic volume from an origin to a destination. If vessels are considered to sail simultaneously from the same origin towards different destinations, because of the existence of TSS with exclusive lanes for each direction, this factor would be one. When there is no TSS in the area, α_i represents the share of traffic going to each direction. The second factor is the maximum flow in one direction without any constraint (q_{1D}), previously defined, and the third one is the occupation time (δ_i). δ_i represents the time that a vessel occupies the intersection, and it is obtained by dividing the length of the direction of stream i, as the conflicting distance previously discussed, by the average speed over ground of all vessels. The conflicting distances are defined for each combination of origin and destination at the intersection. After a vessel has travelled the corresponding conflicting distance, the conflict area is free and a coming vessel from any direction is allowed to enter the intersection.

$$P_i = \alpha_i \cdot q_{1D} \cdot \delta_i \tag{4.3}$$

A conflict matrix (A), which identifies all movements that cannot occupy the area simultaneously, is used to define whether a conflict occurs between two streams (0 if no conflict occurs or 1 if a conflict occurs). The conflicts are defined considering two opposite streams as free of conflicts, while the rest of directions will have conflicts with these free streams. Then, the probability of conflict of each stream ($P_{c,i}$) is defined in equation 4.4. To calculate it, the conflict probability of each stream should be obtained. The probability of occupying the intersection by stream i multiplied by the sum of probabilities that any of the other streams occupies the intersection in case of conflict, and by the conflict factor (A_{ij}), equals to the probability of occupation from stream *i*. When there is no conflict, the resulting value is 0. Hence, $P_{c,i}$ can be calculated as the sum of probabilities of conflict for each of the streams:

$$P_{c,i} = \sum_i (P_i \cdot \sum_{j \neq i} P_j \cdot A_{ij}) \tag{4.4}$$

Equation 4.5 defines the capacity of each stream by multiplying the maximum flow for stream *i* ($\alpha_i \cdot q_{1D}$) and the probability of not having having encounters in stream *i*, which equals to one minus the probability of having an encounter ($P_{c,i}$). The resulting value provides an estimated value of the maximum vessel flow of each stream.

$$C_i = \alpha_i \cdot q_{1D} \cdot (1 - P_{c,i}) \tag{4.5}$$

The value of C for the whole intersection is obtained with the sum of the capacity in each direction by using equation 4.6.

$$C = \sum C_i \tag{4.6}$$

4.4 Case study

The application of the estimation method in a real scenario is used to demonstrate its applicability. Therefore two case studies of intersections from the Port of Rotterdam have been carried out. Data from the Automatic Identification System (AIS) and the radar have been used. An explanation of both types of data and what is included in both datasets is presented in the subsection 4.4.1. The following subsections present the research area and the content of the dataset (subsection 4.4.2), the analysis of the datasets used (subsection 4.4.3), the results of the capacity estimation (subsection 4.4.4) and a evaluation of the method (subsection 4.4.5). To investigate the effect of the input variables from the method, a sensitivity analysis is performed in subsection 4.4.6.

4.4.1 Automatic Identification System (AIS) and radar data background

Since we want to apply the method previously developed in a real waterway intersection, we use data from two different vessel traffic recording systems.

The Automatic Identification System (AIS) was established by The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). AIS is an autonomous and continuous broadcast system, that operates in the Very High Frequency (VHF) maritime mobile band (IALA, 2004). The principal functions of AIS, indicated by IALA (2004), are: (1) the information exchange between vessels within VHF range of each other to increase the situational awareness and safety; (2) the information exchange between a vessel and a shore station, such as a Vessel Traffic Service (VTS), to improve traffic management in congested waterways; and (3) the automatic location reporting in areas of mandatory and voluntary reporting. The shipboard information from the vessel sensors includes static, dynamic and voyage related data.

Similar data can be obtained with radars; they are obtained from the reflection of short pulses of radio waves generated by the radar that are reflected back by the vessels. The distance between the vessel and the radar can be obtained (Sonnenberg, 2013).

There are advantages and disadvantages for both AIS and the radar datasets to be applied in this case study (Lin and Huang, 2006). The coverage for AIS is around 40 nautical miles, while for the radar coverage is limited to 24 nautical miles, even though different radar coverages can be fused. Regarding the vessel position, although the AIS and the radar data have some differences in the dynamic variables (speed, latitude, longitude, etc.), their accuracy is similar (Lin and Huang, 2006). In specific cases there are large differences that might be due to problems with the AIS or the radar signals.

Radar coverage might be limited in space due to radar blind and shadow areas, and some areas might be uncovered. If this happens, it can be identified. Moreover, all vessels are visible under the radar coverage, while in AIS data, only vessels with AIS transmitters are visible. Since 2000, the requirements have been changing and, nowadays, most of the cargo and passenger vessels need to have a transmitter installed

(International Maritime Organization, 2000). Since just part of the inland vessels have an AIS transmitter, and almost none of the recreational ones, the radar coverage is normally better than the AIS inside a port.

Both AIS and radar data have several practical applications, such as collision avoidance, vessel traffic services (VTS), maritime security, aids to navigation, search and rescue and accident investigation (Kujala et al., 2009; Mou et al., 2010; Tsou, 2010; Yip, 2008). The use of AIS and radar data for research provides the opportunity to develop statistical analysis of accidents, vessel behaviour, etc., taking into account different circumstances, including weather, time of the day or year, among other things. The relevant information included in the AIS and radar messages for this research is summarized in table 4.1. As it can be seen, there are few differences in content between AIS and radar datasets, but these differences do not affect the application of the method and the required inputs are available in both datasets. One main difference between the two datasets is the signal identification. The AIS signals are recorded based on the MMSI, which is a unique number for each vessel and allows to follow their path with the consecutive signals. Although, the radar data records signals without any information for the identification of which vessel is it, the dataset used has already a track number that identifies each vessel trip with a unique number. Recent studies have shown the possibility of using data fusion algorithms to combine the both datasets, which might allow the detection of errors in the AIS data among others (Kazimierski and Stateczny, 2015).

Table 4.1: AIS and radar information.

Information	AIS	Radar
MMSI number	✓	
Length [m]	✓	✓
Beam [m]	✓	✓
Longitude (X coord.)	✓	✓
Latitude (Y coord.)	✓	✓
Speed	✓	✓
Heading	✓	✓
Course over ground	✓	✓
Draught	✓	
Date / Time	✓	✓
Vessel type	✓	✓
Track number		✓

4.4.2 Research area and dataset

The estimation method introduced has been tested in two intersections in the Port of Rotterdam (the Netherlands) shown in figure 4.2. The research areas considered are two T junctions between two waterways, Oude MaasHartelkanaal (see plain square in figure 4.2), and Oude MaasNieuwe Maas (see striped square in figure 4.2). The chosen intersections are ones of the busiest intersections in the Port of Rotterdam, and the intersections do not have a TSS scheme. The datasets for this research were provided by the Port of Rotterdam Authority.

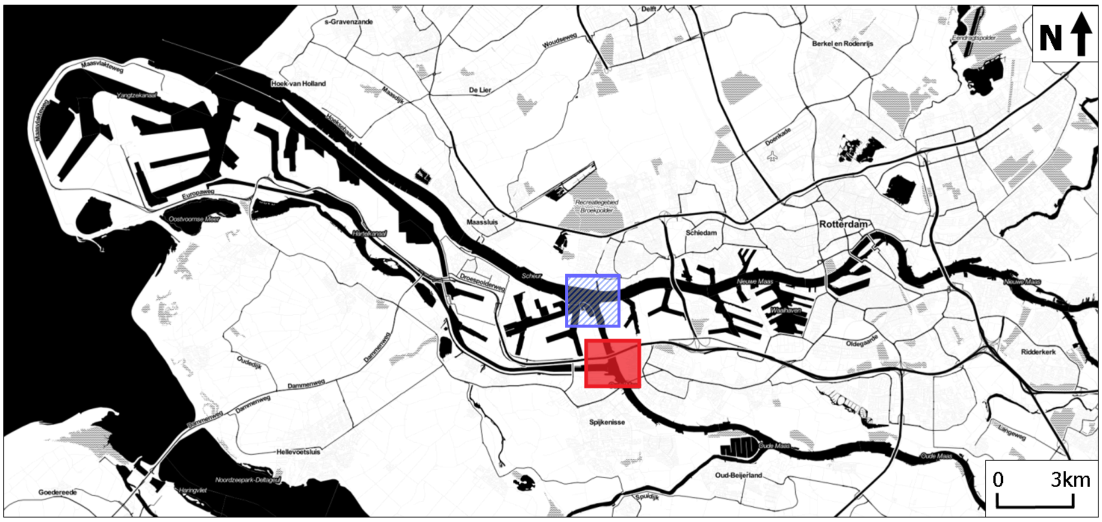

Figure 4.2: Research areas in the Port of Rotterdam (Oude MaasNieuwe Maas intersection (striped square) and Oude MaasHartelkanaal (plain square)).

The first dataset used is from the Oude MaasHartelkanaal intersection (I1), and it contains the information of a week of both AIS and radar data, from the 1st until the 7th of September 2014. A week was chosen to include daily patterns in vessel traffic. The weather conditions during that week were favourable, which do not have any implication on the vessel behaviour from the dataset.

The Port of Rotterdam has radar stations all along their waterways covering the complete area, with some areas with lower radar effectiveness. However, as previously introduced, not all inland vessels are AIS-equipped. In this research, in case of just using the AIS information, the total amount of vessels would be underestimated. The dataset contains all the signals from vessels using radar data, but only 62% of these signals have AIS details. For this reason, the radar data have been used for the analysis.

Figure 4.3 shows a detailed layout of I1 with some vessel trajectories. Although vessels do not follow specific lanes, and there is no a TSS scheme for this intersection, they tend to sail along similar paths. In the research area, based on the density analysis of the dataset, the paths are defined more or less by two separated directions in each waterway (see figure 4.4, left), except for the north part of the Oude Maas, due to an infrastructure constraint. In that location there is a bridge crossing the waterway, thus vessels need to adjust their path between the piles of the bridge. The width between the piles is enough to allow encounters without effects on the navigation. The intersection area chosen for the calculation is the area between each of the cross sections defined in figure 4.4, left.

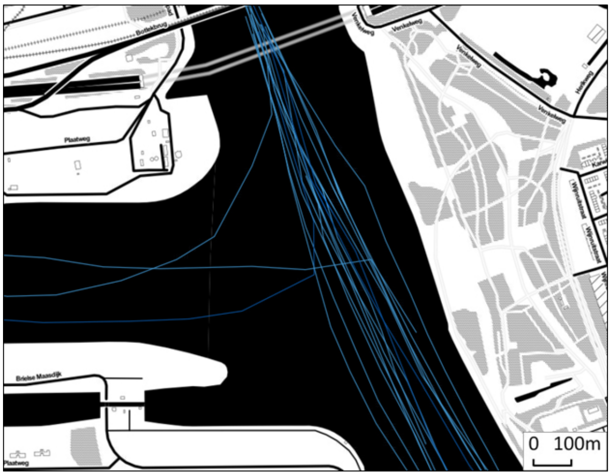

Figure 4.3: Example of vessel trajectories in the Oude MaasHartelkanaal intersection (I1).

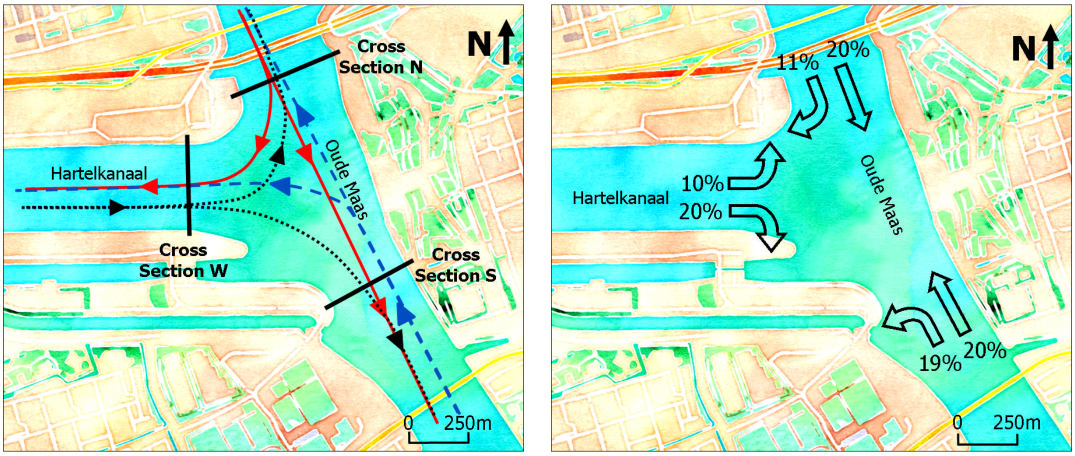

Figure 4.4: Oude MaasHartelkanaal map (vessel paths (left) and traffic shares (right)).

The minimum interval between consecutive signals from a vessel is 5 seconds, and the dataset has almost half a million messages recorded from 5209 different vessels. Each signal consists of a coordinate point in the area and the tracks are obtained by linking all the points that belong to the same track for each vessel. Each of these tracks is a vessel passing the intersection, which means that repeated visits from the same vessel count as independent tracks.

The moored vessels, mainly in the north side of the Hartelkanaal, keep also sending signals every 1 to 3 minutes. This means that from the whole dataset, almost 70% of the messages are from moored vessels, which are removed from the dataset as they do not occupy space in the intersection, and as such, these are not relevant for the capacity estimation. Hence, there are 3395 individual sailing vessel tracks remaining. From the remaining individual vessel tracks, only 66% have a whole track going from one of the cross sections of the intersection to another one (see figure 4.4, right). Most of the partial tracks consist of few signals next to the berthing areas, which are assumed to be moored vessels, and these vessels do not affect to the vessel traffic in the intersection.

The remaining signals are partial tracks with few signals which do not provide enough information for their analysis. These might be erroneous recordings with missing data or signals from vessels moored which coordinates are wrong. Many of these signals have a time interval longer than expected for a sailing vessel to cross the intersection. In this research, we assume that the distribution of wrong signals is equal in all directions, thus, it does not have an effect on the traffic shares in each direction. Therefore, the estimation method is not affected by their removal.

The second dataset is from the Oude MaasNieuwe Maas intersection (I2). This dataset is more limited and it contains the passing vessel information from three cross sections in that intersection (see figure 4.5). This dataset contains the information of a week of radar data during a busy week from 2015, from the 9^{th} until the 15^{th} of May. This dataset contains a total of 8192 recordings, which correspond to a total of 3745 vessel identified vessel tracks that go from a cross section to another one. The rest of the signals (around 9%) are unidentified vessels which cannot be tracked.

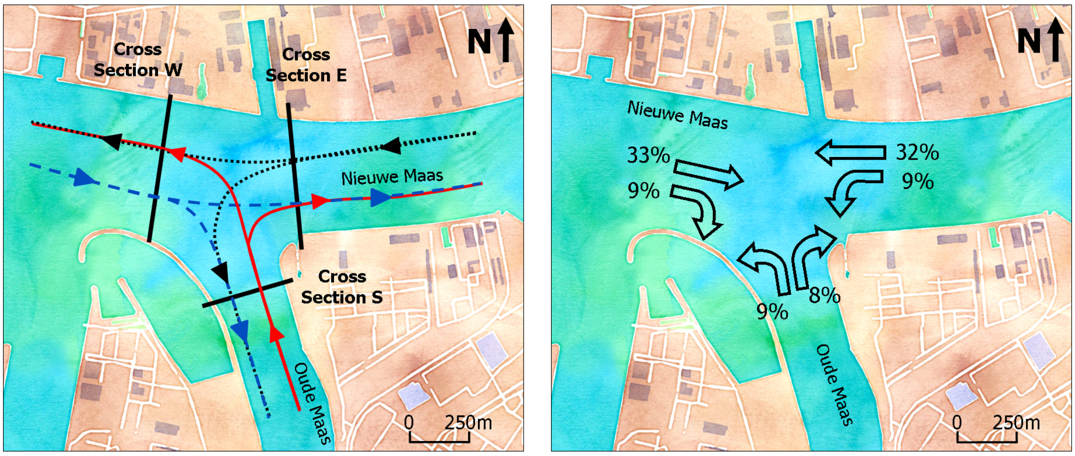

Figure 4.5: Oude Maas Nieuwe Maas map (vessel paths (left) and traffic shares (right)).

4.4.3 Data analyses

Once the datasets have been cleaned, the resulting information has been analysed and used to evaluate the applicability of the estimation method presented in section 4.3.

The estimation method considers the assumption of an average speed for all vessels to calculate the occupation time in the intersection. A first hypothesis is that a correlation between vessel dimensions and sailing speed exists for vessels in a port. However, as shown in table 4.2, the data analysis for I1 revealed a low correlation between the length or the beam of the vessels and their speed. This could be explained because ships are sailing within a limited speed range due to port regulations. So, even though vessels might be able to sail faster, in some cases, they maintain a lower speed. Thus, the assumption of an average speed for all vessel types holds for the application of the method. Regarding the correlation between vessel speed and headway (passing time interval with respect to the predecessor vessel), the dataset does not reflect any pattern between them due to the stochastic traffic flow during the day. Hence, we do not consider any possible correlation in this research.

Table 4.2: Correlation values between variables for I1.

Variables	Speed
Length	-0.32
Beam	-0.31
Headway	-0.07

In order to apply the method, the first step is to obtain the safe headway for each vessel (h_n^{safe}), which is calculated from each vessel length. We expect the safe headways to be lower than the real hedways (h_n). As shown in figure 4.6, it can be seen with a density plot that more than 95% of h_n are higher than h_n^{safe}, and most of the lower ones occur due to overtaking situations or incorrect data that cannot be verified. In reality, vessels maintain always safe distances as shown in previous studies (Pietrzykowski, 2008). Based on this, the authors consider h_s to be a suitable approximation of the minimum headway to calculate the vessel flow. The figure shows two main clusters of results. Since h_n^{safe} is obtained based on d_n, dependent on the vessel length, these clusters might happen because of the most representative vessel lengths.

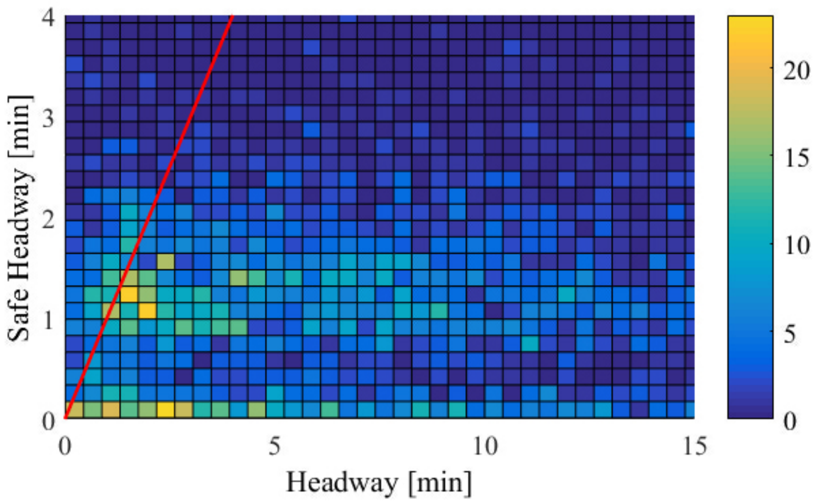

Figure 4.6: Density plot of safe headway vs actual headway in I1.

Similar results are obtained for I2, where more than 93% of h_n are higher than h_n^{safe} (see figure 4.7). The time in this dataset is rounded to minutes. Because of this, the headway values in two columns are 0, and the results show a similar pattern as in the previous dataset.

The method assumes a unique speed for all vessels to calculate h_n^{safe}. As shown in table 4.2, there is little correlation between speed and vessel characteristics. The data showed that vessels with the same characteristics do not keep a specific range of speeds and any vessel type can have low and high speeds. Hence, based on the average speed results from the datasets (see figures 4.8 and 4.9), a vessel speed of 8 knots for I1 and 9 knots for I2 are used to calculate $\overline{h}_n^{safe}$. For I1, with an average vessel length of 120 meters, $\overline{h}^{safe}$ equals to 1.46 minutes. By using $\overline{h}^{safe}$ in equation 4.2, q_{1D} equals 123.5 vessels per hour (ves/h). For I2, with the same average vessel length, the $\overline{h}^{safe}$ equals to 1.30 minutes, and q_{1D} equals 138.9 vessels per hour (ves/h). These values are based on the assumption of uniformly distributed vessel arrivals, but in reality the arrival is not uniform and uncontrolled. When having dense traffic situations, the vessel flow might be substantially influenced by the VTS advice. Hence, the vessel arrival distribution could become uniform. The flow is the maximum value that ideally could be obtained with continuous vessel traffic in one stream.

Figure 4.4, left, shows the possible movements in each direction for I1. Based on these paths, the conflicting movements of vessels in the different directions can be identified. The individual conflicts allow us to build a conflict matrix for the intersection (see table 4.3). The table shows, for example, that there is a conflict between vessels going in the direction SW and NS. Thus, their value in the conflict matrix is identified with 1. Table 4.4 shows the conflicting movements for I2.

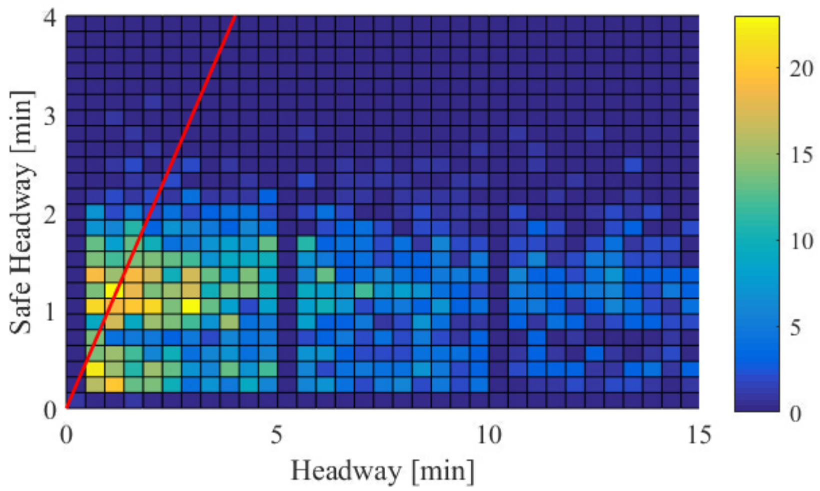

Figure 4.7: Density plot of safe headway vs actual headway in I2.

Table 4.3: Conflict matrix I1.

Direction	NS	NW	SN	SW	WN	WS
NS	-	-	-	-	-	-
NW	0	-	-	-	-	-
SN	0	0	-	-	-	-
SW	1	1	0	-	-	-
WN	1	0	1	1	-	-
WS	1	0	0	0	0	-

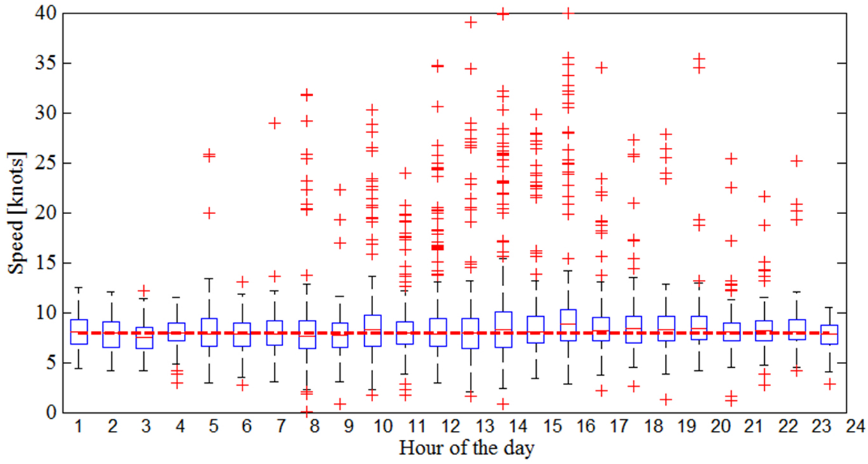

Figure 4.8: Vessel speeds per hour of the day (I1).

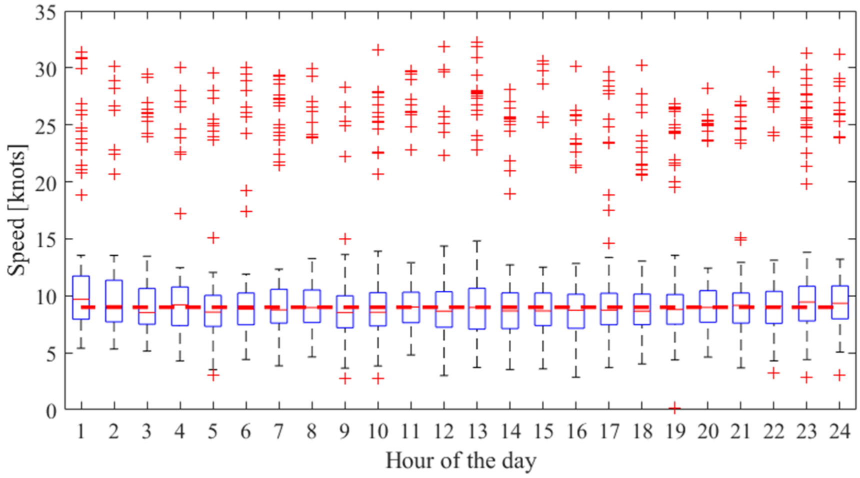

Figure 4.9: Vessel speeds per hour of the day (I2).

Table 4.4: Conflict matrix I2.

Direction	SW	SE	WE	WS	EW	ES
SW	-	-	-	-	-	-
SE	0	-	-	-	-	-
WE	1	1	-	-	-	-
WS	0	0	0	-	-	-
EW	1	0	0	1	-	-
ES	1	0	1	1	0	-

4.4.4 Results of capacity estimation method

With the results from the data analysis, the calculations to estimate capacity can be performed. First, in order to calculate the probability of conflict per direction, there are several values that need to be defined, and these are summarised in table 4.5.

Table 4.5: Probability of conflict per direction (I1).

Direction	Traffic Share	Distance to cross [m]	$\alpha_i \cdot q_{1D}$ [ves/h]	t_i [min]	P_i	1-$P_{c,i}$	C_i [ves/h]
NS	20%	750	26.7	1.52	0.68	1.00	26.7
NW	11%	365	14.5	0.40	0.18	1.00	14.5
SN	20%	750	21.5	1.52	0.54	1.00	21.5
SW	19%	695	19.7	1.41	0.46	0.61	11.9
WN	10%	680	13.3	1.38	0.31	0.49	6.5
WS	20%	575	27.8	1.16	0.54	0.64	17.7

The traffic shares for each direction, which can be extracted analysing the different vessel paths from the dataset, are shown in the second column. The time that a vessel from one stream is occupying the intersection (δ_i) is calculated based on the following conditions: the intersection length is defined for each of the directions of each stream, according to figure 4.4, left, and the distances vary between a minimum of 365 meters up to 750 meters; the distance to be travelled by a conflicting vessel is considered as 50% of these lengths, which leads to a longer distance than 3 times the median vessel length (d_n), as explained in section 4.3; and, a speed of 8 knots is used, as explained in the previous subsection.

Considering this occupation time, the different shares per direction and the flows, the probability that each stream occupies the intersection (P_i) is obtained. With this value, conflict probabilities for each direction ($P_{c,i}$) are obtained. Using equation 4.4, the capacity for each stream is calculated. Hence, the resulting estimated capacity (C) of I1 is the result of the sum of the capacity of each stream, and it equals 98.7 ves/h, considering these specific traffic shares.

When applying the method to the second research area (I2), it can be seen in table 4.6, that the traffic shares in this intersection are different. For this intersection, the vessel speed chose is 9 knots, based on the dataset, and with the specific distances for the intersection, the method results on an estimated capacity (C) of 102.9 ves/h.

Table 4.6: Probability of conflict per direction (I2).

Direction	Traffic Share	Distance to cross [m]	$\alpha_i \cdot q_{1D}$ [ves/h]	t_i [min]	P_i	1-$P_{c,i}$	C_i [ves/h]
WE	33%	800	36.4	1.44	0.87	1.00	36.4
WS	9%	600	9.9	1.08	0.18	1.00	9.9
EW	32%	780	36.1	1.40	0.85	1.00	36.1
ES	9%	580	10.2	1.04	0.18	0.81	8.3
SW	9%	710	24.5	1.28	0.52	0.01	0.3
SE	8%	790	21.8	1.42	0.52	0.55	12.0

4.4.5 Evaluation of the method with real data

In order to assess the capacity estimates calculated with the proposed method, the results can be compared to the maximum observed vessel flow for each intersection from real data. Since usually there are not many traffic peaks in this area due to stochastic arrivals and port regulations, we decided to use a small time interval that allows us to find out significant traffic peaks. Because of this, we decide to use an interval of 6 minutes (0.1 h).

For I1, the dataset reveals that the maximum number of vessels passing the intersection in this interval has a peak of 7 vessels. The peak of 7 vessels per interval of 6 minutes can be considered as the capacity value of the intersection. Using this maximum flow, the resulting maximum flow per hour that would cross the intersection is 70 ves/h. From the estimation method, we obtained a value of 98.7 ves/h. This result shows that the intersection has not reached the capacity value, and the maximum flow is below 75% of utilization during peak times. Thus, the intersection could still allocate higher vessel flows.

In the case of I2, for the same interval of time, the maximum number of passing vessels equals to 9. Considering this flow per 6 minute interval, the resulting maximum flow crossing the intersection is 90 ves/h. Comparing this result with the estimated capacity of 102.9 ves/h, the utilization during peak times reaches almost 90%, which is a really high value. A possible explanation for this is because the main flow is from EW and WE (66% as seen in figure 4.5, right), which means that the number of conflicts is substantially lower than in I1.

4.4.6 Sensitivity analysis

This section presents a sensitivity analysis performed to test the effects of various parameters on the estimated capacity in I1. In figure 4.10, the estimated capacity of the intersection is drawn against various parameters: safe vessel braking distance (d_n), intersection length and average vessel speed.

Figure 4.10, top left, shows that the factor used to calculate dn provides almost the maximum capacity for this intersection. The maximum capacity is obtained when dn equals 2, but the difference between the chosen d_n value and the lower ones is just 3 to 5 ves/h difference. The relevant change appears when d_n increases. When increasing the distance, the capacity would increase the headways between vessels and, consequently, decrease the flows to around 10 ves/h less for each increase.

The relation between capacity and intersection length (figure 4.10, top right) shows a negative relation. An increase in the intersection length leads to a decrease in capacity. Thus, intersections with the same traffic shares, but with different area would have different capacities. However, the difference between the extreme values is less than 10 ves/h, which shows that the specific location of the cross section will not significantly affect the estimated capacity.

The effect of the average vessel speed (figure 4.10, bottom left) is opposite to the previous one. An increase of average vessel speed leads to shorter headways and a higher capacity of the intersection. A variation of 0.5 knots leads to a 5% variation of the estimated capacity. Thus, it is important to choose a suitable speed for the specific study area when applying the method.

As seen for each of the comparisons, the outcome of the method is dependent on the main variables chosen. The safe vessel braking distance (d_n), defined in previous research as 3 times the vessel length, is acceptable for this port location. Regarding the intersection length, the method is not very sensitive to variations of them, which shows that the method is not strongly influenced by the choice of the location for each cross section.

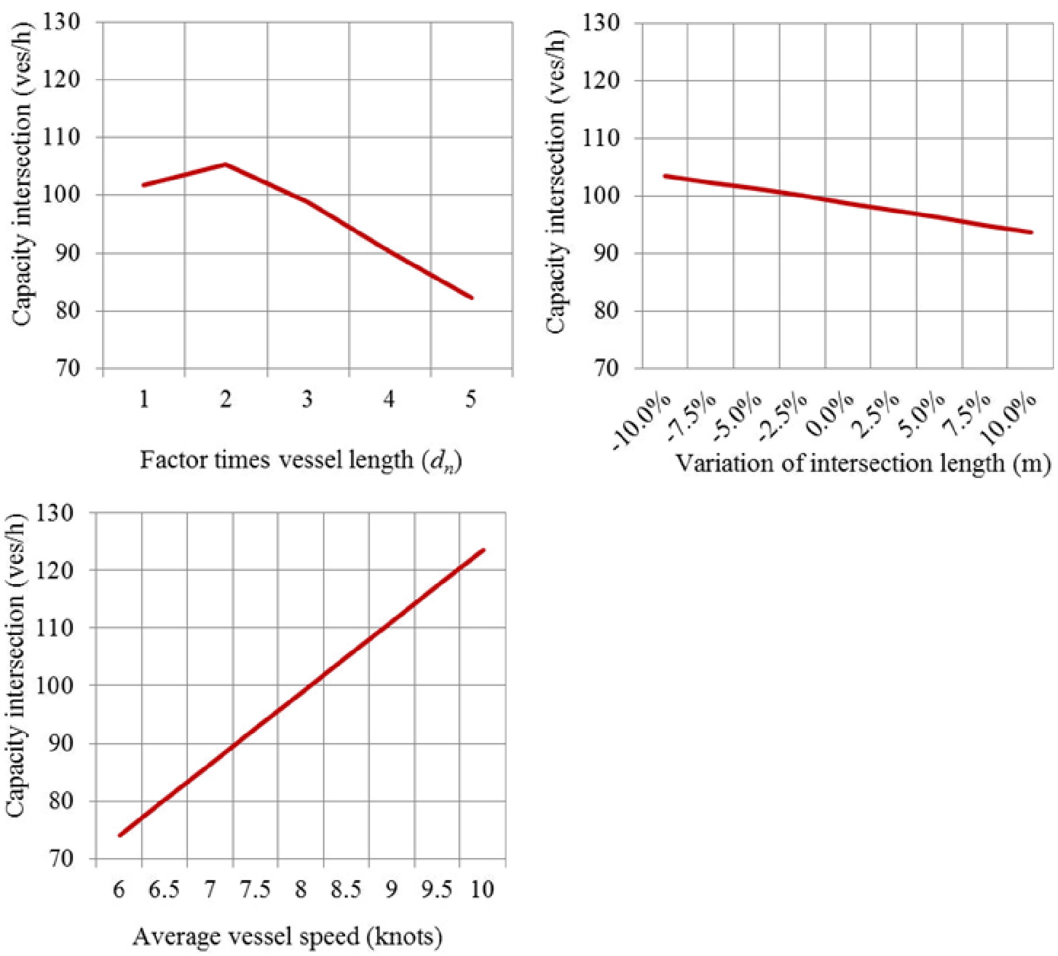

Figure 4.10: Relation between intersection and capacity factor times vessel length (d_n) (top left), % variation of intersection length (top right), and average vessel speed (bottom left).

The average vessel speed used in the method has a strong influence on the resulting estimated capacity. Therefore, a wise choice of every parameter is important because of the sensitivity of the method, and none of them can be excluded because of their relevant effects on the final results. Hence, a comparison of the estimated capacity with real data in busy situations, as we previously presented in this research, is a good way to evaluate the parameters chosen.

4.5 Summary and future research

The method introduced in this paper is a generic method to estimate waterway intersection capacity. The base of this method is the conflict technique, developed for unsignalised road intersections. The analogy between road and waterway traffic helps to develop the method, that identifies the conflicting interactions between vessel movements that occur at an intersection. The result of the method provides the maximum amount of vessels passing the intersection in a time period, e.g. an hour, assuming that we have homogeneous and independent vessel arrivals. The method developed is mainly dependent on the average vessel speed and the traffic shares in each direction, and it slightly depends on the intersection area chosen.

In order to test the feasibility of the method, two case studies from real intersections from the Port of Rotterdam have been performed. The case studies show that the current maximum vessel flow in the intersections is below the estimated capacity, and it proves the applicability of the method. As discussed in the previous section, the method is sensitive to changes in its main variables. Thus, a good initial value has to be chosen carefully for an accurate result in future applications. Moreover, the traffic shares have a considerable impact on the resulting capacity, which proves that different traffic management strategies, such as changing traffic routes or origins and destinations in a port, might lead to higher capacities with less conflicts in waterway intersections.

The estimated capacity value of a waterway intersection can be used as a proxy value to assess the current traffic situation. This may lead to changes in the current traffic management strategies to reach higher vessel traffic flows. It can also be used to change some traffic rules, as well as the assessment of new port designs. In future research, a comparison microsimulation could be used to estimate the capacity of an intersection. The results could be compared to the ones obtained with the presented method at the same intersection to ensure the usefulness of the method and its generic applicability. The sensitivity analysis also shown the influence of a variation in certain parameters, which could be further analysed in other scenarios. Weather conditions such as current or wind effects might also be considered in order to improve the method.

Acknowledgements

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Chapter 5

Risk Assessment Methodology for Vessel Traffic in Ports

In this chapter a risk assessment methodology for vessel traffic in ports is presented. The methodology includes the steps for the risk assessment of ports and a case study in the Port of Rotterdam proves its applicability. Expert knowledge is used to define the most important criteria for vessel navigation in confined waters. The combination of risk perception from expert navigators and consequences from risk experts, results in a new index to assess nautical risks in each port area. A case study using the methodology in the Port of Rotterdam is developed. This methodology can be applied to assess changes in vessel traffic management strategies or in fleet compositions.

This chapter is an edited version of the article:

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Risk Assessment Methodology for Vessel Traffic in Ports by defining the Nautical Port Risk Index. *Safety Science*, under review.

Abstract

Ports represent a key element in the maritime transportation chain. Larger vessels and higher traffic volumes in ports might result in higher risks at the navigational level. Thus, the dire need of a comprehensive and efficient risk assessment method for ports is felt. Many methodologies have been proposed so far with specific purposes such as individual vessel collision analysis, but their application to aggregated vessel traffic risks for the overall assessment of ports is not developed yet. Hence, the development of an appropriate approach for the appraisal of the vessel traffic risks is still a challenging issue. The objective of this research is to develop an assessment methodology to appraise the risk in a port area at an aggregated level by creating a "Nautical Port

Risk Index" (NPRI). After identifying the main nautical risks in ports, the Analytic Network Process (ANP) is used to derive the risk perception (RP) weights for each criterion from data collected through surveys to VTS operators and pilots. The identification of consequences related to each nautical risk is done in consultation with risk experts. By combining the RP values and the consequence of each criterion for a time period, the NPRI is calculated. The quantitative assessment of the vessel navigation in specific areas of a port is presented in a case study, and it has been validated by checking the results with experts in assessing nautical port risks from the Port of Rotterdam Authority. This method can be used to assess any new port design, the performance of different vessel traffic management measures or changes in the fleet composition, by implementing this risk assessment methodology into a simulation model. The methodology can also be applied to assess the risk levels of existent ports using the Automatic Identification System (AIS) data.

5.1 Introduction

Navigation in ports has become more and more complex during the last decades. The increase of the maritime transportation of goods and the vessel sizes lead to higher vessel flows in ports. Consequently, the potential risks at the navigational level increase, due to the lower manoeuvrability of larger vessels in a restricted areas, higher probabilities of close encounters or overtakings, and larger consequences of incidents. For this reason, risk analysis in maritime transportation has become a relevant topic in recent years, as shown by research on historical accident analysis in ports (Darbra and Casal, 2004; Mou et al., 2010; Yip, 2008).

There are different types of risk assessment, such as qualitative or quantitative, with different purposes, such as collisions or terminal operations. This research focuses on the quantification of nautical risks in ports. A wide variety of quantitative maritime risk assessment methods exists (DNV, 2001; Li et al., 2012; Mabrouki et al., 2014). Most of the existing methods calculate the risk in a data-driven or probabilistic way (an in-depth literature review on risk assessment methods is discussed in section 5.2.3). However, since the amount of casualties in ports is limited, maritime traffic in ports cannot be assessed based on single casualties. Moreover, the risk prediction for a non-existent situation could not be performed with a data-driven approach. The risks and uncertainty involved in the navigation process, and the human influence in the navigational vessel behavior are a significant factor contributing to the overall risk. The aim of this research is to provide a methodology that provides a risk indicator for the different port areas that supports decision-makers to assess port navigational risks in different types of future situations, such as changes in traffic or infrastructure design. We have named this index as "Nautical Port Risk Index" (NPRI). The main contribution is that the methodology depends on the overall vessel traffic information and not only on single casualties, and that it combines the relevant nautical risk criteria with expert judgement for the assessment of any port area.

This paper is organized in four sections. The methodology for the new risk assessment methodology is presented in section 5.2. The section includes the definition of NPRI, the choice of the risk criteria in port navigation, the content of the assessment method and the NRPI calculation. Section 5.3 presents the empirical analysis of the previously introduced methodology, the data collection from expert navigators and the results from the risk quantification in a case study, with a sensitivity analysis. Finally, section 5.4 presents the conclusions of the present work as well as recommendations for future research.

5.2 Assessment Methodology for Nautical Port Risk

The methodology proposed in this research for the nautical port risk assessment consists of several steps, which are described in figure 5.1. After identifying the problem to be assessed, the methodology starts with the definition of the Nautical Port Risk Index (NPRI) based on existing risk definitions in subsection 5.2.1. This definition determines the selection of the risk criteria to be used in this research by a group of experts in port navigation in subsection 5.2.2. Once the criteria have been chosen, the risk assessment method has been developed following several steps, that combines expert judgement from navigators and experts in port risks, and it is described in subsection 5.2.3. Finally the theoretical quantification of risks with the NPRI is presented in subsection 5.2.4. This step might lead to the reconsideration of some of the selected risk criteria to avoid inconsistencies or due to the need of more expert judgement data, according to the interests of the corresponding decision makers. Once the methodology is completely defined, it will be applied to case studies by using real or simulation data, followed by a final analysis of the results and assessment of the port. A case study using real data with its application is presented in section 5.3.

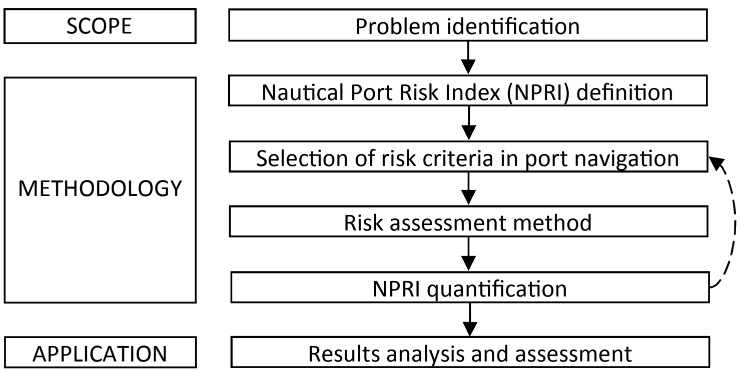

Figure 5.1: General structure for the development of the NRPI methodology.

5.2.1 Nautical Port Risk Index definition

In the field of risk assessment, there is no unique definition of the risk concept, and different ways of defining and understanding risk exist. This concept has evolved with different definitions depending on the field of application or on the risk perspective chosen (Aven, 2012). Recently, a comprehensive classification of risk definitions and an overview of risk analysis approaches for maritime transportation has been presented (Goerlandt and Montewka, 2015). The most common definition of the risk concept is using frequencies and consequences (Aven, 2011). The International Maritime Organization (IMO) (2007) defined risk as “the combination of frequency and severity of the consequence” (p. 4). We consider this definition as an adequate formulation of the risk concept, because it allows a quantification of the risk. However, this quantification is subject to how these frequencies and consequences are defined, and it should be developed for each port according to the decision makers who perform the assessment.

The frequencies have been traditionally defined by means of probability (Debnath and Chin, 2010; Fowler and Sørgård, 2000; Mou et al., 2010; Yip, 2008). Merrick and Van Dorp (2006) presented a methodology to assess uncertainty in maritime risk assessments, but its application is dependent on the availability of data. All these different approaches are mostly based on accidents that can be quantified from historical data, or a probability derived from accident data. However, these approaches do not include a way to quantify the risks caused by near misses, high densities or the effects of external conditions in navigation. The NRPI consists of a combination of the risk perception and consequences, where the terms are introduced more in detail below. In this research, we define Risk Perception (RP) as the frequency of accidents, which can be quantified by defining a weighing system with the contribution to nautical risk of a predefined set of relevant criteria related to risks in navigation. Hence, RP will be derived from expert judgement when comparing different navigational risk criteria according to their experience and background in a given location. Because of the complexity and dependencies between all the factors involved in navigation, the RP cannot be determined in a general way, and it should be related to specific areas of interest.

The RP factor provides a value of the risk level perceived in each situation on potential accident or near miss occurrence. The higher the risk criteria are rated by experts, the higher risk perception, thus the higher their contribution to the overall risk. RP measures the risk without any dependency on historical data, although the expertise of each expert will condition the results. Hence, this is generally applicable to any future port expansion or port under development. Moreover, since the RP value is based on expert judgement, if the experts have deep knowledge in navigation, the uncertainty in navigation and the possible non reported accidents or near misses are implicitly included in this value.

The consequences can be defined by the corresponding decision maker, such as harbor stakeholders or port authorities, who want to assess the specific situation, according to the knowledge and the importance of each factor for their risk evaluation. The scale of consequences is a subjective factor that should be defined, as previously done in other risk assessment (Trbojevic and Carr, 2000; Ulusçu et al., 2009).

The NPRI results from multiplying the RP value by the consequences in each area, based on the chosen scale for the characteristics of the port, which provides the total risk value for each area within the port.

5.2.2 Risk criteria in port navigation

The navigational risks are diverse and have many different specificities inside a port. In order to calculate the NPRI, all risk factors related to navigation should be assessed in a structured way, and a selection of the most relevant factors should be made according to expert judgement. An overview of factors previously used in navigational risk assessment related studies is presented in table 5.1, where the application of each study is explained.

Table 5.1: Previous research using nautical risk factors.

	Reference	Application
(a)	Trbojevic and Carr (2000)	Risk based methodology to improve safety in ports
(b)	Balmat et al. (2009)	Definition of an individual ship risk factor
(c)	Yip (2008)	Identification of risks in Hong Kong port from historical data
(d)	Prabhu Gaonkar et al. (2011)	Definition of a traffic safety index using AHP
(e)	Inoue (2000)	Evaluate ship-handling risks for navigation in congested waterways
(f)	Pak et al. (2015)	Identification of navigational risks and safety evaluation between ports
(g)	Arslan and Turan (2009)	Analysis of marine casualties at the Strait of Istanbul

Table 5.2 shows a detailed overview list of all the factors considered in these studies. The table describes the wide variety of criteria that have been considered and the lack of overlap in many cases. For this research, expert opinion is used to make a thorough assessment of the more influential navigational risks. The choice of the risk criteria used in this research was based on in-depth discussions with port experts and experienced pilots from the Port of Rotterdam. Factors as year of construction, flag or target factor of Paris MOU might not provide sufficiently representative information according to experts. For example, the year of construction does not provide any information about the maintenance or current state of the vessel. Hence, this information does not provide an accurate representation of the vessel conditions and its effects on their navigation, as well as the corresponding risk associated to them. The selection of factors was based on their direct effect on navigation and their possible quantification according to these experts. Table 5.3 summarizes the risk criteria chosen in this research and a detailed explanation of these criteria is provided in the following paragraph.

Table 5.2: Review of nautical risk criteria used in previous research.

Nr.	Main criteria	Sub-criteria	References						
			Trbojevic and Carr (2000)	Balmat et al. (2009)	Yip (2008)	Prabhu Gaonkar et al. (2011)	Inoue (2000)	Pak et al. (2015)	Arslan and Turan (2009)
1	Waterway	Location	χ						
		Traffic separation	χ						
		Type			χ				χ
		Complexity					χ	χ	
		Depth						χ	
		Width						χ	χ
2	Environmental conditions	Wind speed	χ	χ		χ	χ	χ	
		Wind direction	χ						χ
		Tide	χ					χ	
		Current	χ			χ	χ		χ
		Visibility	χ	χ				χ	χ
		Time of the day		χ		χ			χ
		Wave height						χ	
3	Vessel	Size	χ			χ		χ	χ
		Type	χ	χ	χ	χ		χ	χ
		Age	χ						χ
		Crew	χ						
		Maneuverability	χ						χ
		Pilotage requirements	χ						
		Escorting requirements	χ						
		Gross Tonnage		χ					
		Duration detentions		χ					
		Year of construction		χ					
		Flag		χ					
		Target factor of Paris MOU		χ					
		Port of registry			χ				
		Load				χ			
		Speed							χ
4	Traffic conditions	Overall					χ	χ	
		Local							χ
		Passing							χ
		Anchored							χ
5	Vessel reliability	Propulsion, steering, electrical power…	χ						
6	Port control	Traffic rules, navigational equipment, number of pilots / tugs	χ						
		Pilotage							χ
		VTS							χ
		Escort and salvage							χ

Table 5.2: Review of nautical risk criteria used in previous research. (*Continued*)

Nr.	Main criteria	Sub-criteria	References: Trbojevic and Carr (2000)	Balmat et al. (2009)	Yip (2008)	Prabhu Gaonkar et al. (2011)	Inoue (2000)	Pak et al. (2015)	Arslan and Turan (2009)
7	Organization	Management practices	χ			χ			χ
		Developing technologies							χ
		Pipelines							χ
		Regulations							χ
8	Human	Judgement / safety culture	χ						χ
		Knowledge	χ			χ			χ
		Communication	χ			χ			χ
		Experience				χ			
		Over worked				χ			
		Fatigue				χ			χ
		Resource shortage							χ
9	Machinery factors	Failures of engine, rudder, propulsion…				χ			

Table 5.3: Nautical risk criteria.

	Criteria		Sub-criteria
1	Infrastructure design (Infra. design)	1.1	Location (high buildings or flat landscape around)
		1.2	Type of infrastructure (Type infra.)
		1.3	Water depth (W. depth)
		1.4	Width
2	Environmental conditions (Env. cond.)	2.1	Wind speed (Wind sp.)
		2.2	Wind direction (Wind dir.)
		2.3	Current
		2.4	Visibility
		2.5	Time of the day (Time)
3	Vessels characteristics (Ves. char.)	3.1	Length
		3.2	Draught
		3.3	Speed over ground (Speed)
		3.4	Maneuvering capability (Man. cap.)
4	Traffic conditions (Traffic cond.)	4.1	Traffic mix (same or different types)
		4.2	Traffic volume (high/low vessel flows) (Traffic vol.)
5	Vessel Traffic Management (VTM)	5.1	Traffic rules and port regulations (Rules& reg.)
		5.2	Pilotage
		5.3	VTS assistance (VTS)

The infrastructure design is described by the location, depending on if it is close to high or low buildings which might affect sailing perception, the type of the infrastructure (bend, straight, crossing, etc.), the water depth and the width of the waterway or basin. The environmental conditions are considered to be decisive in navigation, thus a contribution to the risk. The criteria considered are wind speed and direction, current, visibility and time of the day. In previous research, Pak et al. (2015) considered these factors as one single environmental factor. However, because of their different effect in navigation, pilots recommended to include them as individual factors. The ones considered most relevant for this research are wind speed, wind direction, current, visibility and time of the day (day or night). To describe the traffic conditions, the vessel types are chosen in a generic way, based on the difference in maneuvering. Hence, we selected only three factors to represent all vessel types, which are length, draught and average speed of the vessels. The traffic conditions in each specific area depend on the traffic mix, when vessels are equal or different, and the traffic volume (vessels/time period), indicating how congested is the area. Finally, the last criterion corresponds to the Vessel Traffic Management (VTM) of the specific port, which includes traffic rules and port regulations, pilotage and Vessel Traffic Service (VTS) assistance, as factors that directly affect safe navigation. The contribution to risk of the traffic rules is considered as how flexible they are to, for example, allow navigators take certain decisions to avoid dangerous encountering or overtaking situations. In case of strict rules, we would consider them as “rule based”, while if they are flexible and adaptive to different situations, we would consider them as “goal based”. As previously mentioned, human factors, that cannot be quantified in an objective way, are left out as a criterion, and they are considered to be implicitly included within the other criteria from the risk perception from navigational experts.

5.2.3 Assessment method

There are different types of risk assessment (DNV, 2001); this research focuses on the quantitative navigational risk assessment of ports. Previous researchers on quantitative risk analysis of vessel navigation have used different methods for risk assessment with different applications, such as event and fault trees (Fowler and Sørgård, 2000), Bayesian Networks (BN) (Goerlandt and Montewka, 2015; Szwed et al., 2006) or the Analytic Hierarchy Process (AHP) (Arslan and Turan, 2009; Pak et al., 2015; Ugboma et al., 2006). Event and fault trees are useful for the causal-effect analysis of a specific risk and they are easy to understand. However, they depend on historical data and they become time consuming when the number of factors increases. BNs are a quantitative tool applied in modelling vessel traffic and they are really extended in the maritime traffic safety field. They allow for the combination of data with expert knowledge, and even though they are suitable for complex systems and include uncertainty in the probabilities, their complexity and the probability determination from experts might be difficult (Hänninen, 2014). In addition, data is necessary for their development.

The Analytic Hierarchy Process (AHP) has been used in several studies for risk assessment in the maritime field, such as for the assessment of shipping routes at sea (Wang et al., 2014). A qualitative hierarchical modelling of perceived collision risks in port fairways from experts was developed by Debnath and Chin (2009) for the Singapore Strait. Balmat et al. (2009) proposed a global risk factor for individual ships based on ships characteristics (dimensions, type of cargo, etc.), meteorological conditions and instant speed. Recent research proposed a port safety evaluation from a captain′s perspective based on fuzzy AHP (Pak et al., 2015). These different researches show different approaches of expert judgement, but the questioners that define the risk weights with AHP assume a top to bottom structure with independency between all the factors.

Despite the extensive literature related to maritime risk assessment, there is an absence of research that quantifies the risk value due the interaction between factors such as infrastructure, vessel traffic and environmental conditions in a proactive way. In navigation, there are many dependencies between factors where a change in one can affect others. The Analytic Network Process (ANP), which is an improved version of the AHP, allows to include these dependencies (Saaty, 2001). The method has been extensively applied in other risk assessment or decision-making processes that proves its usefulness (Sipahi and Timor, 2010), and will be used in this research to derive the RP from experts for each risk criterion.

The assessment method, according to the NPRI definition, is developed in two blocks, the RP and the consequences. The next two sub-sections describe the background on the method chosen for the weighing of RP, and the definition of the consequence scale.

Analytic Network Process (ANP) methodology

ANP is a tool to help solving decision-making problems, based on the analytical hierarchical process method (AHP), developed by Saaty (1990). The AHP method is structured in a hierarchical structure and the problem is divided into different clusters, while the decision problem has a network structure in ANP. One limitation of AHP is that the method assumes independence between factors, and the complex dependencies between the criteria describing real problems cannot be included in this technique. To overcome this disadvantage of the AHP models, the ANP method can be used (Saaty and Vargas, 2012; Saaty, 2001). ANP allows to model more generalized and complicated structures where the factors are divided into clusters which have interdependencies between them or within the same cluster. These relationships are evaluated and their influence over the overall decision-making process is calculated.

The ANP technique has several strengths, as both quantitative and qualitative factors, and individual and aggregated values can be included in the decision-making process. The technique is conceptually easy to apply and allows navigational experts to express their preference with pairwise comparisons between the decision criteria. Moreover, the main criteria and sub-criteria of the problem structure can be determined based on specific objectives from the interested working group. This provides a significant flexibility to adapt the problem design to any situation.

The application of ANP consists of several steps that, according to Saaty (1999), can be structured and summarized in the following steps:

1. Determine the relations between different clusters to relate the different criterion and define the whole network, as depicted in figure 5.2. These relations are determined between the main criteria or sub-criteria previously introduced in table 5.3, with respect to the research objective, according to in-depth discussions with experts. The individual relations between the different risk factors are shown with a 1 in table 5.4, and 0 represents that there is no relation.

When defining other risk criteria for a specific port which might have other characteristics, the ANP network should be accordingly adapted.

2. Perform pairwise comparisons at each level, between clusters of main criteria and between sub-clusters with the sub-criteria elements, according to their contribution to navigational risk. These pairwise comparisons are scaled according to their relative importance (table 5.5). Experts should be asked with questionnaires to rank each pair of elements according to the contribution to risk that has each of them. Their answers provide a pairwise score a_{ij} (eigenvector) is the ratio between the row element (*i*) over the column element (*j*), and it represents the relative importance of each element with respect to the other.

A drawback of the method is the complexity of the comparisons, that might seem abstract or difficult to understand by experts because of being unfamiliar with the method (Aragonés-Beltrán et al., 2010). Another drawback is the difficulty to relate completely different factors for comparison or dependent factors. Hence, the questionnaire should be better carried out with the support of a facilitator.

3. After composing the matrix of pairwise ratios (*A*), the *w* weight is calculated as a unique solution of equation 5.2. Where the largest eigenvalue of *A* is represented by λ_{max} and *w* is its corresponding eigenvector. A consistency index of a matrix of comparisons is defined by CI = (λ_{max}-n)·(n-1). Then, a consistency ratio (CR) is obtained by comparing the CI and the random consistency index (RI) defined by Saaty and Vargas (2012). CR is calculated for each cluster of judgements, and when CR is lower than 0.10, which implies that the adjustment is small compared to the actual values of the eigenvector entries, the comparison is considered to be consistent.

$$\begin{pmatrix} w_1/w_1 & ... & w_1/w_n \\ w_2/w_1 & ... & w_2/w_n \\ ... & ... & ... \\ w_n/w_1 & ... & w_n/w_n \end{pmatrix} \cdot \begin{pmatrix} w_1 \\ w_2 \\ ... \\ w_n \end{pmatrix} = \begin{pmatrix} 1 & ... & a_{1n} \\ a_{21} & ... & a_{2n} \\ ... & ... & ... \\ a_{n1} & ... & 1 \end{pmatrix} \cdot \begin{pmatrix} w_1 \\ w_2 \\ ... \\ w_n \end{pmatrix} = A \cdot w \qquad (5.1)$$

$$A \cdot w = \lambda_{max} \cdot w \qquad (5.2)$$

4. Build a supermatrix, a matrix which includes all the *w* obtained from the paired comparisons for each cluster.

5. Weigh the elements of each cluster respect the other clusters within the supermatrix (unweighted).

6. Perform paired comparisons among the main criteria based on the influence between each element.

7. Use the resulting value of each cluster (main criteria) to weigh each block of the unweighted supermatrix, resulting in a weighted supermatrix.

8. By raising the weighted supermatrix to powers until the weights converge, a limit supermatrix is obtained and the global priority weights are derived.

The resulting global priority weights can be used in this research as the risk perception (RP) values from experts, which indicates the contribution to the risk in navigation of each individual element previously defined. The resulting weights include the influence of some criteria and sub-criteria with others through the network design, which provides more realistic results than assuming them completely independent.

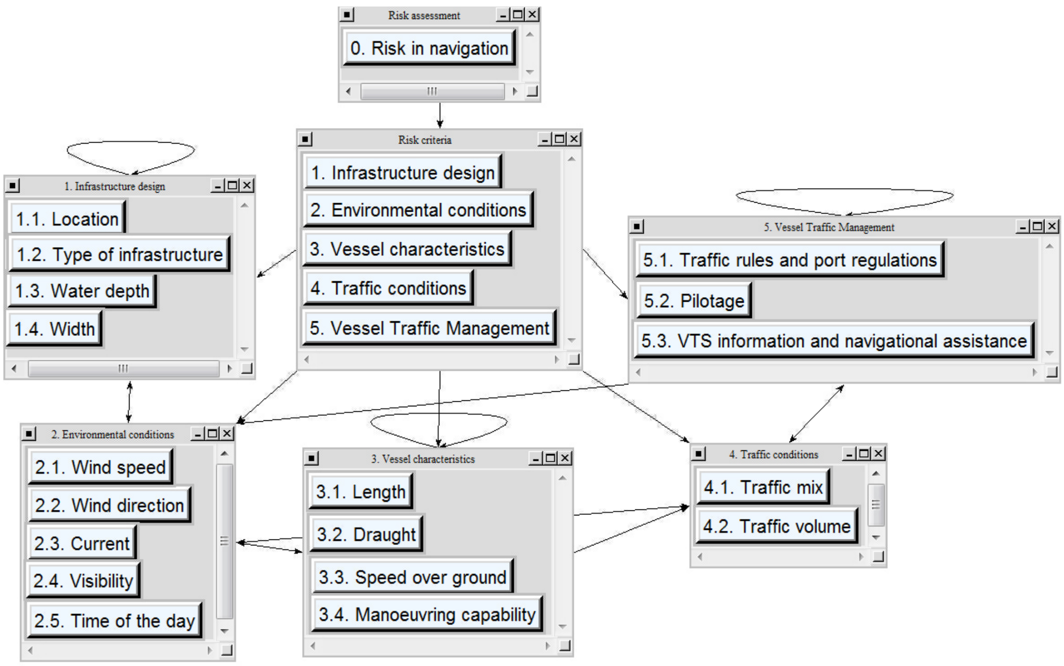

Figure 5.2: Structure of the links between criteria.

Table 5.4: Influence matrix.

		1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2 3.3	3.4	4.1	4.2	5.1	5.2	5.3	
1	Infrastructure design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Environmental conditions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Vessels characteristics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Traffic conditions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Vessel Traffic Management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.1	Location	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
1.2	Type of infrastructure	1	0	0	0	0	1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
1.3	Water depth [m]	1	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
1.4	Width [m]	1	0	0	0	0	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0
2.1	Wind speed [knots]	0	1	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	0	1	1
2.2	Wind direction	0	1	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	0	1	1
2.3	Current [knots]	0	1	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	0	1	1
2.4	Visibility [m]	0	1	0	0	0	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	0	1	1
2.5	Time of the day	0	1	0	0	0	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	0	1	1
3.1	Length [m]	0	0	1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	0	0	0
3.2	Draught [m]	0	0	1	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	0	0	0
3.3	Speed [knots]	0	0	1	0	0	0	0	0	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0
3.4	Manoeuvring capability	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
4.1	Traffic mix	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	
4.2	Traffic volume [ves/h]	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
5.1	Traffic rules and port regulations	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
5.2	Pilotage	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
5.3	VTS assistance	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0

Table 5.5: Fundamental scale to estimate dominance in pairwise comparisons (Saaty, 2008).

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A logical assumption

Consequence scale

The consequences related to each of the risk factors previously chosen should be qualified on a scale that allows the risk calculation. Previous research has qualified consequences using different approaches. As an example, Trbojevic and Carr (2000) introduced a qualitative scale of consequences related to the likelihood with four levels for each of the variables (people, assets, environment and reputation). A similar approach was used by Ulusçu et al. (2009), where the consequences depend on vessel and shore attributes, and their consequence is related to the impacts on property, human casualty, environment and traffic.

Since this is a subjective qualification, we consider that experts in navigation should not quantify or qualify the consequences themselves, since every individual might not have a proper sense of the consequences implied by some criteria. The scale directly depends on the criteria and thresholds of the stakeholders who wants to assess the risks. Hence, consultation with port risk experts should provide the definition of this scale. Each sub-criteria can be qualified in a scale from very low (1) to very high risk (5) in a normalized scale.

5.2.4 NPRI quantification

Once the RP values have been calculated and the consequence values have been defined, the NPRI for each sub-area can be obtained. This step consists of the calculation of the NPRI in the desired area for the specific time period required, which depends on the assessment period desired by the decision makers. This allows the risk qualification at the specified level, in a scale from 1 (very low) to 5 (very high). This level might depend on the requirements for a determined purpose from the decision makers, as explained in the previous sub-section, and the risk calculation can be done using either real or simulated data as follows:

$$NPRI^i(t) = \sum_w (w_k) \cdot c_k^i(t) \tag{5.3}$$

where $NPRI^i(t)$ is calculated for each sub-area i, w_k is the weight of each criterion, $c_k^i(t)$ is the consequence value associated to the criterion k at the interval of time t for the sub-area i. The results provides the NPRI value for each area in each time step.

From all the NPRI values obtained, the maximum could be chosen as a reference value. Since there might be specific situations where the maximum NPRI is extreme due to a certain specific situation, this might lead to an overestimation of the risk in the area. Hence, in this research, we define the final NPRI value by ordering from low to high the results from each area and choosing the 95 percentile higher NPRI value. These results can be mapped for each port area to provide decision makers a clear picture of the areas with higher risks, as done in previous research by Wang et al. (2014), and to support their assessment.

5.3 Case study in the Port of Rotterdam

This risk assessment methodology for ports should be built for each port where it is applied. In this research two areas from the Port of Rotterdam were chosen, and, because of their differences, the methodology will be adapted consequently for each of them. These areas are the Maasvlakte (A1), with large container terminals and big vessels, and the Petroleumhaven (A2), which resembles to an inland or river port, and they are shown in figure 5.3.

By considering the input from navigational experts (VTS operators and pilots from the Port of Rotterdam), the weights related to the RP are obtained. The consequence scale is defined by experts from the Port of Rotterdam Authority. Finally, data from 2014 that includes weather, current and traffic, as well as the infrastructure design details required by the criteria considered in the assessment methodology, was provided by the Port of Rotterdam Authority for this research. This section includes all the steps required for the complete application of the risk assessment method previously introduced to quantify the NPRI in two different port areas.

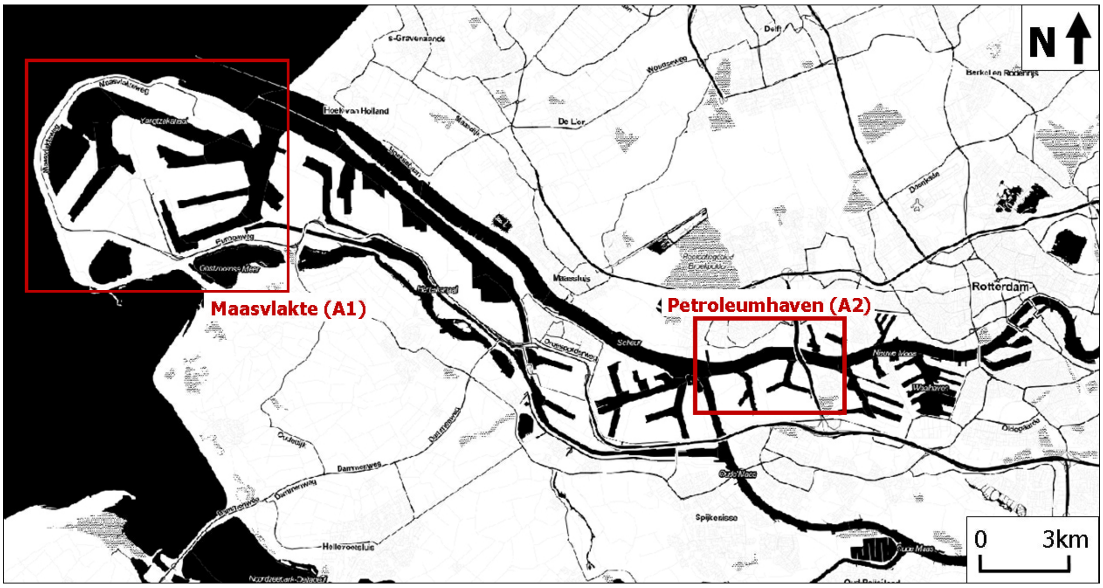

Figure 5.3: Port of Rotterdam (Maasvlakte left square and Petroleumhaven right square).

5.3.1 Risk Perception using ANP

The risk assessment model has been developed using the risk criteria identified in section 5.2.2. The criteria selected are set in a network structure (see figure 5.2) and the relations between criteria are defined, as previously described in table 5.4. This section includes the data collection necessary for the ANP through a survey to derive the weights of the RP, the analysis of the collected answers and a sensitivity analysis.

ANP survey

In order to collect the data necessary from navigation experts to apply the ANP, a questionnaire was designed, where the different criteria are ranged in a pairwise structure as shown with an example in table 5.6, comparing assigning strongly more importance (9) to one factor compares to the other, to equally important (1). For this research we used the expertise from VTS operators and pilots from the Port of Rotterdam, who have vast knowledge about navigation and the characteristics from the case study areas. The answers were collected either in person or with an online survey, including detailed explanations and clarifications to experts. A total of 23 VTS operators and 12 pilots filled in the survey for one of the port areas. Since each port has its own singularities, we asked them to answer based on the area were they had larger expertise. From the VTS operators, there were 14 respondents for the Maasvlakte area (A1) and 9 for the Petroleumhaven area (A2), and from the pilots, there were 10 and 2 respondents respectively, which leads to a total of 24 respondents for A1 and 11 for A2. Even though the experts provide their risk perception in a thorough way, the ANP method includes a consistency check. After calculating the consistency ratio (CR) for each of the questionnaires, some of them resulted higher than 0.10. Hence, a total of 11 respondents were excluded from the calculation for A1, 5 from the VTS operators and

6 from the pilots and, 3 respondents were excluded for A2, 2 from the VTS operators and 1 from the pilots. This leads to a total amount of responses of 13 for A1 and 8 for A2. These consistent answers are used for the ANP calculation, but, before that, we performed a brief analysis of the answers provided to see how large are the variations between respondents.

Table 5.6: Sample question from the survey to experts.

With respect to the RISKS IN NAVIGATION please indicate the relative importance of the following factors, according to your expertise and perception.																		
Location	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Env. cond.

Figure 5.4 and figure 5.5 show the results for the pairwise comparisons for the questions in each main criteria group for both port areas. For several questions, there is a clear preference for one of the criteria, while in others the answers are close to 1, which means that the contribution to risk for both factors is considered to be equal. The answers also show that the perception changes a lot within each pairwise comparison between experts, so the larger the sample, the more normalized the results will be.

One interesting thing to point out is that when comparing the answers between the two areas, for some of the questions the answers are similar, while for others, the perception is different for each area. For example, respondents have a clear preference in the comparison between visibility with respect the time of the day in both areas. However, when looking at the question comparing layout of the infrastructure and water depth, their risk perception is different, as water depth is considered more important in A1, whereas respondents for A2 assign slightly more importance to layout of the infrastructure, probably due to the presence of narrow basins and more complex turnings to access these basins in A2. Another example when comparing between wind direction and current, the results for both areas are considerably different. As vessels visiting A1 are larger, the effect of wind has larger influence in their maneuvering. This shows how the characteristics and specificities of each port might affect the risk perception from experts, and how important it is to consider ports individually for this method.

ANP results

The ANP software Superdecisions is used to calculate the risk perception weights for the risk criteria by considering the data collected. The software calculates the weights based on a set of results, and since there are two groups of experts in this research, VTS operators and pilots, we considered all the answers as one single dataset for each area. In the next section, a sensitivity analysis is performed considering two independent groups of respondents for the risk perception weight calculation. The software used considers the network formed by relating the different criteria and uses the input from the experts to calculate the comparison matrices described in section 5.2.3.

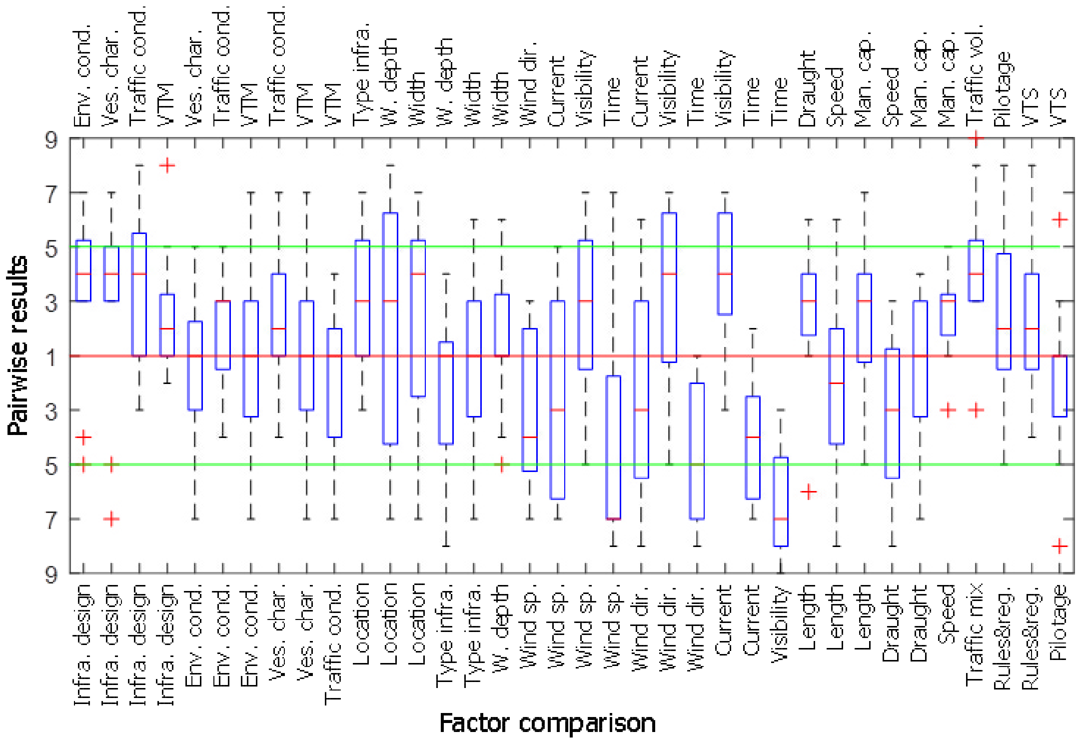

Figure 5.4: Port of Rotterdam (Boxplot answers for Maasvlakte (A1).

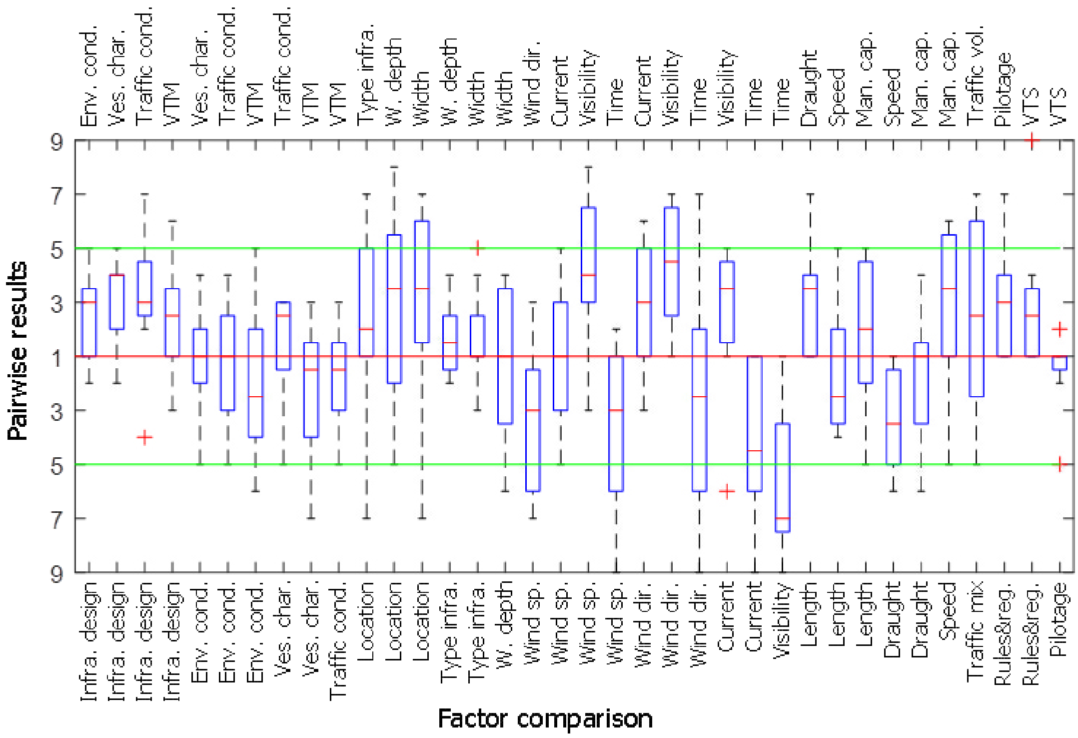

Figure 5.5: Port of Rotterdam (Boxplot answers for Petroleumhaven (A2).

Some intermediate steps from the ANP calculation were performed, leading to the final weights. First, the unweighted supermatrix containing the local priority values for each cluster is built for each area (see Appendix 1, table 5.10 for Maasvlakte (A1) and table 5.13 for Petroleumhaven (A2)). The cluster priorities are used to generate the weighted supermatrix (see Appendix 1, table 5.11 for A1 and table 5.14 for A2). Raising this supermatrix to powers until the weights converge, the limit supermatrix is obtained (see Appendix 1, table 5.12 for A1 and table 5.15 for A2).

Finally, figure 5.6 summarizes the resulting priorities for each criterion. It can be seen in both areas that the traffic volume and the visibility are the two criteria that most contribute to risk. The main differences between the two study areas are that, in A1, the factors type of infrastructure, wind speed, wind direction and traffic volume have a slightly higher weight, probably due to the higher size of the vessels in the area. On the other hand, the width of the infrastructure and the current have more influence in the final weights in A2, due to the narrow basins and sharper bends connecting with the river area. The results for each criterion will be used for the NPRI calculation.

ANP sensitivity analysis

Since VTS operators and pilots might have different risk perceptions, we tested how sensitive the ANP method is to the aggregation of the answers as a unique group of experts. For that, we derived the weights using ANP by considering two sets of answers, one for each group of experts. From the results obtained for each port (see figure 5.7 and figure 5.8), the weights for each factor have slight differences. In figure 5.7, the weights for A1 show that VTS operators perceive that the type of infrastructure and the visibility have stronger contribution to the navigational risk, since they have to guide vessels when they do not have a clear view during their navigation in the port. On the other hand, pilots give more relative importance to the width of the fairways and the wind direction, due to the big size of the vessels. Hence, their risk perception is different probably due to their different role in the vessel navigation in the port.

In A2, the main differences between pilots and VTS operators are that the depth and width of the fairway and the vessel draught have a slightly higher contribution to risk according to VTS operators, while the type of infrastructure and the maneuverability have more relative importance to pilots.

The resultant risk perception weights have on average less than 10% difference compared to the combined results from section 5.3.1, and the importance of the weights is really similar to the previous results. Since the slight difference in perception does not outweigh the benefits of having a larger sample, we consider the experts as a single group of respondents and the case study will be based on the results described in the previous section.

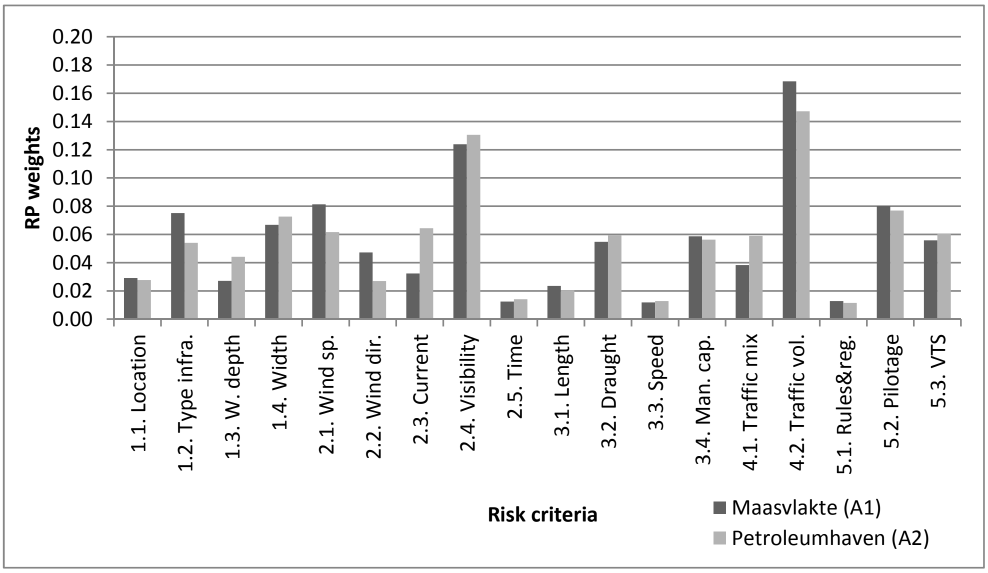

Figure 5.6: Factor weights of the research areas.

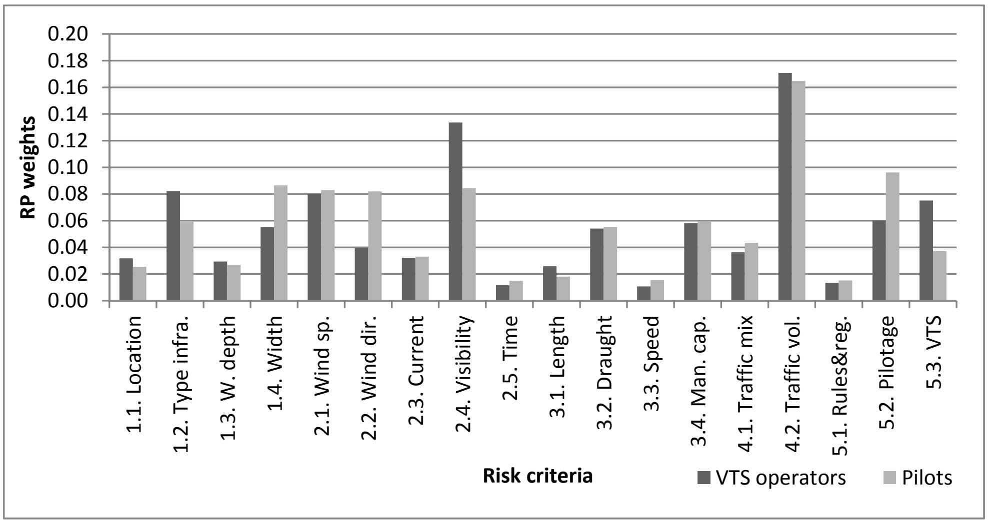

Figure 5.7: Weights for each expert group in Maasvlakte (A1).

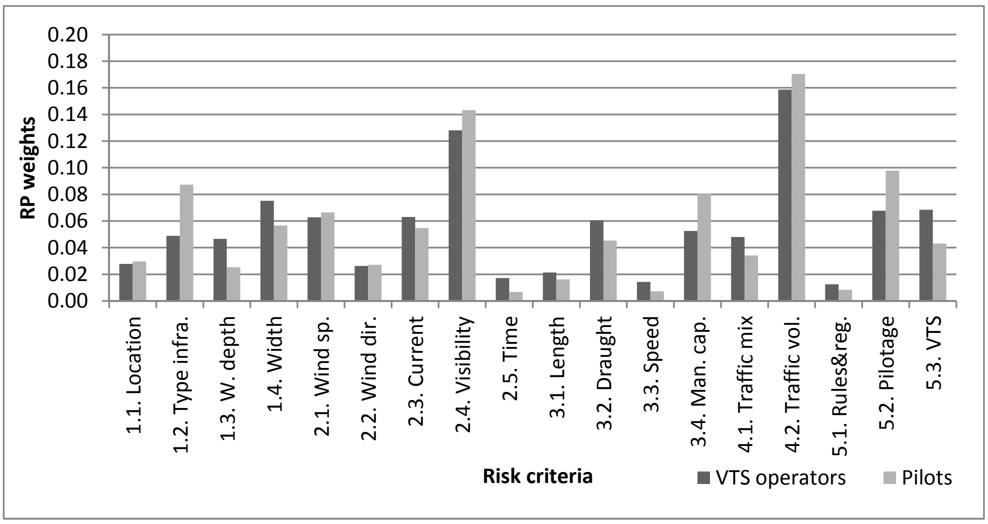

Figure 5.8: Weights for each expert group in Petroleumhaven (A2).

5.3.2 Consequence scale for the Port of Rotterdam

After obtaining the contribution to the navigational risk in ports of each of the criteria according to expert judgement, the consequences related to each of them should be defined to calculate the NPRI. As explained before, the consequences should be defined by port risk experts. For this research, experts from the Port of Rotterdam were interviewed to define a suitable scale of consequences for each of the study areas, based on their knowledge of the port and the scale of risk that they considered adequate for the risk assessment.

Although the Port of Rotterdam has high vessel traffic volumes, the aggregation period for the traffic volume quantification chosen is 3 hours. According to the experts, this is because the average time of many of the vessel trips is around 2.5 hours, and shorter periods would not provide valuable insight into the real amount of vessel traffic.

Table 6.5 describes the different consequence values from very low (1) to very high risk (5) for each of the criteria for A1. For A2, the consequences have been scaled in two groups, one for the river area, where there is more traffic with higher speeds and wider nautical space and one for the inner basins (see table 5.8).

Table 5.7: Consequence table for Maasvlakte (A1).

CONSEQUENCE RISK NAVIGATION SCALE									
	Criteria		**Sub-criteria**	**Very low risk**	**Low risk**	**Medium risk**	**High risk**	**Very high risk**
1	Infrastructure design	1.1	Location (high/flat landscape/buildings)	Low	-	Medium	-	High
		1.2	Type of infrastructure	Straight	-	Bend	-	Crossing
		1.3	Water depth [m]	> 25	25 - 21	21 - 17	17 - 15	< 15
		1.4	Width [m]	> 500	500 - 425	425 - 350	350 - 300	< 300
2	Environmental conditions	2.1	Wind speed [m/s]	<=5.5	5.5 - 8	8 - 10.7	10.7 - 13.8	>=13,8
		2.2	Wind direction	Bow/sternwind (<20°)	20° - 35°	Diagonal (35° - 55°)	55° - 80°	Crosswind (>80°)
		2.3	Current [knots]	<1	1 - 1.5	1.5 - 2	2 - 2.5	>2.5
		2.4	Visibility [m]	> 1500	1500 - 1200	1200 - 900	900 - 500	< 500
		2.5	Time of the day	Day	-	Dawn / Dusk	-	Night
3	Vessels characteristics	3.1	Length [m]	<100	100-150	150-225	225-300	>300
		3.2	Draught [m]	< 12 m.	12 - 13	13 - 14	14 - 15	> 15 m.
		3.3	Speed [knots]	< 5	5 - 6	6 - 7.5	7.5 - 10	> 10
		3.4	Manoeuvring capability	1	2	3	4	5
4	Traffic conditions	4.1	Traffic mix (same or different types)	1	2	3	4	5
		4.2	Traffic volume [ves/h]	< 1.7	1.7 - 4.3	4.3 - 6.7	6.7 - 8.3	> 8.3
5	Vessel Traffic Managment	5.1	Traffic rules and port regulations	100% Goal based	-	50	-	100% Rule based
		5.2	Pilotage	> 90%	90-80%	80-70%	70-60%	< 60%
		5.3	VTS assistance	X	-	-	-	-

Table 5.8: Consequence table for Petroleumhaven (A2) (*River area and, between brackets, basins).

CONSEQUENCE RISK NAVIGATION SCALE								
Criteria		**Sub-criteria**	**Very low risk**	**Low risk**	**Medium risk**	**High risk**	**Very high risk**
1 Infrastructure design	1.1	Location (high/flat landscape/buildings)	Low	-	Medium	-	High
	1.2	Type of infrastructure	Straight	-	Bend	-	Crossing
	1.3	Water depth [m]	> 16 (> 15)	16 - 14.5 (15 - 13.5)	14.5 - 13 (13.5 - 12)	13 - 12 (12 - 11)	< 12 (< 11)
	1.4	Width [m]	> 300 (> 250)	300 - 250 (250 - 200)	250 - 180 (200 - 140)	180 - 150 (140 - 100)	< 150 (< 100)
2 Environmental conditions	2.1	Wind speed [m/s]	<=5.5	5.5 - 8	8 - 10.7	10.7 - 13.8	>=13,8
	2.2	Wind direction	Bow/sternwind (<20°)	20° - 35°	Diagonal (35° - 55°)	55° - 80°	Crosswind (>80°)
	2.3	Current [knots]	<1	1 - 1.5	1.5 - 2	2 - 2.5	>2.5
	2.4	Visibility [m]	> 1500	1500 - 1200 (1500 - 1000)	1200 - 900 (1000 - 750)	900 - 500 (750 - 400)	< 500 (< 400)
	2.5	Time of the day	Day	-	Dawn / Dusk	-	Night
3 Vessels characteristics	3.1	Length [m]	<100	100-150	150-225	225-300	>300
	3.2	Draught [m]	< 8	8 - 10	10 - 11	11 - 12	> 12
	3.3	Speed [knots]	< 5 (< 4)	5 - 6 (4 -5)	6 - 7.5 (5 - 6.5)	7.5 - 10 (6.5 - 8)	> 10 (> 8)
	3.4	Manoeuvring capability	1	2	3	4	5
4 Traffic conditions	4.1	Traffic mix (same or different types)	1	2	3	4	5
	4.2	Traffic volume [ves/h]	< 1.7	1.7 - 4.3 (1.7 - 2.7)	4.3 - 6.7 (2.7 - 3.3)	6.7 - 8.3 (3.3 - 4)	> 8.3 (> 4)
5 Vessel Traffic Managment	5.1	Traffic rules and port regulations	100% Goal based	-	50	-	100% Rule based
	5.2	Pilotage	> 90%	90-80%	80-70%	70-60%	< 60%
	5.3	VTS assistance	X	-	-	-	-

5.3.3 NPRI calculation

This subsection describes the NPRI calculation steps for the two case studies previously described. The first step was to collect the necessary data to determine the NRPI, and The Port of Rotterdam provided several datasets needed for each criterion from the year 2014. These data includes weather, current and traffic, as well as the infrastructure design details. By combining all the data and processing them, we use it to calculate the NPRI. The dataset includes 12 areas for Maasvlakte area (A1) and 8 for Petroleumhaven (A2) (see figure 5.11). For each area there is an individual recording of each passing vessel during a specific time period.

For the calculations, the period considered is 3 hours and all criteria are averaged. For example, the vessel characteristics of all passing vessels through each area during each 3 hour period are recorded and averaged, as if all vessels had the same average characteristics, except the traffic mix that counts the different types of vessels for that period.

Figure 5.9 shows the number of observations for each area (shown in figure 5.11), meaning that in case of no traffic during that period, there is no observation. The first four areas have a low number of observations due to the low vessel traffic in that area, which shows that in that areas there were many 3 hour periods without any traffic. Other areas with few observations show that they have traffic only for a limited amount of the time.

The vessel draught data is manually included as it is not part of the Automatic Information System (AIS) data. Because of this, we found out that only 65% of the data have a non-zero vessel draught. The missing values are considered as average draught in this research.

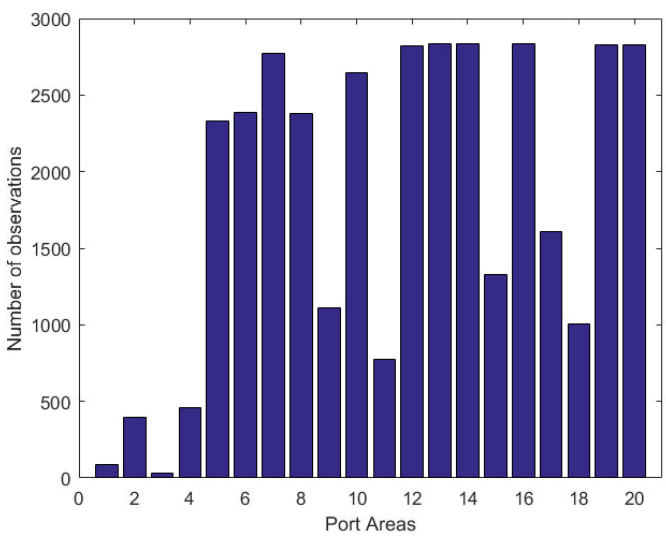

Figure 5.9: Number of observations per area.

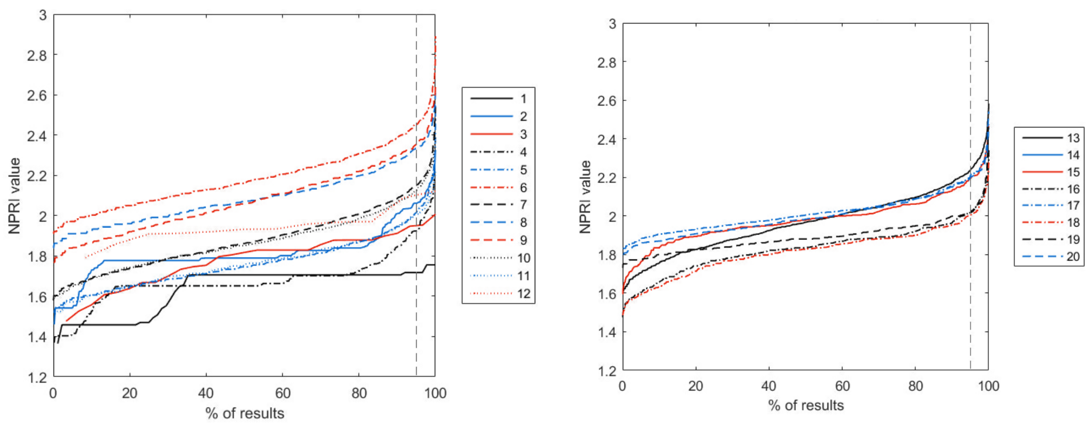

Figure 5.10: NPRI cumulative values per port - Maasvlakte (A1), left, and Petroleumhaven (A2), right.

Once all the data have been cleaned and properly structured, the NPRI is calculated for each area by multiplying the RP weights obtained from the ANP model times the consequences value for each specific sub-criteria, according to the characteristics of each area. The NPRI value is calculated for each period of time when vessel traffic exists for each area. In figure 5.10 (left), the results for A1 are represented in a normalized scale, where the NPRI values are ordered from lowest to highest. It can be seen that there is a large difference between the lower and higher risk values in each area. The difference appears due to the relation between the RP weights and the consequence values in each period. When the environmental conditions are favorable, and the vessel characteristics and the traffic conditions are small, the risks appear to be low, while the highest risk values appear when the environmental conditions are not so favorable and the other factors are higher too. Figure 5.10 (right) shows all the results for A2, where a substantial difference in the NPRI exists between the 3 areas from the inner basins and the others from the river. Because of the high vessel traffic in the river and the high weight of this criterion, the risks are higher.

Even though NPRI values are high for the worst situations, the maximum values do not reach even 3 out of 5, which represents a total low risk and shows the safety of these two areas from the Port of Rotterdam. According to risk experts from the Port of Rotterdam, the results are representative of the current situation in the port and proves the validity of the methodology introduced.

Once all the NPRI values are calculated for all samples, to avoid taking an overestimated risk for a single casualty which could be considered an outlier, the 95 percentile NPRI value is selected for each area to assess the situation among the different areas, represented with a dashed vertical line in figure 5.10. The results are summarized in table 5.9 and, for a more clear representation, they are presented in a risk map for each port (see figure 5.11).

When looking at the final NPRI values, it can be seen that the highest risks in A1 are in the areas 6, 8 and 9, which correspond to slightly narrower basins compared with the rest of the area. In A2, the highest risks appear in the crossing area 13 and two of the inner basin areas 15 and 18.

The results show that the risk level in the Port of Rotterdam in 2014 had a medium risk level with the combination of all the criteria considered. Even though the results are not extreme, decision makers should define a threshold for the unacceptable NRPI and assess the need for further safety measures if they would like to reduce the risks in specific areas.

Table 5.9: NPRI results.

Area	95% NPRI	Area	95% NPRI
1	1.72	13	2.20
2	2.06	14	2.02
3	1.95	15	2.21
4	1.92	16	2.00
5	2.01	17	2.02
6	2.45	18	2.20
7	2.15	19	2.01
8	2.33	20	2.06
9	2.35		
10	2.12		
11	2.00		
12	2.24		

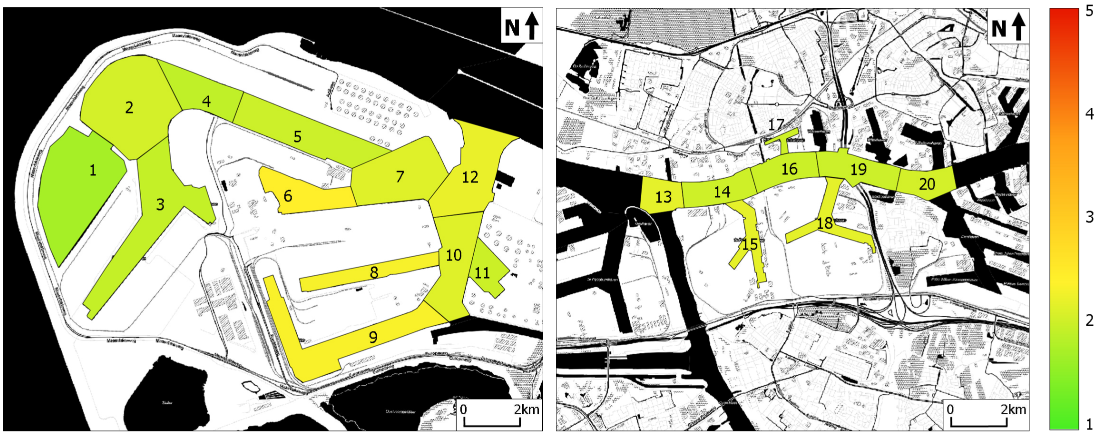

Figure 5.11: Risk maps Maasvlakte (A1), left, and Petroleumhaven (A2), right.

5.3.4 Sensitivity analysis

As previously introduced, the weighting values for the RP are obtained from pairwise comparisons from experts judgement. These priorities have a strong influence on the final NPRI calculation. For this reason, it is of great importance to check the robustness of the ANP model used to make the final risk calculation. The model would be robust when small changes in the RP values do not lead to big changes in the final NPRI values.

In order to test the robustness of this research, a sample of 100 random scenarios was created, where the RP values are randomly generated with a normal distribution. The distribution considered has as mean value the result obtained from the ANP model and a standard deviation of 10% of this mean RP value.

In figure 12, the dots show the NPRI values and the boxplots the variation of results from the random scenarios generated. The variation appears to be larger in A1 (figure 5.12, left) than in A2 (figure 5.12, right), which is mainly caused by larger variation between vessel types and flows within different time periods.

In A1, the interquartile range, corresponding to the 50% of the results, is always in a similar position as the original result. The largest variation is less than 0.1, which represents a variation smaller than 2.5% on the overall scale. When looking at the whole set of results, the highest variation appears to be than 0.25. For A2, the variation is really small, with a maximum variation of less than 0.1 (see figure 5.12, right). The results for this study area appear to be less sensitive to variations of the RP weights.

This analysis proves the robustness of the methodology developed, as well as the effect that different consequence scales might have on the final result.

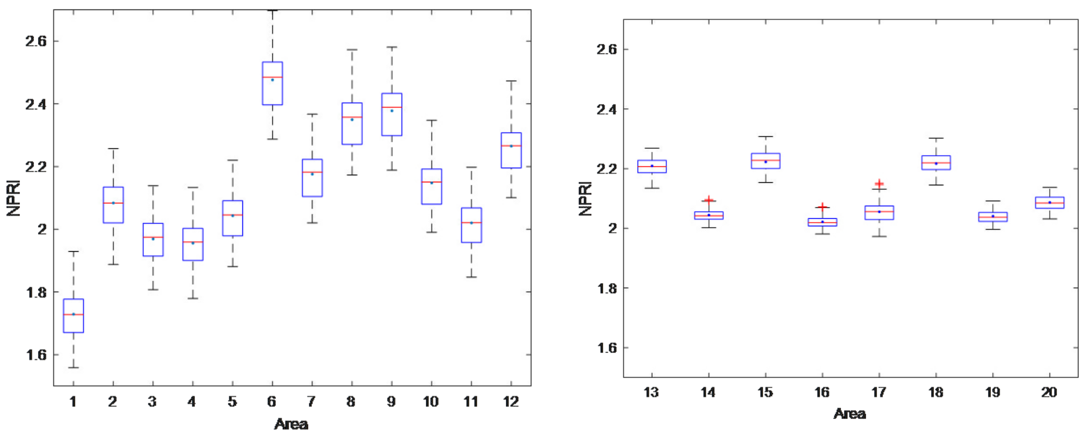

Figure 5.12: Results variation for Maasvlakte (A1), left, and Petroleumhaven (A2), right.

5.4 Conclusions

In this research, a new methodology to assess nautical risks in ports has been presented. By combining knowledge from navigational experts and risk experts, we have developed a methodology to quantify the risk in different areas of any port, with the calculation of the Nautical Port Risk Index (NPRI). The navigational experts have contributed to the definition of the risk perception weights for each criterion by using the ANP method to derive them, and the consequence scale is defined by the risk experts.

This new index allows the quick assessment of the nautical risks within a port, based on its specific characteristics. As an advantage with respect to most of the previous risk assessment methods, for vessel navigation, this method can be based on historical as well as simulated data, and it can be used to assess current or future risks in existent or future ports. The method presented can be used by port stakeholders to assess the nautical risk in different situations at different levels and time periods, in order to identify problems or high risks at different moments in time.

The implementation of this method with simulated data or historical data would provide a dynamic NPRI to forecast port risks for any desired scenario and time period, which would allow a dynamic and proactive port risk assessment to decision makers. It has several applications, since it could be used for planning new ports or port expansions in the design phase, or to assess the current risks in existing ports or assess new traffic management solutions.

Future research could focus on the application of this methodology in other ports, with other navigational experts and port decision makers to see how the risk perception changes in different places of the world. In addition, the methodology could also be developed for different time periods to assess different scenarios, such as seasonality risks or the evolution of risk along several years.

Acknowledgements

This work is part of the research program “Nautical traffic model based design and assessment of safe and efficient ports and waterways”, sponsored by the Netherlands Organization for Scientific Research (NWO). The authors are immensely grateful to all the VTS operators and pilots from the Port of Rotterdam who took part of the survey and provided really valuable input for this research. Moreover, we would also like to thank the experts from the Port of Rotterdam Authority, especially to Raymond Seignette (Port of Rotterdam Authority), and to the pilots Harry Tabak and Patrick van Erve for their fruitful contributions to this research.

Appendix 1

Table 5.10: Unweighted supermatrix for A1.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1. Infrastructure design	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2. Envionmental conditions	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3. Vessel characteristics	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4. Traffic conditions	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5. Vessel characteristics	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.1. Location environment	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.18	0.16	0.15	0.16	0.16	0.11	0.16	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.2. Type of infrastructure	0.00	0.37	0.00	0.00	0.00	0.00	0.43	0.00	0.46	0.55	0.46	0.46	0.37	0.46	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.3. Water depth	0.00	0.20	0.00	0.00	0.00	0.00	0.20	0.33	0.00	0.29	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.4. Width	0.00	0.32	0.00	0.00	0.00	0.00	0.37	0.49	0.39	0.00	0.39	0.39	0.32	0.39	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.1. Wind speed	0.00	0.00	0.26	0.00	0.00	0.00	0.26	0.26	0.57	0.26	0.00	0.00	0.00	0.00	0.00	0.26	0.26	0.26	0.26	0.26	0.26	0.00	0.26	0.26
2.2. Wind direction	0.00	0.00	0.15	0.00	0.00	0.00	0.15	0.15	0.27	0.15	0.00	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15	0.15	0.15	0.00	0.15	0.15
2.3. Current	0.00	0.00	0.11	0.00	0.00	0.00	0.11	0.11	0.16	0.11	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.11	0.11	0.00	0.11	0.11
2.4. Visibility	0.00	0.00	0.44	0.00	0.00	0.00	0.44	0.44	0.00	0.44	0.00	0.00	0.00	0.00	0.00	0.44	0.44	0.44	0.44	0.44	0.44	0.00	0.44	0.44
2.5. Time of the day	0.00	0.00	0.04	0.00	0.00	0.00	0.04	0.04	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.04	0.04	0.00	0.04	0.04
3.1. Length	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.17	0.18	0.18	0.18	0.00	0.00	0.17	0.28	0.00	0.00	0.00	0.00	0.00
3.2. Draught	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.48	0.41	0.41	0.41	0.00	0.00	0.48	0.57	0.00	0.00	0.00	0.00	0.00
3.3. Speed over ground	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.11	0.11	0.11	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00
3.4. Maneuvering capability	0.00	0.00	0.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.35	0.31	0.31	0.31	1.00	1.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00
4.1. Traffic mix	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.00	0.00	0.19	0.19	0.19
4.2. Traffic volume	0.00	0.00	0.00	0.00	0.81	0.00	0.00	0.00	0.00	0.00	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.00	0.00	0.81	0.81	0.81
5.1. Traffic rules and port regulations	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.26
5.2. Pilotage	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.64	0.00	0.00	0.74
5.3. VTS information and navigational assistance	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.36	0.00	0.71	0.00

Table 5.11: Weighted supermatrix for A1.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1. Infrastructure design	0.072	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2. Envionmental conditions	0.224	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3. Vessel characteristics	0.173	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4. Traffic conditions	0.346	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5. Vessel characteristics	0.185	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.1. Location environment	0.000	0.114	0.000	0.000	0.000	0.000	0.000	0.089	0.079	0.077	0.052	0.052	0.038	0.052	0.052	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.2. Type of infrastructure	0.000	0.374	0.000	0.000	0.000	0.000	0.213	0.000	0.228	0.277	0.152	0.152	0.125	0.152	0.152	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.3. Water depth	0.000	0.197	0.000	0.000	0.000	0.000	0.100	0.164	0.000	0.146	0.000	0.000	0.066	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.4. Width	0.000	0.315	0.000	0.000	0.000	0.000	0.187	0.246	0.194	0.000	0.129	0.129	0.105	0.129	0.129	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.1. Wind speed	0.000	0.000	0.259	0.000	0.000	0.000	0.130	0.130	0.287	0.130	0.000	0.000	0.000	0.000	0.000	0.086	0.086	0.086	0.086	0.130	0.130	0.000	0.086	0.086
2.2. Wind direction	0.000	0.000	0.154	0.000	0.000	0.000	0.077	0.077	0.134	0.077	0.000	0.000	0.000	0.000	0.000	0.051	0.051	0.051	0.051	0.077	0.077	0.000	0.051	0.051
2.3. Current	0.000	0.000	0.107	0.000	0.000	0.000	0.053	0.053	0.079	0.053	0.000	0.000	0.000	0.000	0.000	0.036	0.036	0.036	0.036	0.053	0.053	0.000	0.036	0.036
2.4. Visibility	0.000	0.000	0.437	0.000	0.000	0.000	0.218	0.218	0.000	0.218	0.000	0.000	0.000	0.000	0.000	0.146	0.146	0.146	0.146	0.218	0.218	0.000	0.146	0.146
2.5. Time of the day	0.000	0.000	0.044	0.000	0.000	0.000	0.022	0.022	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.015	0.015	0.015	0.015	0.022	0.022	0.000	0.015	0.015
3.1. Length	0.000	0.000	0.000	0.177	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.058	0.059	0.059	0.059	0.000	0.000	0.058	0.092	0.000	0.000	0.000	0.000	0.000
3.2. Draught	0.000	0.000	0.000	0.408	0.000	0.000	0.000	0.000	0.000	0.000	0.136	0.159	0.136	0.136	0.136	0.000	0.000	0.159	0.192	0.000	0.000	0.000	0.000	0.000
3.3. Speed over ground	0.000	0.000	0.000	0.107	0.000	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.036	0.036	0.036	0.000	0.000	0.000	0.050	0.000	0.000	0.000	0.000	0.000
3.4. Maneuvering capability	0.000	0.000	0.000	0.308	0.000	0.000	0.000	0.000	0.000	0.000	0.103	0.116	0.103	0.103	0.103	0.333	0.333	0.116	0.000	0.000	0.000	0.000	0.000	0.000
4.1. Traffic mix	0.000	0.000	0.000	0.000	0.185	0.000	0.000	0.000	0.000	0.000	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.000	0.000	0.185	0.062	0.062
4.2. Traffic volume	0.000	0.000	0.000	0.000	0.815	0.000	0.000	0.000	0.000	0.000	0.272	0.272	0.272	0.272	0.272	0.272	0.272	0.272	0.272	0.000	0.000	0.815	0.272	0.272
5.1. Traffic rules and port regulations	0.000	0.000	0.000	0.000	0.000	0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.098	0.088
5.2. Pilotage	0.000	0.000	0.000	0.000	0.000	0.513	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.321	0.321	0.000	0.000	0.246
5.3. VTS information and navigational assistance	0.000	0.000	0.000	0.000	0.000	0.329	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.179	0.179	0.000	0.235	0.000

Table 5.12: Limit supermatrix for A1.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1. Infrastructure design	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2. Envionmental conditions	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3. Vessel characteristics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4. Traffic conditions	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5. Vessel characteristics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.1. Location environment	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
1.2. Type of infrastructure	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
1.3. Water depth	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
1.4. Width	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
2.1. Wind speed	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081
2.2. Wind direction	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047
2.3. Current	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
2.4. Visibility	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124	0.124
2.5. Time of the day	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
3.1. Length	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
3.2. Draught	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
3.3. Speed over ground	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
3.4. Maneuvering capability	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
4.1. Traffic mix	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
4.2. Traffic volume	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169
5.1. Traffic rules and port regulations	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
5.2. Pilotage	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080
5.3. VTS information and navigational assistance	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056

Table 5.13: Unweighted supermatrix for A2.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1. Infrastructure design	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2. Envionmental conditions	0.269	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3. Vessel characteristics	0.244	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4. Traffic conditions	0.264	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5. Vessel characteristics	0.142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.1. Location environment	0.000	0.107	0.000	0.000	0.000	0.000	0.000	0.145	0.157	0.160	0.157	0.157	0.107	0.157	0.157	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.2. Type of infrastructure	0.000	0.221	0.000	0.000	0.000	0.000	0.237	0.000	0.338	0.339	0.338	0.338	0.221	0.338	0.338	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.3. Water depth	0.000	0.356	0.000	0.000	0.000	0.000	0.415	0.463	0.000	0.501	0.000	0.000	0.356	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.4. Width	0.000	0.315	0.000	0.000	0.000	0.000	0.348	0.393	0.505	0.000	0.505	0.505	0.315	0.505	0.505	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.1. Wind speed	0.000	0.000	0.188	0.000	0.000	0.000	0.188	0.188	0.443	0.188	0.000	0.000	0.000	0.000	0.000	0.188	0.188	0.188	0.188	0.188	0.188	0.000	0.188	0.188
2.2. Wind direction	0.000	0.000	0.087	0.000	0.000	0.000	0.087	0.087	0.137	0.087	0.000	0.000	0.000	0.000	0.000	0.087	0.087	0.087	0.087	0.087	0.087	0.000	0.087	0.087
2.3. Current	0.000	0.000	0.200	0.000	0.000	0.000	0.200	0.200	0.420	0.200	0.000	0.000	0.000	0.000	0.000	0.200	0.200	0.200	0.200	0.200	0.200	0.000	0.200	0.200
2.4. Visibility	0.000	0.000	0.473	0.000	0.000	0.000	0.473	0.473	0.000	0.473	0.000	0.000	0.000	0.000	0.000	0.473	0.473	0.473	0.473	0.473	0.473	0.000	0.473	0.473
2.5. Time of the day	0.000	0.000	0.051	0.000	0.000	0.000	0.051	0.051	0.000	0.051	0.000	0.000	0.000	0.000	0.000	0.051	0.051	0.051	0.051	0.051	0.051	0.000	0.051	0.051
3.1. Length	0.000	0.000	0.000	0.155	0.000	0.000	0.000	0.000	0.000	0.000	0.155	0.166	0.155	0.155	0.155	0.000	0.000	0.166	0.225	0.000	0.000	0.000	0.000	0.000
3.2. Draught	0.000	0.000	0.000	0.451	0.000	0.000	0.000	0.000	0.000	0.000	0.451	0.530	0.451	0.451	0.451	0.000	0.000	0.530	0.615	0.000	0.000	0.000	0.000	0.000
3.3. Speed over ground	0.000	0.000	0.000	0.109	0.000	0.000	0.000	0.000	0.000	0.000	0.109	0.000	0.109	0.109	0.109	0.000	0.000	0.000	0.160	0.000	0.000	0.000	0.000	0.000
3.4. Maneuvering capability	0.000	0.000	0.000	0.285	0.000	0.000	0.000	0.000	0.000	0.000	0.285	0.304	0.285	0.285	0.285	1.000	1.000	0.304	0.000	0.000	0.000	0.000	0.000	0.000
4.1. Traffic mix	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.000	0.000	0.286	0.286	0.286
4.2. Traffic volume	0.000	0.000	0.000	0.000	0.714	0.000	0.000	0.000	0.000	0.000	0.714	0.714	0.714	0.714	0.714	0.714	0.714	0.714	0.714	0.000	0.000	0.714	0.714	0.714
5.1. Traffic rules and port regulations	0.000	0.000	0.000	0.000	0.000	0.142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.250	0.250
5.2. Pilotage	0.000	0.000	0.000	0.000	0.000	0.487	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.600	0.600	0.000	0.000	0.750
5.3. VTS information and navigational assistance	0.000	0.000	0.000	0.000	0.000	0.371	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.400	0.400	0.000	0.750	0.000

Table 5.14: Weighted supermatrix for A2.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1. Infrastructure design	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2. Envionmental conditions	0.269	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3. Vessel characteristics	0.244	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4. Traffic conditions	0.264	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5. Vessel characteristics	0.142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.1. Location environment	0.000	0.107	0.000	0.000	0.000	0.000	0.000	0.072	0.079	0.080	0.052	0.052	0.036	0.052	0.052	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.2. Type of infrastructure	0.000	0.221	0.000	0.000	0.000	0.000	0.119	0.000	0.169	0.170	0.113	0.113	0.074	0.113	0.113	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.3. Water depth	0.000	0.356	0.000	0.000	0.000	0.000	0.207	0.231	0.000	0.251	0.000	0.000	0.119	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.4. Width	0.000	0.315	0.000	0.000	0.000	0.000	0.174	0.196	0.252	0.000	0.168	0.168	0.105	0.168	0.168	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.1. Wind speed	0.000	0.000	0.188	0.000	0.000	0.000	0.094	0.094	0.221	0.094	0.000	0.000	0.000	0.000	0.000	0.063	0.063	0.063	0.063	0.094	0.094	0.000	0.063	0.063
2.2. Wind direction	0.000	0.000	0.087	0.000	0.000	0.000	0.043	0.043	0.069	0.043	0.000	0.000	0.000	0.000	0.000	0.029	0.029	0.029	0.029	0.043	0.043	0.000	0.029	0.029
2.3. Current	0.000	0.000	0.200	0.000	0.000	0.000	0.100	0.100	0.210	0.100	0.000	0.000	0.000	0.000	0.000	0.067	0.067	0.067	0.067	0.100	0.100	0.000	0.067	0.067
2.4. Visibility	0.000	0.000	0.473	0.000	0.000	0.000	0.237	0.237	0.000	0.237	0.000	0.000	0.000	0.000	0.000	0.158	0.158	0.158	0.158	0.237	0.237	0.000	0.158	0.158
2.5. Time of the day	0.000	0.000	0.051	0.000	0.000	0.000	0.026	0.026	0.000	0.026	0.000	0.000	0.000	0.000	0.000	0.017	0.017	0.017	0.017	0.026	0.026	0.000	0.017	0.017
3.1. Length	0.000	0.000	0.000	0.155	0.000	0.000	0.000	0.000	0.000	0.000	0.052	0.055	0.052	0.052	0.052	0.000	0.000	0.055	0.075	0.000	0.000	0.000	0.000	0.000
3.2. Draught	0.000	0.000	0.000	0.451	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.177	0.150	0.150	0.150	0.000	0.000	0.177	0.205	0.000	0.000	0.000	0.000	0.000
3.3. Speed over ground	0.000	0.000	0.000	0.109	0.000	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.036	0.036	0.036	0.000	0.000	0.000	0.053	0.000	0.000	0.000	0.000	0.000
3.4. Maneuvering capability	0.000	0.000	0.000	0.285	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.101	0.095	0.095	0.095	0.333	0.333	0.101	0.000	0.000	0.000	0.000	0.000	0.000
4.1. Traffic mix	0.000	0.000	0.000	0.000	0.286	0.000	0.000	0.000	0.000	0.000	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.000	0.000	0.286	0.095	0.095
4.2. Traffic volume	0.000	0.000	0.000	0.000	0.714	0.000	0.000	0.000	0.000	0.000	0.238	0.238	0.238	0.238	0.238	0.238	0.238	0.238	0.238	0.000	0.000	0.714	0.238	0.238
5.1. Traffic rules and port regulations	0.000	0.000	0.000	0.000	0.000	0.142	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.083	0.083
5.2. Pilotage	0.000	0.000	0.000	0.000	0.000	0.487	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.300	0.000	0.000	0.250
5.3. VTS information and navigational assistance	0.000	0.000	0.000	0.000	0.000	0.371	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200	0.200	0.000	0.250	0.000

Table 5.15: Limit supermatrix for A2.

	0	1	2	3	4	5	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3
0. Risk in navigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1. Infrastructure design	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2. Envionmental conditions	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3. Vessel characteristics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4. Traffic conditions	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5. Vessel characteristics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.1. Location environment	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
1.2. Type of infrastructure	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
1.3. Water depth	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
1.4. Width	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
2.1. Wind speed	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
2.2. Wind direction	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
2.3. Current	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064
2.4. Visibility	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131
2.5. Time of the day	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
3.1. Length	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
3.2. Draught	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
3.3. Speed over ground	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
3.4. Maneuvering capability	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
4.1. Traffic mix	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
4.2. Traffic volume	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147
5.1. Traffic rules and port regulations	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
5.2. Pilotage	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077
5.3. VTS information and navigational assistance	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060

Chapter 6

Multi-criteria Evaluation of Vessel Traffic for Port Assessment

In this chapter a multi-criteria evaluation methodology to assess vessel traffic in ports is presented. The methodology identifies the assessment criteria with main focus on risk and capacity. Based on these criteria, the input and output data required for the analysis and the decision making method are identified. By using a simulation model, several scenarios are created and the multi-criteria evaluation can be performed. The methodology is applied in a case study in the Port of Rotterdam.

This chapter is an edited version of the article:

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Multi-criteria Evaluation of Vessel Traffic for Port Assessment: A Case Study of the Port of Rotterdam. *Case Studies on Transport Policy*, under review.

Abstract

Vessel traffic is a key element determining port safety and capacity. The growth of port calls and cargo can have implications in port operations. Decision makers need to take decisions to anticipate any future capacity drop or increase in nautical risks. In this research, a multi-criteria decision making methodology is developed to evaluate the trade-off between safety and capacity of vessel traffic in ports, as well as other assessment indicators. The methodology first identifies the most relevant risk and capacity assessment criteria and the input required. A simulation model is used to calculate the criteria for a variety of different scenarios. The outcome results for the criteria from the simulations are used into a decision-making method that includes unknown decision makers′ preferences. The use of this methodology provides the best scenario for port vessel traffic, when strategic and operational decisions should be taken, and it can

be used as a framework for port assessment by decision makers for future changes in traffic management strategies or changes in the port infrastructure, such as port expansions.

6.1 Introduction

World seaborne trade has duplicated in the last ten years and the growth is maintained (UNCTAD, 2016). This implies a growth in port calls, with ports hosting larger vessels and higher flows within their nautical infrastructures. Hence, the analysis and assessment of ports has gained importance during the last years addressing different research topics, such as terminal capacity (Kia et al., 2002; Ligteringen and Velsink, 2012), traffic density analysis (Merrick et al., 2003), risks in ports (Chin and Debnath, 2009; Yip, 2008) or port selection (Guy and Urli, 2006). However, the existing research does not provide yet a methodology that allows decision makers (DM) to combine several of these topics for assessing vessel traffic in ports.

The assessment of vessel traffic in ports is a critical issue to keep port capacity and safety at an adequate level for future port planning or traffic management. Since these are several relevant topics of interest for port DMs, research to support DMs assessments is needed. In this research, we aim to provide a methodology that combines two of these main topics, risk and capacity, for port assessment. DMs might have difficulties on making decisions when there are several objectives which can be conflicting with each other. Decision-making include many criteria where a variation in the relative importance between them changes the final result. Hence, an optimal solution does not exist and it is up to DMs preferences to decide for the "best" alternative (Guy and Urli, 2006). In these cases, multi-criteria decision making (MCDM) methods can be used for structuring the problem involving multiple criteria and multiple DMs.

In this paper we develop an MCDM evaluation methodology to assess vessel traffic in ports with the contribution of combining risk and capacity indicators in this field. Based on the framework provided and the analysis of the results, DMs can better decide on future port designs and expansions, traffic management measures or changes in traffic distributions.

Section 6.2 describes the methodology, which includes the choice of the assessment criteria based on risk and capacity indicators, the description of simulation model to be used, the input data required for the evaluation and the choice of the MCDM method and weighting method used in this research. Section 6.3 describes the characteristics of case study developed in the Port of Rotterdam, and includes the input data for the model, the validation of the model, the structure of the scenarios, the output of the simulation and the weighting method. Section 6.4 describes the results of the simulation model and the application and analysis of the MCDM method outcomes. Section 6.5 presents the main conclusions and recommendations from this research.

6.2 Methodology for Port Assessment

A methodology for the assessment of risk and capacity of vessel traffic in ports by using the MCDM methods is developed in this research. The methodology considers five steps as shown in figure 6.1. First, the relevant assessment criteria for the specific evaluation purpose need to be identified. Simulation models can reproduce vessel traffic and generate the results that DMs can use for the evaluation of present or future situations in a port. Thus, a simulation model that fits the requirements for the previously defined criteria should be used for the calculation process. The input data for the model should fit the model characteristics and the output calculation. Later, the choice of an MCDM method and a weighting method according to DMs preferences should be determined. Most of the MCDM methods are subject to DMs preferences, but when assuming unknown preferences, these should be generated with a weighting method.

The development and subsequent assessment of a wide variety of scenarios allows DMs to make comparisons. Finally, when applying this methodology to assess any case study, the evaluation and analysis of the results will provide insights about the vessel traffic situation and information to support DMs decisions. The following subsections describe each step of the methodology in detail.

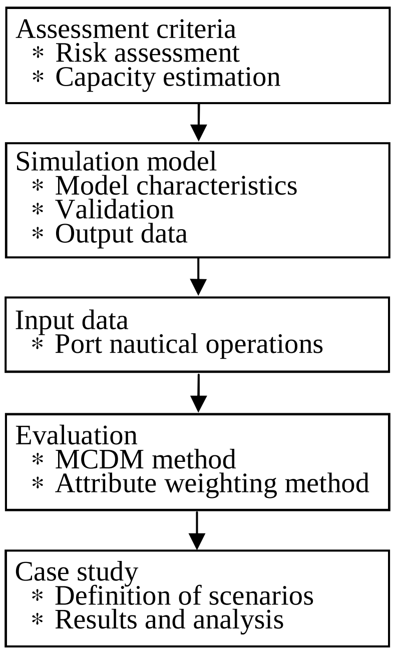

Figure 6.1: Structure of the Methodology for Port Assessment.

6.2.1 Determining assessment criteria

DMs would like to maximize the total number of vessels arriving to a port, with the consequent effect on risk and capacity. For this reason, this research focuses on the assessment of vessel traffic in ports by combining these indicators. As introduced, the combination of these two fields has not been previously addressed for the evaluation of vessel traffic. We first need to identify the main indicators related to capacity and risk in port vessel traffic.

A recent study reviewed the indicators related to port *capacity* and developed a methodology to estimate the vessel traffic capacity of an overall port network (Bellsolà Olba et al., 2017), and defined capacity as "the maximum average vessel flow within a time period". This work showed that the relation between the total number of trips in a port (TTs) and the ratio Waiting Time to Service Time (WT/ST) can be used to estimate a capacity value of a port network. The berth occupancy (BO) proved to follow an exponential distribution where above a certain occupation rate, the WT/ST ratio would increase without BO improvement, as previously shown by UNCTAD (1985) and Radmilović and Jovanović (2006). This can be used as an indicator of reaching capacity due to berth unavailability, although it is not sufficient to identify bottlenecks due to nautical restrictions in the infrastructure. Since ports want to attract the highest number of vessels visiting the port per year, also called port calls per year (PCs). The individual days are not representative due to the stochasticity in the vessel arrivals and the long ST that might be longer than a day, thus the daily traffic changes in different moments. In addition, PCs and TTs are both a measure of the number of vessels arriving in the port with different time periods. The turnaround time (TAT), time spent by vessels in each visit to the port, is also a good indicator to identify some effects of changes in the traffic in ports. However, this indicator might be misleading since its growth can be due to an increase on PCs or ST.

Risk is a more subjective topic and it is difficult to quantify. For our purposes, the risk contribution of different factors affecting navigation, and its consequences, e.g. the infrastructure design, the environmental conditions and the traffic conditions will be used, as done in a recently developed risk assessment methodology (Bellsolà Olba et al., 2018a). The method calculates a risk index, called Nautical Port Risk Index (NPRI), for each area in the port by the product of the risk perception values from a set of criteria times their consequences. The nautical risk cannot be obtained for the whole network as the capacity, due to the different influence of different infrastructure designs and environmental conditions on vessel traffic. Hence, the port is divided in areas, where each area has specific characteristics, different than the surrounding areas. The risk values are derived from the combination of the vessel characteristics and traffic conditions over certain time periods for each port area, considering the infrastructure design, the environmental conditions and the port regulations. The results provide the NPRI values for each time period in each port area. When ordering the values from low to high, the maximum NPRI values could be found, but there might be certain situations that give a peak risk which might happen only eventually. If considering that, the NPRI of the overall period might be overestimated. For our purposes, we will use the 95% maximum NPRI value for the area with highest risk.

This research focuses on these specific two topics, risk and capacity, and the indicators used are WT/ST ratio and PCs as capacity indicators, and NPRI as risk indicator for decision-making.

6.2.2 Simulation

Simulation models are useful tools for forecasting different scenarios. These scenarios can be compared and evaluated without having known data of future results and they can support DMs in their choices. The outputs from these models can be used as an input for the evaluation step.

As discussed in previous research, simulation models are developed with a certain scope to fit a specific purpose (Bellsolà Olba et al., 2018b). The characteristics of the model and its assumptions should provide the level of detailed required for the evaluation. Hence, for this research, a simulation model that includes nautical infrastructure and traffic characteristics with simplified individual vessel navigation behaviour, influenced by environmental conditions (wind, visibility, etc.) that affect navigation, is used to replicate properly vessel navigation and port operations.

For a realistic representation of vessel traffic, the model should simulate single vessels with their specific characteristics, where different vessel types have specific traffic rules and sailing limitations (Bellsolà Olba et al., 2018b). The model should include individual vessel information, and it should allow the calculation of the desired indicators previously introduced. The main indicators already identified need to be calculated using the model and it should be validated either with some data, if available, or based on the information provided by port stakeholders. As main results the WT/ST and PCs should be provided by the model. Moreover, individual results for each port area should be available to calculate the NPRI and to validate the results.

For this research, the "*Generic Port Capacity Model*" developed by the company *Systems Navigator* is used. The simulation model is an object oriented simulation that is built under Simio platform (Pegden, 2007). The interface "*Scenario Navigator*", also developed by *Systems Navigator*, is used to set up the input data for the different scenarios, run the model and generate the output results. The main processes represented by the model are the vessel navigation in the anchorage, access channel and basins, manoeuvring areas and berthing areas (see figure 6.2), without detailed manoeuvring behaviour of vessels. Speed variations in each section and due to encountering and overtaking situations are considered. Since the analysis of the capacity and risk of an overall port is at a high level, the simplifications considered in the model do not have a strong effect on the criteria to be calculated. The model reproduces properly all the port operations to be considered with the required quality for the research purposes. A complete description of the model and its characteristics was included in the research developed by Macquart (2017).

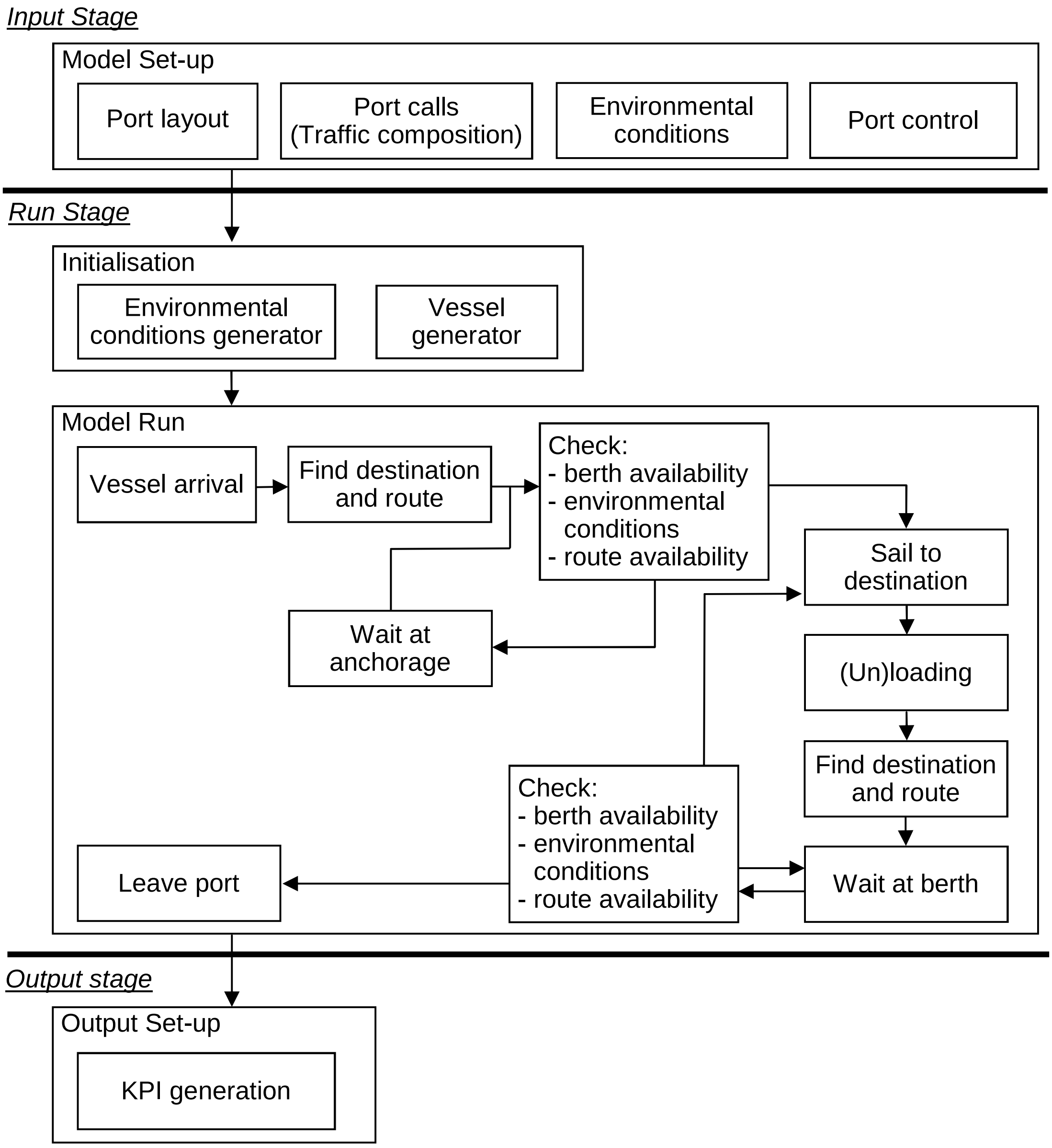

Figure 6.2: Model structure (adapted from Macquart, 2017).

6.2.3 Input data

The *input data* to represent the port nautical operations, and to obtain the necessary information to calculate the performance indicators chosen for the methodology needs to be defined. These data will be used by the model to generate the scenarios.

The different components for a safe and efficient vessel navigation in waterways have been comprehensively summarized by Froese (2015), and these components are used as input for a simulation model that represents vessel navigation in ports for our purposes. The input can be grouped in 4 main components, which are traffic composition, infrastructure configuration, environmental conditions and port control (see figure 6.2). The traffic composition includes the information related to the vessel flows inside the port in an OD matrix with the PCs of each vessel type per terminal. Since vessels have different sailing requirements and restrictions in different layouts, the infrastructure configuration should describe the different port spatial areas that represent different navigational situations within a port. When looking at vessel traffic, there might be traffic restrictions due to the combination between certain environmental conditions (wind direction and speed, current, visibility and tide), infrastructure designs and traffic compositions in specific areas of a port that do not allow certain vessels to sail. The tidal window can be a limiting factor in some ports, where vessel arrivals are constrained to certain hours where there is high tide and the water depth is enough for the vessel draughts. The port control includes the international laws and regulations, as well as specific regulations which are needed for the port of study.

The input can be divided into fixed and variable input. The fixed components are the infrastructure configuration and the port control, while the traffic composition, PCs and environmental conditions are variable and thus their input values for each run are different to create diversity of scenarios.

Table 6.1: Input data for port vessel traffic representation.

Main component	Sub-component
Traffic composition	Vessel class (container, bulk, tanker, etc.)
	Dimensions (length and draught)
	Origin-Destination flows
Infrastructure configuration	Type (straight, bend, intersection, etc.)
	Location (influence of the surroundings)
	Depth
	Width
	Speed regulations
Environmental conditions	Wind
	Visibility
	Time of the day
	Current
Port control	Laws and regulations
	Specific port regulations

6.2.4 Multi-criteria decision making and weighting methods

Multi-Criteria Decision Analysis has been extensively used in the past decades with an increase in its application in wide variety of areas, such as energy, environment, medical or transportation (Greco et al., 2005). MCDM methods are specially useful for complex situations where many variables are involved for both qualitative and quantitative analyses. A recent review of MCDM methods showed the importance of these methods for the evaluation of wide range of projects in the transportation field and their extensive application (Macharis and Bernardini, 2015).

There are a wide variety of MCDM methods, such as SAW (Simple Additive Weighting), TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution), AHP (Analytic Hierarchy Process), and ELECTRE (*Elimination and Choice Translating Reality*; English translation from the French original), among others, and each of them has their advantages and disadvantages. The use of different methods for the same problem is likely to provide slightly different results, and the validity of the method is not objective, since it depends on the preferences chosen for using a specific method (Triantaphyllou, 2000; Velasquez and Hester, 2013). Most important is that the DMs understand the method and the information necessary to use it, and that the method is compatible with the criteria chosen (Løken, 2007; Zanakis et al., 1998). The main disadvantages of most MCDM methods are the complexity of developing the method: they should never result in a "black box" to DMs who loose the relation between their preferences and the outcomes of the method, otherwise they might not trust the results achieved (Løken, 2007).

MCDM methods include the desired criteria for the assessment of their results. The application of most of these methods is subject to the use of weights to express the relative importance of criteria, which can be determined through analytical, simulation or empirical (heuristic) procedures. The weights are normally determined by DMs judgements, but the values can be difficult translate from their preferences to numbers and they depend on the DMs involved. When the values for these preferences are unknown or not clear enough to DMs, *attribute weighting methods* can be used to determine the weights while including uncertainty in DMs preferences in a more objective approach (Jia et al., 1998). This uncertainty can be translated to different sets of weights to be used in the decision-making process that provide different outcomes. For doing this, the MCDM methods that allow this possibility are SAW, TOPSIS and AHP, which in several studies have proven to provide similar results (Janic and Reggiani, 2002). Previous research compared several methods under different number of alternatives and criteria, and it showed that the distribution of criteria weights have lower effects when comparing SAW and AHP methods, while TOPSIS appears to be more sensitive to the number of alternatives (Zanakis et al., 1998). Thus, when not having many alternatives, the choice should be between the two first methods previously mentioned.

In this research, we use the SAW method due to its ability to compensate among criteria, its intuitive structure to DMs and the possibility to use a weighting method for weighting the criteria. A drawback of this method is that the results might not always reflect a real situation (Podvezko, 2011; Velasquez and Hester, 2013). This drawback will be taken into account when analysing the results.

According to previous research, there are several methods for weighing criteria, which are *equal weight* (EW), *rank-order centroid weight* (ROC), *rank-sum weights* (RS) and *inverse (or reciprocical) weights* (RR) (Barron and Barrett, 1996; Jia et al., 1998; Roszkowska, 2013). The use of linear MCDM models makes them quite robust to changes on the weights and the differences between the methods is not too large and any method is applicable. However, many of these studies showed that the ROC method performs slightly better than the rest (Roszkowska, 2013).

Therefore in this research, we combine the SAW method with both, EW and ROC weighting methods, to show the effect of several combinations of weights. The mathematical formulation of the different weighting methods is described in the following subsections.

Simple Additive Weighting (SAW) method

Simple Additive Weighting (SAW) is the most widely known method and extensively used in practice. The method consists of the integration of the criteria and weight values into an overall score for each alternative. The analytical structure of SAW for N alternatives and M criteria can be summarized as follows:

$$S_j = \sum_{i=1}^{M} w_i \cdot r_{ji} \qquad \text{for} \quad i = 1, 2, ..., N \tag{6.1}$$

where

S_j is the overall score for the j_{th} alternative;
r_{ji} is the normalised rating for the j_{th} alternative for the i_{th} criterion;
w_i is the weight corresponding to the i_{th} criterion.

The SAW method uses the normalization of maximising criteria of the values into the [0,1] interval and the values are calculated by the formula (Podviezko and Podvezko, 2015):

$$r_{ji} = \frac{(r_{ji} - \min_j r_{ji})}{\max_j r_{ji} - \min_j r_{ji}} \tag{6.2}$$

Rank-Order Centroid (ROC) weights

Rank-Order Centroid (ROC) weights method is based on an ordinal ranking of the criteria in order of importance (Barron and Barrett, 1996) and the weights can be calculated as:

$$w_i = \frac{1}{n} \sum_{k=i}^{n} \frac{1}{r_k} \qquad \text{for} \quad i = 1, ..., n \tag{6.3}$$

where

n is the number of criteria;
r_k is the ordered rank of the k criteria;
w_i is the weight for the criterion ranked k.

Equal Weights (EW)

The Equal Weight (EW) method does not require any knowledge about priorities of criteria or any input from DMs. The weights are equally represented as a uniform distribution and the calculation is as follows:

$$w_i = \frac{1}{n} \qquad \text{for} \quad i = 1, ..., n \tag{6.4}$$

where

n is the number of criteria;
w_i is the weight for the criterion ranked k.

6.2.5 Scenarios and analysis of results

The analysis of vessel traffic is complex and different situations might occur. Hence, the definition of different scenarios allows DMs to evaluate the impact of certain changes in different cases. The generation of scenarios consider different changes of the input variables to include the uncertainty and stochasticity of the nautical processes. The development of the previous steps are followed by the application of the SAW method and different sets of weights using ROC and EW methods with the calculated assessment criteria. The results show the effects of these changes on the criteria. Based on the information provided by the outcomes of each scenario, DMs can assess the implications on each vessel traffic situation and support DMs decisions based on the results obtained depending on their interests.

6.3 Case Study: Scenario Description

The methodology previously described has been applied to a case study of the Maasvlakte I and Maasvlakte II areas from the Port of Rotterdam (see figure 6.3). The aim of the case study is to show the application of the methodology as well as assess the effects of vessel traffic in future possible scenarios in the port. In this section the input data for the simulation model, its validation, the structure of the scenarios, the output data from the model and the weighting method are described in detail.

6.3.1 Input data for simulation

The first step to build the case study is to arrange the input necessary for the simulation model. The data was provided by The Port of Rotterdam Authority and it includes: 1) quay lengths and infrastructure dimensions, 2) water depths for each area in the port, 3) expected number of arrivals of sea-going vessels within a year per terminal and vessel class (10 different classes), 4) service times for all the terminals divided per vessel class, 5) sailing rules per vessel class in each port area, such as vessel minimum

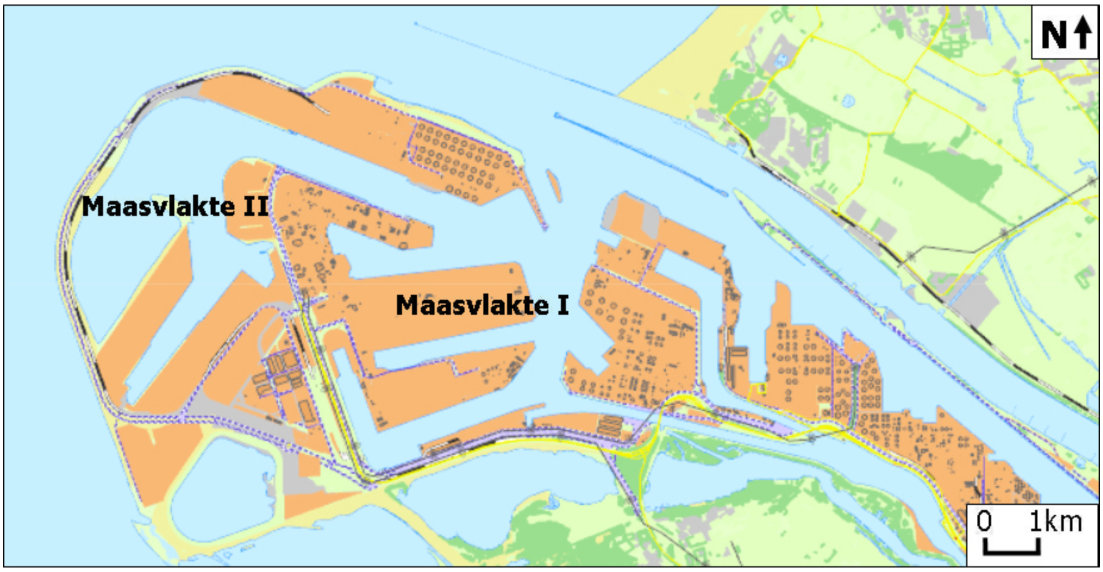

Figure 6.3: Research area map.

and maximum speeds, encountering limitations, safety distances and manoeuvrability restrictions in each port area, and 6) environmental conditions (current, wind and visibility) from the whole year 2014.

The base Origin-Destination matrix (OD) includes the PCs of each vessel type per terminal, although they might visit up to three different terminals during their stay, according to the information provided from the Port of Rotterdam Authority. After the first visit, a probability matrix of a next trip within the port is defined for each vessel type in each terminal. The OD table is defined at terminal level, and the capacity of each terminal is determined by the quay length available and the coming vessels length. Because of the competition between terminals, we consider that the shares per terminal will remain equal, and the OD table is unchanged in this research.

An assumption done in this research is that vessels arrive with stochastic arrivals. The Port of Rotterdam plans the vessel arrivals with a minimum of 24h in advance, with that, their waiting times are negligible at arrival, since they already informed the navigators when they should arrive, so they adjust their sailing speed to make it on a specific time. However, since this is not the case for many ports, stochastic arrivals will be used for this research.

6.3.2 Simulation validation

A simulation model could provide a set of results that are not corresponding to reality. Hence, the simulation should be validated to guarantee that the analysis of the MCDM method are meaningful. Thus model validation is necessary.

First, the input data was used to test the model developed by the company *Systems Navigator*. From the data provided by the Port of Rotterdam, the vessel arrivals follow an Erlang distribution for each terminal and vessel type. As previously mentioned, there are 10 different vessel types, and not all the vessels visit all terminals, each terminal has fixed vessel types visiting. The service times were derived from real data and they fitted a normal distribution in each terminal and vessel type with different parameters.

The only real data available were service times and trips between terminals. These data are used to adjust the model. Changes in trips between terminals and ST are used to provide simulation results that approximate the real data. The model set-up that provided a lower difference than 15% in both, real data in service time and number of trips for each terminal, was chosen as the base case (BC). With the data available, it is not possible to achieve a difference lower than 15% in both values for all terminals. When looking at the total values combining all the terminals, the differences are below 3% for both values. Changes in the distribution of trips between terminals creates large difference between certain set-ups and real data.

6.3.3 Scenario structure

For the assessment of the methodology, we created a set of different scenarios to compare the effect of changes in vessel traffic in the upcoming future in the Port of Rotterdam, and later apply the MCDM method. The infrastructure is considered to remain the same, since there is not an extension plan after the recent expansion of Maasvlakte II. The scenarios chosen are based on the possible situations that are more feasible to happen, such as gaining in the competition to other ports or the improvement of the global economy. The evaluation of these scenarios with different inputs and outputs will be useful for testing the methodology.

The first scenario would happen if the *port attractiveness* increases due to factors as location (country), hinterland connections or other interests from shipping companies, and the number of PCs increases. The effect of an *economic growth* would lead to vessels transporting more cargo, and longer stays at terminals as an effect of more ST needed during the loading and unloading processes. Another situation that could happen is the combination of both, where more PCs and larger ST happen. The last situation considered would be that the growing trend in vessel sizes continues, and having the same amount of PCs, the types of vessels are larger, with its consequence in also larger processing times due to more cargo transported.

In all three scenarios, a decrease or increase in percentage is shown for the specific variable that changes. For the scenario that combines the port attractiveness and the economic growth, the increase in percentage of PCs is the same as the increase in ST. In order to determine the size of the sample for each run, a z test was used to analyse the variation of the assessment criteria values. From the results with larger variation respect the BC, five replications per scenario fulfil a 95% reliability level for all the criteria with a 90% of confidence level.

6.3.4 Simulation output

The assessment criteria previously described are obtained from simulation. The results are used as an input for the application of the MCDM method as the next step of the methodology. One of these criteria, the risk indicator (NPRI), was validated in previous research in these areas (Bellsolà Olba et al., 2018a), and the values of the risk perception and the consequences for its calculation are included in the Appendix 2.

The results from the simulation take the BC as reference, where 0% variation of the specific variable is considered. The variation in each scenario is represented as an increase if positive and a decrease if negative. There are changes in demand and ST, depending on the scenarios, to evaluate several future scenarios.

6.3.5 Weighting method

As described in the previous section, this research assumes unknown preferences from DMs, thus unknown weights. In cases where DMs do not have an agreement in how to set the preference values, this would be the best approach to compare between them. The preferences would be linked directly to whom are these DMs, if they are port authorities, port planners or political authorities with different interests. When obtaining the information from DMs, the larger the sample would be, the more reliable the results would be. However, when only having a limited number, it might be more useful to make a blind evaluation without revealing their preferences and see what are the differences, for later better choose among the results and determine their real preferences.

We use two methods for determining weights for the analysis. There are 3 assessment criteria considered for the analysis. For the EW method, the weights are equal, but for the ROC method we have several combinations, when assuming that DMs would rank the criteria with different preferences. The following table shows the possible combinations considered with the resulting weights.

Table 6.2: Possible decision-making weights.

Method	EW	ROC											
	W_1	r_k	W_2	r_k	W_3	r_k	W_4	r_k	W_5	r_k	W_6	r_k	W_7
WT/ST	0.333	1	0.611	2	0.278	3	0.111	1	0.611	2	0.278	3	0.111
NPRI	0.333	3	0.111	3	0.111	2	0.278	2	0.278	1	0.611	1	0.611
PC	0.333	2	0.278	1	0.611	1	0.611	3	0.111	3	0.111	2	0.278

6.4 Case Study: Simulation Results and Decision-Making Results

The last two steps of the methodology consist of defining the scenarios, analyzing the simulation results and using the results in the MCDM evaluation step to assess the port. The scenarios were simulated considering the changes in parameters based on the previously described characteristics. For each variation of any of the parameters, five replications are simulated. The results and analyses are provided per scenario, and the decision-making method is developed using the results.

6.4.1 Simulation results

Port attractiveness

The BC, with a 0% variation, shows that with the current PCs per year (around 8200), the approximate results provide a WT/ST of 10% and 22 TTs per day in the port. TTs and PCs proved to follow a linear relation therefore, we use PCs as indicator because it is a more intuitive value for DMs.

As shown in figure 6.4 (left), the variations in PCs are represented by different colours from the 0% variation situation (BC). When having a reduction in demand, the results show an important drop in PCs and produces a not so considerable reduction in WT/ST because this value is already low. On the other hand, when increasing the number of PCs, it can be seen that the increase of WT/ST becomes relatively higher compared to PCs.

Figure 6.4 (right) shows the risk variation in the risk values (NPRI) within the port. With the current layout and vessel traffic management, the maximum possible risk would be 4.45 in a scale 1 to 5. The results show a small variation of risks values, where the BC has a 2.74 and the highest NPRI is 2.84 for the scenario with highest PCs. This small variation is due to the traffic rules already defined by the port, and considered in the simulation. The results prove that the safety level in this area of the Port of Rotterdam is high and it is not considerably influenced by the growth in PCs. As shown by the results, the risk in this research area is not a remarkable issue, and since its variation is really low, the highest weights for this scenario would not provide relevant results for DMs. Because of this, we decide to work with W_1, W_2 and W_3.

As previously introduced by Bellsolà Olba et al. (2017), the capacity of a port network could be found because the TTs (or PCs, since they are linear), would reach a capacity limit at a certain point. This effect happens when the limiting factor is the nautical infrastructure, but in this research, as it can be seen in figure 6.4 (left), after an inflection point around the 25% of WT/ST, the PCs still increase. The relation between PCs and TAT, shown in figure 6.5 (left), proves that the turnaround of vessels in the port suffers a huge increase after an increase of demand above 15%. This can be explained by the effect of berth availability in the port. In figure 6.5 (right), the relation between

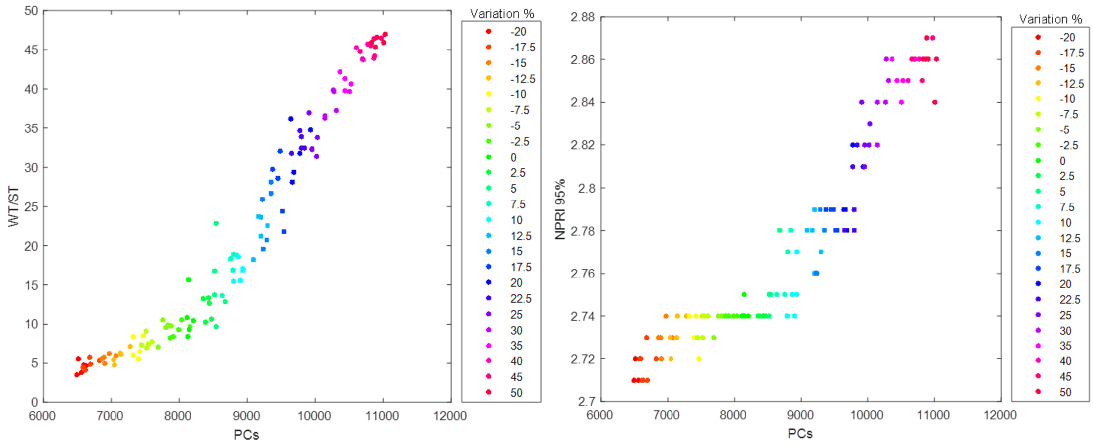

Figure 6.4: PCs vs WT/ST (left) and PCs vs NPRI 95% (right) (Scenario port attractiveness).

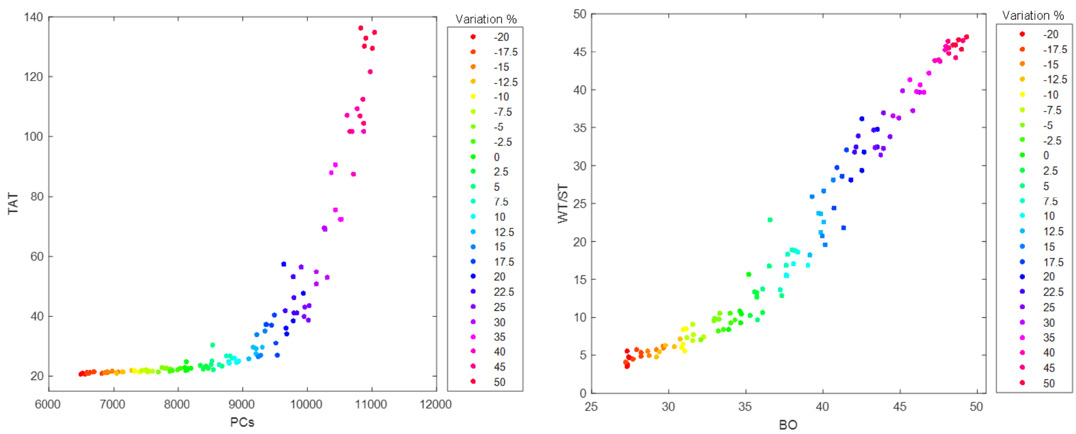

Figure 6.5: PCs vs TAT (left) and PCs vs BO (right) (Scenario port attractiveness).

BO and WT/ST shows that after the same point as the previous case, the increase in WT/ST becomes exponential. Although the BO appears to be not too high, this value is different between terminals. According to the arrival distribution of vessels between terminals and the vessel visits to different terminals, there are 6 terminals out of the 15 terminals in the port that have more than 75% of the total vessel arrivals, while the BO is calculated based on the total weighted quay length from all terminals. Hence, the main bottleneck in this case study is the quay availability. The TAT increase can be explained due to the vessel shifts between terminals, when other terminals have vessels in the quay and these vessels cannot go to their next destination, they are occupying a berth without being served. This also proves the relevance of a good planning of these shifts for a better the growth in PCs in a port.

Economic growth

The case of an economic growth would be translated in larger ST for vessels in ports due to the increase in cargo transported. This would be translated in larger times with berths occupied, and if the increase in cargo goes above the 10% on average in all vessels, the WT/ST increases to the detriment of the number of PCs (see figure 6.6 (left)), which correspond with the point on the right where the shortage of available berths starts. The change in trend of BO for the results above 10% increase is due to the reduction in PCs (see figure 6.6 (right)). The number of vessels entering the port decrease and the WT/ST ratio does not increase more. In relation to the NPRI, since there is not an increase in PCs, the traffic does not get to a worse situation and the maximum values go between 2.71 and 2.8, as it would be expected.

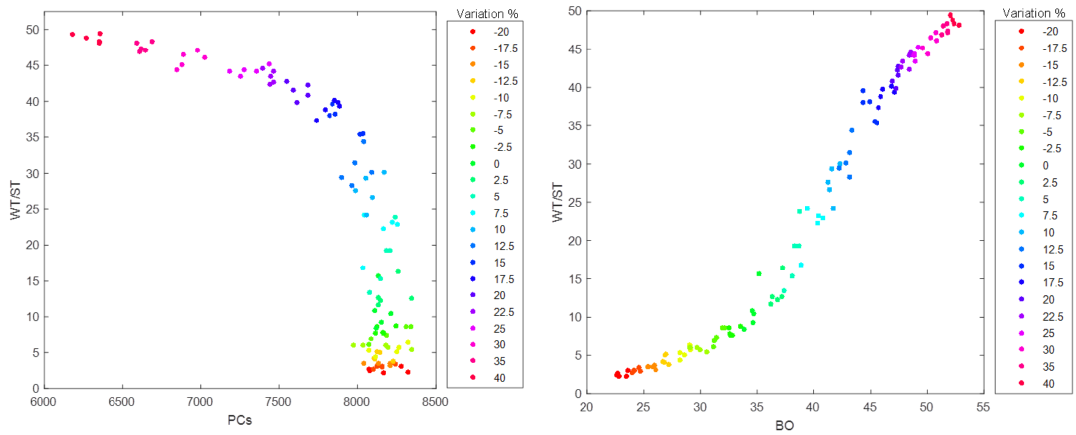

Figure 6.6: PCs vs WT/ST (left) and PCs vs BO (right) (Scenario economic growth).

Port attractiveness and economic growth

In case of a combination of both situations, where the port attracts more PCs per year and an economic growth happens, the results appear to be different. The increase in PCs creates a slight increase in the WT/ST, but the parallel increase of ST creates an inflection point above a 5% increase, where the WT/ST keep increasing while the PCs start going down (figure 6.7 (left)). Figure 6.7 (right) shows the same trend as in the previous case and it proves the effects of the berthing limitations.

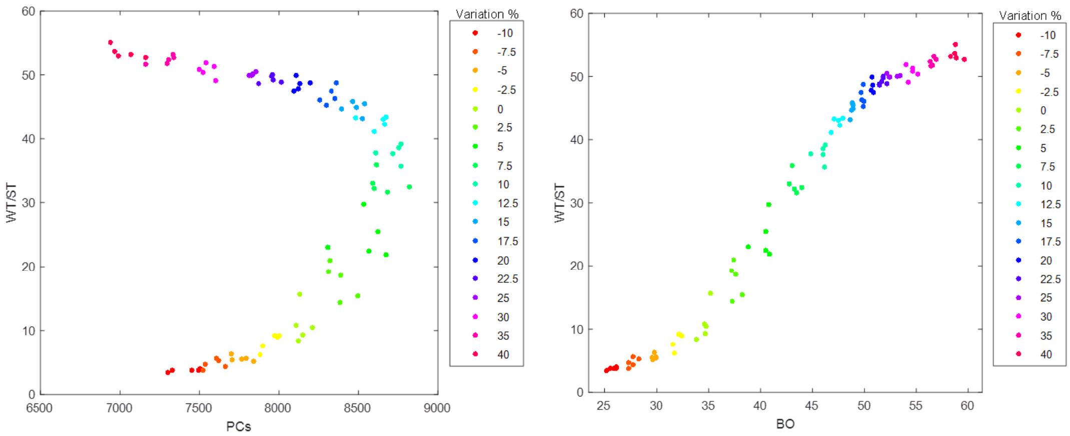

Figure 6.7: PCs vs WT/ST (left) and PCs vs BO (right) (combined scenario of port attractiveness and economic growth).

6.4.2 Decision-making evaluation

The last step of the methodology is to apply the MCDM method, with the values for the assessment criteria described in the previous section, to assess the vessel traffic in the port. The values considered for each percentage of variation on PCs are the average of the 5 replications obtained from the simulation. It has been shown that when PCs or ST would increase, the limitation of berths in some terminals would be the bottleneck in this port area, while the traffic situation would remain on the safe side. However, DMs might need to take a decision given a certain point in time and decide until which threshold they would allow the variables to reach.

In the case of WT/ST, the higher values of this criterion are worse than the lower and their order is reversed because the SAW method only allows maximizing criteria (Podviezko and Podvezko, 2015). The acceptable WT/ST are considered up to 35%. The NRPI value is normalised between 1 and 4.45, since the latest represents the maximum risk in the worst possible scenario and to have the same scale for all the scenarios. For the PCs, they are normalized between the BC and the maximum before the inflection area, which represent the starting point where the bottleneck effects appear.

Before making the calculations, it needs to be pointed out that in the case of an economic growth, the future situations would be worse both in lower PCs and higher WT/ST, with the consequence in a slight reduction in the NPRI. If DMs expect this scenario to happen, they should look in detail at the current BO of each terminal to apply some changes or restrictions on the multiple visits within the port. If this growth leads to an increase in total cargo higher than 7.5%, the WT/ST reaches the 35% and the situation worsens. In this case, no MCDM method is necessary, since the best scenario would be the actual one. If DMs consider this scenario to be feasible to happen, they should apply some changes in the current traffic operations to reduce the impacts.

The calculation of the SAW method in combination with the different sets of weights provide the results for each scenario, as presented in table 6.3. These results can be compared and used by DMs when preferences from DMs have been defined beforehand. As it can be seen, the outputs are different when using different preferences, depending on their preferred indicator.

In the case of port attractiveness, the results obtained differ when the preferences of decision makers are different. In the case of equal weights, the optimum scenario would be optimum for the 10% growth in vessel traffic and no change for the future would be necessary up to that point. After that moment on time, the steady increase of demand would worsen the situation and the capacity of the port is reduced. When DMs would consider the WT/ST the most important factor (W_2), the most efficient situation occurs when the increase is only of 2.5%, which means that changes on the future traffic strategies, such as limit the terminal visits or make some traffic regulations more flexible, by maybe assuming slightly higher risks due to more encounters or overtakings allowed, would help on this. The last situation is when DMs preference give more importance to the number of PCs, when the best situation would be on the limit of the acceptable WT/ST threshold. As in this case study, the maximum value for the normalisation was 35%, the most efficient scenario for this situation would be the 25% increase in PCs. If DMs use these preferences, the capacity for the future keeps increasing until that moment.

For the scenario combining port attractiveness and economic growth, the results are different. The results show that when DMs preferences would consider equal weights or larger importance to WT/ST, the BC situation is the most efficient and, consequently, changes in the future traffic management would be necessary almost immediately. When having larger preference for PCs, the best scenario is the 2.5% increase, which also do not give much slack to DMs before they apply new regulations.

Table 6.3: MCDM method results (best results shown in grey).

	Port attractiveness			Port attractiveness and economic growth		
Variation percentage	W_1	W_2	W_3	W_1	W_2	W_3
0.0	0.382	0.588	0.303	**0.608**	**0.790**	0.704
2.5	0.404	**0.592**	0.357	0.594	0.730	**0.726**
5.0	0.402	0.551	0.392	0.565	0.658	0.721
7.5	0.401	0.524	0.417	0.530	0.567	0.718
10.0	**0.434**	0.559	0.470	0.501	0.509	0.699
12.5	0.424	0.486	0.517	0.448	0.431	0.636
15.0	0.410	0.445	0.520	0.408	0.382	0.580
17.5	0.400	0.398	0.540	0.367	0.334	0.518
20.0	0.397	0.338	0.590	0.323	0.285	0.451
22.5	0.382	0.311	0.578	0.286	0.249	0.390
25.0	0.412	0.337	**0.634**	0.252	0.216	0.336

As shown in table 6.3, the application of the methodology described in this paper provides a single best solution for each scenario and set of weights. It is interesting to compare how differently the sets of weights affect the final results from the SAW method. For the first case, there are significant differences in the final result, which shows the sensitivity of the MCDM method for this scenario. However, the second scenario have almost the same results for all the different sets of weights. The use of the *attribute weighting methods* shows to DMs the effect of their preferences in the final result. This might help them to make a more reasoned choice when setting up their preferences.

6.5 Conclusions and Recommendations

This paper presents a methodology to evaluate risk and capacity of vessel traffic for port assessment through the clear definition of the assessment criteria related to risk and capacity, the input required for a simulation and the use of the simulated results in the Simple Additive Weights (SAW) method for MCDM evaluation.

The methodology has been developed and applied to a case study. The final results show that this methodology is a good structured framework to support DMs in the assessment of vessel traffic in ports. The use of unknown preferences can reveal the impact of DMs preferences in the final results and provide them insight in the consequences of their decision-making process.

In the presented example, three different feasible future situations were selected with three criteria, and the attributes were quantified for different variations and used as evaluation results. This method requires weights to be given by decision makers (DMs). When not having explicit preferences from DMs, the use of different weighting methods provide a larger view over the situation than it would be the single use of a set of weights that provide a unique result. The results showed that DMs preferences have an effect in the outcome of the method and they should be considered for the evaluation of these outcomes.

For the possible assessment of future situations, the use of a port simulation model allows the generation of stochastic scenarios with changes that allow the forecasting of future situations. The use of this results for the multi-criteria evaluation helps DMs to make reasoned choices based on their preferences without knowing in detail all the complexity of the vessel traffic. Once DMs have identified their efficient scenarios, their thinking should focus on which changes are necessary from the current traffic management, the terminal regulations or the sailing rules that could be changed to become more efficient and allow higher PCs, with lower WT/ST and NPRI.

Multi-criteria decision making methods are a useful tool when having more than one criteria when evaluating different situations, with certain DMs preferences. Sometimes, as it happened in this research, the variation of one of the criterion can end up not being relevant compared to the others. However, all the relevant criteria should be considered at the beginning of any evaluation study.

The choice of diversity of factors adds complexity to the understanding of the situation for DMs. Future research should be done in this field by considering more factors that play a role in vessel traffic in ports, such as vessel emissions or costs. The implementation of this decision-making methodology in simulation models would be really beneficial for DMs.

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Appendix 2

Table 6.4: Risk perception values for Maasvlakte I & II (Bellsolà Olba et al., 2018a).

Criteria	Sub-criteria	Risk Perception weights
Infrastructure design	Location	0.029
	Type of infrastructure	0.075
	Water depth [m]	0.027
	Width [m]	0.067
Environmental conditions	Wind speed [knots]	0.081
	Wind direction	0.047
	Current [knots]	0.032
	Visibility [m]	0.124
	Time of the day	0.012
Vessels characteristics	Length [m]	0.024
	Draught [m]	0.055
	Speed [knots]	0.012
	Manoeuvring capability	0.059
Traffic conditions	Traffic mix	0.038
	Traffic volume [ves/3h]	0.169
Vessel Traffic Managment	Traffic rules and port regulations	0.013
	Pilotage	0.08
	VTS assistance	0.056

Table 6.5: Consequence table for Maasvlakte I & II (Bellsolà Olba et al., 2018a).

CONSEQUENCE RISK NAVIGATION SCALE								
Criteria		Sub-criteria		Very low risk	Low risk	Medium risk	High risk	Very high risk
1	Infrastructure design	1.1	Location (high/flat landscape/buildings)	Low	-	Medium	-	High
		1.2	Type of infrastructure	Straight	-	Bend	-	Crossing
		1.3	Water depth [m]	> 25	25 - 21	21 - 17	17 - 15	< 15
		1.4	Width [m]	> 500	500 - 425	425 - 350	350 - 300	< 300
2	Environmental conditions	2.1	Wind speed [m/s]	<=5.5	5.5 - 8	8 - 10.7	10.7 - 13.8	>=13,8
		2.2	Wind direction	Bow/sternwind (<20°)	20° - 35°	Diagonal (35° - 55°)	55° - 80°	Crosswind (>80°)
		2.3	Current [knots]	<1	1 - 1.5	1.5 - 2	2 - 2.5	>2.5
		2.4	Visibility [m]	> 1500	1500 - 1200	1200 - 900	900 - 500	< 500
		2.5	Time of the day	Day	-	Dawn / Dusk	-	Night
3	Vessels characteristics	3.1	Length [m]	<100	100-150	150-225	225-300	>300
		3.2	Draught [m]	< 12 m.	12 - 13	13 - 14	14 - 15	> 15 m.
		3.3	Speed [knots]	< 5	5 - 6	6 - 7.5	7.5 - 10	> 10
		3.4	Manoeuvring capability	1	2	3	4	5
4	Traffic conditions	4.1	Traffic mix (same or different types)	1	2	3	4	5
		4.2	Traffic volume [ves/h]	< 1.7	1.7 - 4.3	4.3 - 6.7	6.7 - 8.3	> 8.3
5	Vessel Traffic Managment	5.1	Traffic rules and port regulations	100% Goal based	-	50	-	100% Rule based
		5.2	Pilotage	> 90%	90-80%	80-70%	70-60%	< 60%
		5.3	VTS assistance	X	-	-	-	-

Chapter 7

Conclusions

The overall motivation of this thesis is to contribute to the assessment of port nautical safety and capacity through the development of a vessel traffic port evaluation methodology. More specifically, the idea is to identify and combine the most prominent indicators related to vessel traffic in ports, namely capacity and risk, that can be used to assess its efficiency. In order to achieve this objective, better understanding of vessel traffic was gained through in-depth analyses of vessel traffic data in ports and discussions with port, risk and navigation experts. The capacity and risk topics for ports are investigated in detail, which led to a variety of new methods to evaluate these topics. These topics have been mostly addressed separately in literature, but this research brings together both topics, capacity and risk, to provide a methodology for vessel traffic port assessment.

This chapter begins with a description of the main findings and contributions of this research in section 7.1. The scientific and practical implications of the research presented in this thesis are reflected upon in sections 7.2 and 7.3. Finally, section 7.4 outlines topics for future research.

7.1 Main findings and contributions

In this section, the main findings and contributions of the research on the assessment of vessel traffic for port efficiency are summarized. To this end, the research questions introduced in chapter 1 have been answered.

RQ1. What are the characteristics of current port simulation models to represent realistic vessel navigation? Can these models be used for port risk and capacity assessment? (Chapter 2)

Vessel navigation in ports is complex and it involves different processes. The processes that have a larger importance for vessel navigation in ports are identified to review and assess the existing simulation models. The state-of-the-art of existing port simulation models focused on infrastructure design and navigational behaviour. The assessment of the elements related to vessel traffic in ports reveals that detailed infrastructure, detailed traffic rules, interactions between vessels and navigational behaviour should be considered when modelling ports. Some simulation models already include one or more of these features but none of them included all aspects. Moreover, the application of these models into port capacity and risk assessment shows that the existing models were designed to fit only one of the assessment criteria. Thus, future models should consider all these features for a more realistic vessel traffic representation and the support of an assessment decision-making methodology to better understand their outcomes is necessary.

RQ2. What is the definition of capacity for a port as a network of waterways? Which indicators and method can be used to estimate the vessel traffic capacity of a port network? (Chapter 3)

Previous research has used different capacity definitions for different purposes, such as terminal capacity, and also different indicators to define it. In this research, we proposed a suitable capacity definition for port vessel traffic as “the maximum average vessel flow that can be handled by a port, with its specific infrastructure layout, vessel fleet, traffic composition and demand, satisfying the required safety and service level”. A review of the indicators leads to the choice of the total number of trips and the ratio waiting time to service time (WT/ST) as indicators. By using a simulation model, new insights about trade-offs between these indicators lead to a maximum number of trips with an increasing WT/ST, which provides the value of the nautical capacity of a port network, and a step-by-step methodology is developed. The port network traffic capacity (PNTC) estimation methodology provides a structured approach to find out the relation between port traffic related indicators to determine a capacity limit. Finally, setting a demand/capacity ratio of 0.92, as done in road traffic, an acceptable flow for a given port design is estimated. The results show that above that value, the traffic becomes unstable and WT/ST increases dramatically in relation to the increase on vessel traffic.

RQ3. Which method can be used to determine the capacity of an intersection of waterways? (Chapter 4)

A new estimation method is based on an analogy with the conflict technique for road intersection capacity estimation. First, a safe headway between consecutive vessels sailing from each direction is defined based on a safe distance and their speed over ground. The probability of encounter between each direction and the other directions is defined and, using a conflict matrix that includes all the possible encounters, the probability of conflict of each of the directions with the rest is defined. This probability is used to calculate the capacity of each stream, and the sum of them results in the total capacity of the intersection. As a result, the maximum amount of vessels that a certain intersection can accommodate is estimated by using any data, real or simulated. The method was validated with two case studies in two intersections from the Port of Rotterdam using AIS data. The estimated capacity can be used by port stakeholders to assess current or future traffic situations, new port designs or changes in the traffic management strategies.

RQ4. Which criteria contribute to the navigational risks in a port? Which methodology can be used or developed for nautical risk assessment of ports? (Chapter 5)

As a first step, risk is defined as the combination between risk perception during navigation (frequency) and its consequences. The risk criteria in port vessel navigation are defined thanks to the knowledge from expert navigators. This criteria is divided in five groups: infrastructure design, environmental conditions, vessel characteristics, traffic conditions and vessel traffic management. The risk perception values associated to each criteria are derived from navigational experts whom provided their answers to a survey and from this, using the Analytical Network Process (ANP) method, the importance of each risk criteria is translated to a weight. The combination of these weights and the consequences associated to each criterion provides the Nautical Port Risk Index (NPRI) for every port area within a time period. This new risk quantification provides a flexible tool for analysing navigational risks in ports, with the advantage of not only being based on historical data. This methodology allows the dynamic and proactive assessment of nautical risks in ports by stakeholders and it can be performed with real or simulated data.

RQ5. Which methodology can combine several indicators to evaluate vessel traffic efficiency in ports with practical applicability? (Chapter 6)

A multi-criteria method to combine vessel traffic capacity and risks in ports is developed. The first step is to identify the efficiency criteria for related to capacity (port calls and waiting time to service time ratio) and risk (NPRI). In order to test several scenarios, the necessary input for a simulation model to obtain these criteria was identified. By using a port simulation model from the company *Systems Navigator*, a variety of scenarios were generated and the results were used for the Simple Additive Weighting (SAW) decision method. With different weighting methods, different preference were assigned to decision makers to evaluate the different results that would be obtained. The evaluation methodology provides the most efficient situation and determines the moment when strategic and operational decisions should be taken. Decision makers can use these results for future changes in traffic management strategies or changes in the port infrastructure.

This thesis develops different methodologies using a multidisciplinary research approach. The main objective of the research has been covered by the methodology presented in chapter 6, which englobes and applies the findings from previous chapters. The theoretical background and the use of both, historical and simulated data, enriches the different research steps performed to achieve the final result. The applicability of this research into real ports by practitioners is highlighted in the following section.

7.2 Implications for science

There are several contributions provided in this thesis that are of special interest for the scientific community. The contributions are summarized in the following paragraphs.

The state-of-the-art of port simulation models, presented in this thesis, provides a wide overview of the content and functionalities of nautical traffic simulation models, which provide better insight into the modelling of vessel traffic in ports. This research can support the choice to apply certain models for specific research. In addition, this can help future researchers in choosing which features should be considered for the development of suitable future port simulation models.

This thesis proposes a new Port Network Traffic Capacity (PNTC) estimation method based on the most suitable indicators related to vessel traffic in ports. The methodology describes the theoretical steps to be followed to determine the capacity of a port network. New insights about relations between several indicators and the effects on the PNTC are revealed. Historical data and simulation results can be used for the study.

The current traffic has its specific rules and priorities within a port. However, due to higher vessel flows, busy waterway intersections in ports might become a bottleneck. The intersection capacity estimation method developed in this thesis provides a theoretical approach to find out a proxy capacity value from historical or simulated data, for current or future situations.

This thesis developed a Nautical Port Risk Index (NPRI) that can be used to assess the current risk situation or future risk from forecasting results in different areas from any port. The methodology describes the steps to obtain the risk perception and consequence values from expert knowledge, which makes the method less subjective. The use of the Analytic Network Process (ANP) to extract the risk perception has been developed. The methodology results in a quantitative risk value.

The overall evaluation method uses three indicators that can be calculated by a simulation model for future decisions. This methodology introduces the combination into a single value of multiple indicators to assess vessel traffic. The use of an understandable multi-criteria decision making method makes it easy to understand and the weighing method can be adapted to the decision makers' preferences, which provides a flexible and generic methodology.

7.3 Implications for practice

The research developed in this thesis has a strong focus on its generic applicability into real cases in any port. The research has several contributions to practice which can be used by port related decision makers, planners and practitioners.

The PNTC estimation method developed in this thesis can be used by port planners and designers to estimate the capacity of port waterway networks when designing port expansions or during the evaluation of new port designs. Based on the results, the effects of different infrastructure designs or distributions of trips between terminals or the effect of larger vessels can be compared. The method can also be used to compare changes in capacity due to new traffic rules or port regulations to improve current traffic operations.

The capacity of the whole port can be affected by bottlenecks at single locations. Since intersections are a key area to avoid traffic drops, the results allow the comparison on how different vessel flow shares for different directions affect the intersection capacity. Port practitioners can analyse different traffic situations where higher capacity is required by applying changes of traffic regulations or traffic management strategies which can reduce the influence of these bottlenecks for the overall traffic.

Risk experts, or the corresponding decision makers, can apply the risk assessment method presented in this thesis to quantify risks with the NPRI value. This result can be used when comparing data from different time periods to explore how risks develop over time, and in the future. Moreover, it can be used to evaluate the effect on risk of new traffic regulations, future traffic demands, or the relation between these two factors in expected scenarios. This method can also support the assessment of risks for the future transition to autonomous ships.

Finally, port practitioners can benefit from the clear structure and description of the multi-criteria evaluation methodology to combine multiple indicators for port assessment. It has generic applicability for any case study, and the weighting method used provides them a wide range of solutions which can help port practitioners to define their preferences or to give the opportunity to include their opinions. The results can be applied widely in the evaluation of port designs, changes in traffic rules or when forecasting different vessel traffic scenarios.

7.4 Recommendations for future research

This research focused on the assessment of vessel traffic in ports, a relevant topic for the future due to the continuous increase of the maritime traffic. The traffic in ports is expected to keep growing, both in flow and vessel sizes, which implies larger and less manoeuvrable vessels and busier waterways and intersections. Further research in this field will be necessary to adapt the current methodologies to the previously mentioned changes in traffic or the transition to automated shipping.

Current simulation models that reproduce realistic vessel navigation are mostly implemented for single vessel manoeuvring for local studies and not to whole ports due to the long computational times. With the fast-paced technological evolution, the processing times might drop and encourage more researchers and companies to develop more extensive and complex models. Moreover, the growth in data availability has already allowed researchers to simulate vessels as autonomous agents (Xiao, 2014) or the effects of human behaviour in vessel manoeuvring (Hoogendoorn et al., 2013; Shu et al., 2015). However, the effects of current, weather or encountering effects is still a challenge for the future models. The incorporation of these three factors in the simulation of vessel traffic in ports would eliminate several simplifications of the current port models and allow new types of analysis of port traffic.

Capacity estimation methods for intersections and port networks have been developed in this thesis and they have been applied to case studies in the Port of Rotterdam. Further research could apply these methods into other ports to assess them under different conditions. The formulation of the intersection capacity method could be further improved by considering different vessel types instead of a single one. Further research into port network capacity estimation could lead to new trade-offs between indicators that have not been considered yet in this research, and an methodological changes might be incorporated in the current research to include new indicators.

The risk assessment methodology developed in this thesis, focuses on the hourly risk assessment of different port areas with a case study for the Port of Rotterdam. Future research could focus on the validation and robustness analysis of the methodology in other case studies. The method could be extended to assess different time periods, such as yearly risks, or seasonal risks which might be beneficial for ports to adapt or change certain regulations and improve their traffic management. The applicability of the method is limited to the area where experts are asked about. Hence, research into how to make this approach generic, without depending on individual opinions, could be developed. Finally, the implementation of this methodology in a simulation model could be used for forecasting future risks in the port in any situation. This framework could be used as a design tool to assess new ports or to assess the operational risks in existing ports.

This thesis developed a methodology that combines two relevant topics for vessel traffic port efficiency, capacity and risk. First, further research could explore the effect on the results when using other multi-criteria decision making methods that are suitable for the same purposes. Moreover, there are other topics of interest for port decision makers that should be considered and combined in future research for the methodology. An issue of interest for future ports is, for example, sustainability and how the presence of a port and vessel emissions affects the environment.

In relation to the technological evolution, automated vessels are expected to sail in ports, and new communication systems between vessels might improve the current navigation. Such changes will require new regulations and models that fit the new characteristics of the vessel traffic to assess future scenarios. The methodologies developed in this thesis for vessel traffic, as understood nowadays, can be adapted and extended assess the future scenarios.

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About the author

Xavier Bellsolà Olba was born in Montornès del Vallès, Spain in 1985. He studied Civil Engineering at the Universitat Politècnica de Catalunya (Barcelona), were he obtained his M.Sc. degree in Civil Engineering in 2011. He did his master thesis about control of bus bunching strategies. After two internships and working for other two engineering companies in Spain, he moved to Chile in September 2012, where he worked as project engineer developing and managing mini hydroelectric power plant projects.

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At the Transport & Planning department, he has assisted in teaching activities in the courses "Traffic Flow Theory & Simulation" and "Empirical Analysis for Transport & Planning", and he has supervised a master student.

Besides research related tasks, he was part of the board of *Young Delft* from the beginning of 2015 until early 2017. He organized and coordinated events for networking and soft skills development for young employees from TU Delft, as well as being treasurer.

List of Publications

Journal articles

1. Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2018). State-of-the-Art of Port Simulation Models for Risk and Capacity Assessment based on the Vessel Navigational Behaviour through the Nautical Infrastructure. *Journal of Traffic and Transportation Engineering (English Edition)*.

2. Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2017). Network capacity estimation of vessel traffic: an approach for port planning. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, 143(5), 1-9.

3. Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P.(2015). Estimating Port Network Traffic Capacity. *Scientific Journals of the Maritime University of Szczecin*, no. 42 (114) / 2015.

The following articles are currently under review:

4. Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. A Method to Estimate the Capacity of an Intersection of Waterways in Ports. *Transportmetrica A: Transport Science*, under review.

5. Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Risk Assessment Methodology for Vessel Traffic in Ports by defining the Nautical Port Risk Index. *Safety Science*, under review.

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1. Zhou, Y. and Bellsolà Olba, X. (2018). Autonomous Ships: Nautical Traffic in Ports. In *Port Technology International*, Edition 78: Linking the Supply Chain.

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Summary

Vessel traffic in ports is a key issue due to the high increase in vessel flows that lead to busier waterways. This dissertation presents novel methodologies to assess vessel traffic in ports based on capacity and risk independently and jointly. These methodologies have been applied to case studies using simulation models and AIS data. They provide a framework to support decision makers when assessing new infrastructure designs, expansions or changes in the vessel traffic management strategies.

About the Author

Xavier Bellsolà Olba conducted his PhD research at Delft University of Technology. He holds a MSc degree in Civil Engineering from the Universitat Politècnica de Catalunya (UPC).

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