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Delft University of Technology

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Cooperation between Vessel Service Providers for Port Call Performance Improvement

Dissertation

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Chair of the Board of Doctorates,
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Dedicated to my parents

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Shahrzad Nikghadam

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Table of contents

List of abbreviations

ABM	Agent-Based Modelling
DES	Discrete Event Simulation
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
FCFS	first-come-first serve
HCC	Harbour Coordination Center
HM	Harbour Master
ICT	Information and Communication Technologies
JIT	Just-in-time
MILP	Mixed Integer Linear Programming
MADES	Multi-Agent Discrete Event Simulation
NC	Nautical Chain
PA	Port Authority
PCO	Port Call Optimization
PCS	Port Community Systems

1 Introduction

1.1 Relevance and aim of the research

Ports are vital for maritime logistics. In 2022, 80% of the world's cargo was transported through ports (UNCTAD, 2022). The size and number of vessels calling ports are increasing drastically (Notteboom, Pallis and Rodrigue, 2022). At the same time, increasing waiting time of vessels in ports shows that ports are struggling to accommodate this growing demand. Recent port call statistics show that vessels may spend up to 40% of their port time waiting to be served (Slack, Claude and Wiegmans, 2018). To accommodate more vessels in shorter times, improving port performance is essential.

Conversely, ports' aim to improve their performance is challenged by their self-organizational nature. Ports comprise many actor organizations of different types and sizes. These organizations work together to serve the vessels by offering various services, including pilotage, towage, and mooring. Once a vessel arrives at a port, a variety of vessel services are needed for its safe manoeuvring through the port and must be readily available. These services are offered by individual organizations, called vessel service providers, the pilot organization, the tugboat company and the boatmen organization. Besides the vessel service providers, the Harbour Master (HM), and terminal operator are also involved in the port call process. The Harbour Master guides the vessels during their passage. The terminal provides a free berth for the vessels to perform cargo operations. These actors have their resources to deliver their services. When any of these services are unavailable, vessels have to wait. Hence, a port's performance highly depends on its service providers' performance.

Port service providers can improve their services by expanding the capacity for their critical resources, such as personnel and fleet (Notteboom, Pallis and Rodrigue, 2022). Capacity expansions are constrained, as they typically require high capital investments. The unreliability of vessel arrival and departure times, as well as the uncertainties in their servicing durations and requirements due to, e.g., weather, water and visibility conditions, disturb the initial planning. As a result, the initial planning of the service providers is subject to change, and they are expected to be ready to act shortly after their services are requested. The performance of ports in offering their vessels services can improve by developing cooperative relationships between the vessel service providers. Cooperative service providers can share information regarding their resources' availability, and adjust their initial plans. Such synchronization can create a seamless sequence of services, which is expected to shorten vessel waiting times.

Cooperative relationships between organizations can take different forms (Huo et al., 2018). In the port context, a short definition of cooperative relationships between the port actors was given by Talley et al. (2014) as when parties work together toward a common goal rather than merely maximizing their own objectives. In the literature, the cooperation of port actors is modelled by pooling the resources and centralized planning of them (Talley et al., 2014). In later chapters, I will explore and extend alternative cooperation strategies based on information sharing between the port actors.

There is a general consensus on the benefits of cooperation. These benefits include improvements in cost and time efficiency, reliability, flexibility, responsiveness, resilience and environmental sustainability for the ports and port users (Lee, Park and Lee, 2003; Paixão and Bernard Marlow, 2003; Fruth and Teuteberg, 2017; Lind, 2019; Kanamoto et al., 2021). With these numerous important benefits, the pursuit of developing cooperative relationships in ports is undoubtedly worthwhile, though the progress is still slow, worldwide.

In this thesis, I argue that a crucial missing piece for the advancement of cooperation in ports is the perspective of service providers. The existing literature, generally, points out the benefits of cooperation for the port as a whole (Talley, Ng and Marsillac, 2014). Implicitly, they are established on the assumption that the port service providers would cooperate if it benefits the whole port, regardless of the benefits for the cooperating parties. However, this assumption is highly debatable. Major ports today are landlord ports in which the Port Authority (PA) acts as a regulatory body and a landlord, while the port services are offered by self-governed organizations each of which has its own (public or private) interests (de Langen and van der Lugt, 2017). As these organizations run their own business and have their own resources, characteristics and culture, they are likely to avoid actions and decisions that are not in line with their business, even if collective benefits exist. Therefore, considering the service providers’ perspectives for designing mutually beneficial strategies is crucial. Ignorance of the service provider’s individuality and uniqueness can result in counter-productive strategy design for ports, which are most likely to be resisted by the service providers and fail, eventually. This gap in the port cooperation literature is significant and needs to be addressed.

In short, by addressing the service provider perspectives, I aim to support the development of vessel service providers' cooperation and thus improve port call performance. To achieve this aim, the following research questions are formulated:

1.2 Research questions

With the self-organizational properties of ports in mind, the main research question (RQ) I aim to answer is the following:

RQ: How can vessel service providers cooperate to improve their joint services during the port call, considering their individual organizational interests and characteristics?

The main research question breaks down into four sub-research questions:

RQ 1: Which type of information is needed to be shared with whom to improve port call performance?

The first step for addressing the main research question is to determine where cooperation of the vessels service providers, through information sharing, is most needed and, port call performance improvements can be obtained. I aim to obtain an inventory of information sharing links with the information content and actors involved, where the most critical information sharing links are highlighted. The main function of information sharing is to create a timely initial notice of delays, thus allowing port actors to limit the propagation of the delay or to reduce its impact. The insights are used in the next research steps to facilitate the exchange of the most critical information.

RQ 2: How willing are the port actors to engage in cooperative relationships?

Sharing sensitive information across organizations is considered costly and risky. Therefore, it is essential to explore the extent to which port actors are willing to share information with others. As this depends on their inter-organizational relationships, I aim to measure their general potential to cooperate. Next, potential for information sharing can be investigated. The results of this question together with the identified information sharing needs, in RQ1, will be the basis for the later research questions.

RQ 3: How does cooperation through joint resource deployment impact the performance of the port and its individual service providers?

This research question builds on the previous two. After identifying needs and potential for information sharing, I addresses the impact of a specific cooperation strategy: joint deployment of resources. By looking at both the performance of the port as a whole and at its individual service providers, I intend to find out whether service providers have an incentive for their participation.

RQ 4: How to jointly schedule service providers and vessels?

This RQ addresses a specific approach for cooperation between service providers. An advanced form of cooperation involves the proactive and joint scheduling of resources. Moving beyond an ad-hoc synchronizations of the services towards systematic cooperation, I consider optimizing the schedules of vessel arrivals and departures, jointly with service providers sailing to and from their assignments. The scant literature on the scheduling of vessels and service providers (Abou Kasm, Diabat and Bierlaire, 2021) has limited applicability for larger ports.

1.3 Research approach

This thesis employs both qualitative and quantitative approaches. I start by employing qualitative approaches to explore the concepts, learn from the experts’ knowledge and gain insights into port services. Later, I build on those insights using quantitative approaches for testing, measuring and comparing results. This combination enables addressing the main RQ by gaining insights on what can and needs to improve first, and to suggest viable models and tools later, which provide quantitative evidence.

For answering RQ1, I conduct expert interviews and surveys accompanied by data analysis and direct observations. The data includes 28000 port visits (in 2018-2019). The experts represent the various actors in the port. For field observations, service providers' operations are followed, also documenting the actual communications between the actors and asking experts to explain the information sharing guidelines that apply during the operations. The approach is based on (1) the mapping of information sharing links using a diagramming technique, (2) the identification of the root causes of delays through root cause analysis (3) the ordering of critical information sharing links associated with the root causes of delays during port calls. Finally, the results are validated by experts.

To address RQ2, I propose a conceptual framework to assess the actor's potential to engage in cooperative relationships in the context of the port call: the Lambert (2008) partnership model. This assessment enables determining their potential for information sharing, consequently. Expert surveys amongst the port actors are conducted. Surveys are complemented with semi-structured interviews for validation and further elaboration. I also carry out desk research to get insights into the current state of information sharing as practiced currently. Finally, the findings about actors' potential for information sharing are matched with the current information sharing practices, which provides new insights into opportunities for promoting the actors' relationships to support more advanced information sharing.

To answer RQ3, I employ simulation modelling. I develop a generalizable simulation model of the port in which information sharing between the service providers is explicitly modelled. The underlying uncertainty and dynamism of the port operations, and the ability of the simulation models to tackle the stochastic and dynamic environments, have encouraged the wide implementation of simulation models for ports. There exist a variety of simulation techniques, such as Discrete Event Simulation (DES), and Agent-Based Modelling (ABM), each with its principal characteristics and use (Brailsford et al., 2019). I chose a hybrid Multi-Agent Discrete Event Simulation (MADES) technique. This modelling technique enables defining the correct sequence of services for vessels, and the service provides based on port regulations, using the principals of DES, while modelling the vessel and service providers as agents of ABM enables introducing their interactions. The first application of the model is shown for the Port of Rotterdam.

For RQ 4, I employ mathematical modeling to formulate the joint scheduling of vessels and service providers. Scheduling of vessels has similarities to the Hybrid Flowshop scheduling where each vessel has to go through a set of services followed sequentially, while scheduling of service providers is similar to the Vehicle Routing Problem considering that each service provider starts at its station, serves vessels one after the other, and returns to its station. In order to gain insights about alternative scheduling strategies, I test three alternative objective functions based on a minimal level of service, the best overall port capacity utilization, and the currently prevailing first-come-first-serve (FCFS) approach. I implement the model using the data from the Port of Rotterdam.

1.4 Contributions

This thesis contributes to scientific literature and practice in several ways. Its main contribution is that it provides generic models and insights for improving port call performance through cooperation between service providers, considering the perspectives of both the visiting vessels as well as the service providers. More specific contributions are as follows.

First, this thesis proposes a systematic approach that determines the critical information sharing links for port call performance improvements. Through a case study for the Port of Rotterdam, it demonstrates the value of the approach for practice. The results provide insights into the root causes of port delays and their relevance in terms of information sharing between the actor organizations.

Second, given that little is known about the port actors’ willingness to engage in cooperative relationships and exchange information, this thesis offers a model that assesses the actors’ potential for a relationship in general and, specifically, for information sharing. This model supports port managers and policy-makers with the design of effective development strategies for ports.

Third, it contributes to the literature by exploring a viable cooperation strategy and quantitatively assessing its impact on the port as a whole and its individual service providers. To this end, it proposes a generalizable simulation model in which information sharing between the service providers is explicitly modelled to represent the cooperation between the service providers. A first application of the model is shown for the Port of Rotterdam. The results provide new empirical evidence about the mutuality and magnitude of the impacts of cooperation.

Fourth, this thesis offers a mathematical tool to design joint port call schedules for vessels and service providers. This tool determines the time based on which ports can guarantee their resource availabilities. An extended optimization model is proposed and alternative objectives are tested for the illustrative case of the Port of Rotterdam. The application offers insights to port managers and practitioners regarding alternative strategies for optimal scheduling.

Together, these findings provide inputs for addressing the key port call management challenges regarding the facilitation of information sharing, currently on the agenda of port policy makers. Adoption of these recommendations is expected to bring significant port performance improvements.

1.5 Organization of the thesis

Figure 1.1 illustrates the organization of the thesis. Chapter 2 addresses RQ1. I start my exploration by understanding the information needs of the port and vessel service providers. With RQ1, I aim to identify where the exchange of information is most necessary to build upon them for performance improvement strategies in the following research questions. As discussed earlier, besides the needs, it is crucial to identify the actors’ willingness to cooperate with one another and share information. Chapter 3, addresses RQ2, for exploring the organizational potentials for cooperation and information sharing. Next, I employ the findings of RQ1 and RQ2 to focus on the cooperation of actors where there is a *need* and *potential.* Subsequently, RQ3 and RQ4 explore performance improvement strategies. Chapter 4 and 5 respectively, suggests joint resource deployment and joint scheduling models and assess the benefits of these strategies for the ports and individual service providers.

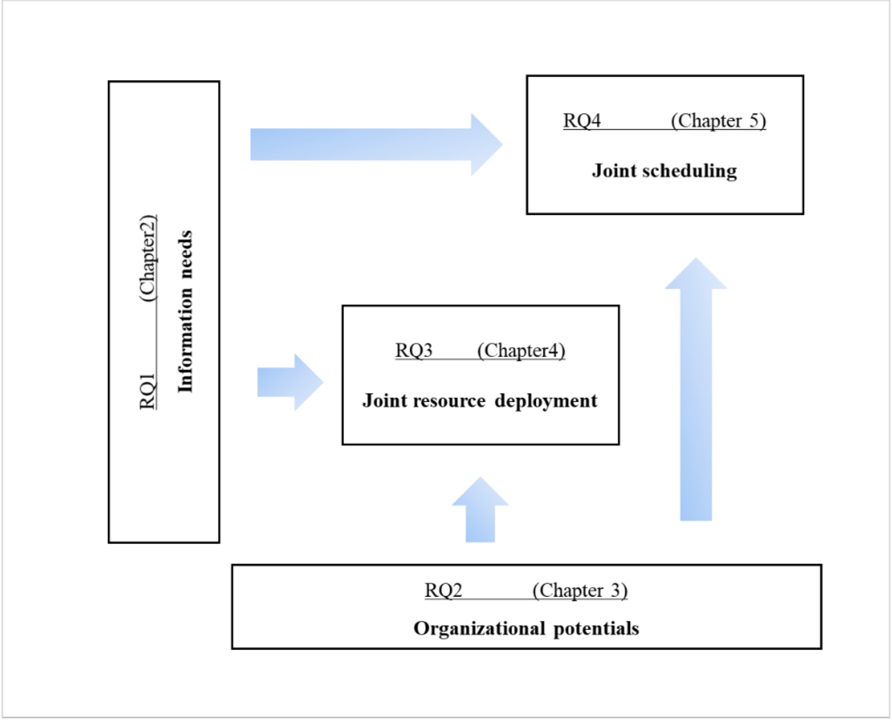

Figure 1.1. Organization of the thesis

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2 Critical information sharing links to improve port call performance

This chapter presents a systematic approach that identifies where port call performance can improve through information sharing between the port actors. The approach is based on a mapping of information sharing links and their association with the root causes of frequently occurring delays. We identify the kind of information which is critical in mitigating delays. Critical information links are then re-ordered to create information sharing groups between the actors, which further condenses the required information sharing actions. We apply the proposed approach to the Port of Rotterdam. Quantitative data of 28000 port calls is complemented by qualitative data collected through direct observations and expert interviews with port actors.

Section 2.1. presents the background on information sharing in ports. Section 2.2 provides a review of the extant scientific literature. Section 2.3 defines the main characteristics of the vessel services offered at the port. Section 2.4 introduces the approach. In section 2.5, we apply the approach to the case of the Port of Rotterdam. Section 2.6 discusses the findings and implications for practice. Finally, section 2.7 concludes the study and puts forward future research directions.

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2.1 Introduction

International trade is growing and, with maritime transportation representing approximately 90% of the global trade volume, ports are becoming busier (Lind *et al.*, 2020). In response, ports try to become smarter and more efficient, aiming to serve more vessels in shorter times by reducing port delays (Paixão & Bernard Marlow, 2003). In the past years, ports have reinvented themselves from cargo transhipment nodes to an integral part of supply chains, as important hubs for materials and information flows. Latest developments in the digital technologies of Industry 4.0, such as blockchain, Internet of Things (IoT) and Physical Internet have pushed ports beyond their traditional limits and have provided new opportunities for their development (Fahim et al., 2021; Parola et al., 2020). Although ports have transformed radically, some aspects of port operations still need improvement. For example, one of the key issues in many ports is delays. Disruptions and deviations from the initial plan occur frequently resulting in delays (Cheon, Song and Park, 2018; Park, Sim and Bae, 2021). While exact figures are not available, shipping companies report that up to 80% of their vessels face delays in ports along their route (Notteboom, 2006). These delays disrupt port call processes, increase congestion, decrease service reliability and lead to inefficiency for both vessels and ports. Where delays can be mitigated, this enhances port efficiency, sustainability and safety.

The complexity of port operations severely challenges the mitigation of port delays. Vessel arrival times to the ports are typically uncertain. Even though vessels must submit their estimated time of arrival (ETA) and Estimated Time of Departure (ETD) in advance, these estimates are usually inaccurate. The submitted ETAs are often too optimistic and they are adjusted multiple times (Veenstra and Harmelink, 2021). Once a vessel arrives at a port, *nautical-technical* services, i.e., pilotage, towage and mooring, must be readily available. Only when the availability of berth, tugboats, pilot and port fairways are confirmed, vessels are allowed to enter the port. When any of these services is unavailable, vessels have to drift, loiter or anchor outside the port, which exacerbates delays. Inaccuracies in vessel arrival times, as well as uncertainties in handling processes due to e.g., weather, challenge port planning and usually oblige port actors to coordinate their services on short notice. Although port actors may share information to align operations under normal circumstances, information sharing during delays is less well-developed.

In recent decades, the maritime sector has provided a growing number of digital solutions to support information sharing processes (Urciuoli and Hintsa, 2021). The main exponent of this movement is Port Community Systems: electronic platforms that connect multiple actors inside the port domain, allowing them to share digitized data and information. PCS are widely used in major ports like Rotterdam, Antwerp and Singapore. They generate value by facilitating data and information sharing between different stakeholders, including terminals, the port authority, shipping companies, vessel agents and freight forwarders (Aydogdu and Aksoy, 2015). So far, however, PCS do not provide solutions for operational coordination of port operations, between port service providers, like pilot organizations and tugboat companies. Although bilateral information sharing is common between port service providers, investigation of their information needs is still at the stage of experimentation. In port management practice, information sharing solutions still need to develop.

Previous work has extensively addressed the importance of information sharing as a key enabler of port efficiency, resilience, agility and sustainability (Paixão and Bernard Marlow, 2003; Bichou and Gray, 2004). The emphasis has been on improvements in information flows by means of digitalization.

Nevertheless, the significant question of which information has to be shared with whom has not yet been addressed in the literature. This gap is remarkable because the first step to improve information sharing in ports is not just improving the information flow, but also understanding the information needs of the port and its actors. This paper aims to address this gap by examining information sharing in ports, to support the sharing of relevant information among the relevant parties for mitigating service delays.

To identify where coordination is most necessary, and where efficiency gains can be achieved, we focus on the most frequently occurring delay causes. Here, the main function of information sharing is to create a timely initial notice of such delays, thus allowing actors to limit the propagation of the delay or to reduce its impact. We contribute to the literature by presenting an approach that determines the critical information sharing links for mitigating delays. By providing a case study for the Port of Rotterdam, we demonstrate the value of our approach in practice. The proposed approach relies on (1) the mapping of port processes and information sharing links, (2) identification of the root causes of frequently occurring delays and (3) the mapping and ordering of critical information sharing links associated with the frequently occurring delays and their causes.

This chapter is organized as follows. Section 2.2 provides a review of the scientific literature about information sharing in ports. Section 2.3 defines the main characteristics of the vessel services offered at port. Section 2.4 introduces the approach. In section 2.5, we apply the approach to the case of Port of Rotterdam. Section 2.6 discusses the findings and implications for practice. Finally, section 2.7 concludes the study and puts forward future research directions.

2.2 Literature review

The impact of information sharing on the performance of businesses has been an important subject in many different domains, including maritime logistics. Information sharing is recognized as a key challenge in the movement towards smart, agile and green ports (Paixão and Marlow, 2003; Lind et al., 2020; Park, Chang and Lam, 2020). The benefits and necessity of information sharing have been well-recognized by the maritime industry (Zheng et al., 2020). The benefits include improvements in cost and time efficiency, reliability, flexibility, responsiveness, resilience and sustainability (Kanamoto et al. 2021; Lind 2019; Fruth and Teuteberg 2017). The literature suggests that improved collaboration between maritime logistic actors through better information sharing will reduce the uncertainties along the logistic chain, both in hinterland and foreland, enhance reliability, efficiency, flexibility (Heaver, 2015), improve resilience (Shaw, Grainger and Achuthan, 2017) and boost performance (Bichou and Gray, 2004). Most studies report time and cost improvements as results of improved information sharing, vertically between ports and port users, as well as horizontally with adjacent ports (Lau and Li, 2015; Takebayashi and Hanaoka, 2021). In addition to efficiency improvements, sustainability is another reason to enhance the information sharing of ports. Notteboom et al. (2020) emphasized the role of ports in green supply chains, indicating that information sharing is key for green shipping, green port operations and green inland logistics. Empirical evidence from short sea shipping shows that further information sharing between the relevant parties will improve operational speed optimization in slow-streaming and hence lead to fuel savings (Schøyen and Bråthen, 2015). Besides the studies on the benefits of improved information sharing, there is another stream of literature that addresses the problems that occur as a result of insufficient information sharing. For example, a lack of information sharing regarding waiting times and turnaround times are found to frustrate hinterland transport (Wiegmans, Menger, Behdani & van Arem, 2017). Or, a variety of coordination problems can occur in the entire transport chain if the required information is not shared between the shipping lines, terminals and hinterland transport companies (Van Der Horst and De Langen, 2008).

The degree and quality of information sharing between port actors is challenged by several contextual factors, including the complexity of port-related operations, organizational silos, privacy and confidentiality issues, lack of incentives, security issues, conflicts of interest, information overload and information quality (Van Der Horst and De Langen, 2008; Lanzini, Ubacht and De Greeff, 2021). The presence of various organizations makes it difficult to determine which organizations are relevant for information sharing. Also, there can be a mismatch between a user's real information requirements and the perception of these requirements by the information owner (Shaw, Grainger and Achuthan, 2017). Information needs of different stakeholders in maritime hinterland processes were identified in a study by Wiegmans et al. (2017). However, the study did not include the nautical side of the transport chain. Another challenge to information sharing is that actors may not have an incentive to share information of sufficient quality. A wide variety of relationships exists with asymmetric information availability, power, and interest, limiting information sharing for reasons like confidentiality, privacy and conflicts of interest (Bichou and Gray, 2004). For example, terminals possess information that can benefit Port Authority’s business, but sharing it can be disadvantageous for the terminal’s own business (Zerbino et al., 2019). In sum, although port logistics is very data-intensive, it is challenging to access value-adding quality information considering the parties’ diverse needs and interests.

To overcome the challenges of information sharing and facilitate the collection of up-to-date data, Information and Communication Technology (ICT) developments try to enhance safety, security and traceability (Lee, Tongzon and Kim, 2016; Parola et al., 2020). Carlan et al. (2016) analyzed recent digitalization projects and initiatives aimed at improving the information flow in maritime logistics, including information systems in seaports like Port Community Systems (PCS) (Carlan, Sys and Vanelslander, 2016). The implementation of PCS was found to improve information sharing, increase time reliability for port users (Zerbino et al., 2019) and play a significant role in port competitiveness (Tsamboulas, Moraiti and Lekka, 2012). However, the benefits of PCS have been on information sharing between port users rather than information sharing between port actors. Whether and how PCS will play a role in operational information exchange between port actors is still unclear.

From the above, we conclude that the scientific debate is no longer about whether information should be shared but about which information to share with whom. Many studies have looked at information sharing between ports and port users, but, to date, there has been very little research that focuses on information sharing within the port domain itself. In addition, information sharing between essential services such as towage, pilotage and mooring operations has yet to be addressed in the literature. This gap is remarkable, as earlier research does recognize the importance of information sharing as far as port operations are concerned (Notteboom et al. 2020). Filling this gap calls for approaches that investigate information sharing arrangements in relation to the reliability of port services, which is the main purpose of this study.

2.3 The nautical chain and its process

In port studies, defining the scope of the study is very important because many logistics processes are at the interface between the sea and hinterland. This process continuity makes it difficult to identify where the port processes start and end (Bichou and Gray, 2004). In this section, we present the scope of our study, including the actors and processes involved and the definition of the nautical chain. Ports support the turnaround processes of vessels with traffic management, piloting, towage and mooring as main services. We call this chain of services the Nautical Chain (NC). We refer to the executing organizations involved as the actors of the NC. These are the Harbour Master (HM), vessel agents, terminals, the pilot organization, tugboat companies and the boatmen organization. The HM is the responsible authority for smooth and safe shipping, and it provides services from the Harbour Coordination Center (HCC) and the Vessel Traffic Services (VTS). The HCC controls the tactical planning of accessing and exiting vessels of the port area, while the VTS assists the safe handling of vessels at an operational level. The vessel agent, the shipping company's representative at the port, arranges all administrative tasks related to the port visit for the vessel, such as ordering nautical services. The terminal provides berth for the vessel and operates the (un)loading process. Among the actors of the NC, the pilot organization, the tugboat company and the boatmen organization together are called the nautical service providers. We note that, as opposed to the concept of *port service chain* (Talley, Ng and Marsillac, 2014), the services beyond the turnaround processes of vessels such as hinterland rail and truck services are not included in the NC.

The process of a vessel's call at a port can be summarized as follows. For an incoming vessel, well before arrival, the vessel's agent requests a berth from the terminal for the unloading and loading procedures. After the terminal's confirmation, the vessel's agent reports this to the HCC, which assesses nautical safety, port health, security and capacity. The agent is obliged to report the vessel at least 24 hours before ETA. If the HCC approves the vessel's report, administrative clearance is provided. Without clearance from the HM, the vessel is not allowed to enter the port. Before the vessel arrives, it frequently submits and updates its ETA, which is consecutively forwarded to nautical service providers. When the vessel arrives at the port, the vessel captain makes operational contact with the VTS operator, who checks the details of the vessel report and registers any updates when necessary. If port traffic allows, with the guidance of VTS, the vessel starts communicating with the pilot organization, to take a pilot on board for pilotage. After the pilot has boarded the vessel, the vessel enters the harbour. Under the pilot's command, when tugboat assistance is needed, the pilot orders tugboats to connect and tow/push the vessel to the designated berth. Once arrived, boatmen help moor the vessel. Here, the NC service for incoming vessels is completed and the terminal can begin cargo handling operations. Note that, typically, large vessels require pilotage, towage, and mooring services. However, exemptions can be made for certain vessels under strict conditions, for example, Ro-Ro vessels frequently visiting a dedicated berth, for instance once every two days, can obtain a pilot exception certificate. Some terminals with frequent vessel visits are allowed to perform their own mooring services. Figure 2.1 presents the overview of the NC services for incoming vessels.

Figure 2.1. NC services for an incoming voyage

For outgoing vessels, the vessel agent orders a voyage. The agent thus reports the vessel's ETD to the HCC. The HCC assesses the administrative clearance. Next, the nautical service providers plan their services. As soon as a vessel is ready for departure, i.e., when all nautical service providers are present and terminal operations have finished, the pilot makes operational contact with the VTS operator to start pilotage. When the vessel is ready to leave, the boatmen unmoor and the tugboats tow to help the vessel leave the berth. After the vessel has safely sailed out of the harbour the tugboats disconnect and later, the pilot leaves the vessel completing the pilotage. Finally, the vessel notifies the HM that it has successfully departed.

The descriptions above explain the NC services when all operations proceed as planned and no disruptions happen. Whenever delays occur, the NC actors ideally perform additional coordinating actions supported by sharing of process information. The quality of the coordination depends on the quality of the information sharing. In the next sections, we introduce our approach to identify those information sharing links that are critical for improved coordination of the NC.

2.4 Approach

The leading principle behind our approach is that port actors need to flag potentially occurring delays as early as possible. They can only do so if they are informed in a timely manner about the occurrence of delays. Once a potential delay is signalled inside the system, actors need to inform each other to take mitigating or hedging actions. Our aim is to identify the information sharing links that are critical for mitigating port delays. This consists of 3 main steps:

1. Creation of an inventory of information sharing links.
2. Identification of root causes of frequently occurring delays.
3. Identification of critical information sharing links.

Figure 2.2 depicts the approach and the main techniques used.

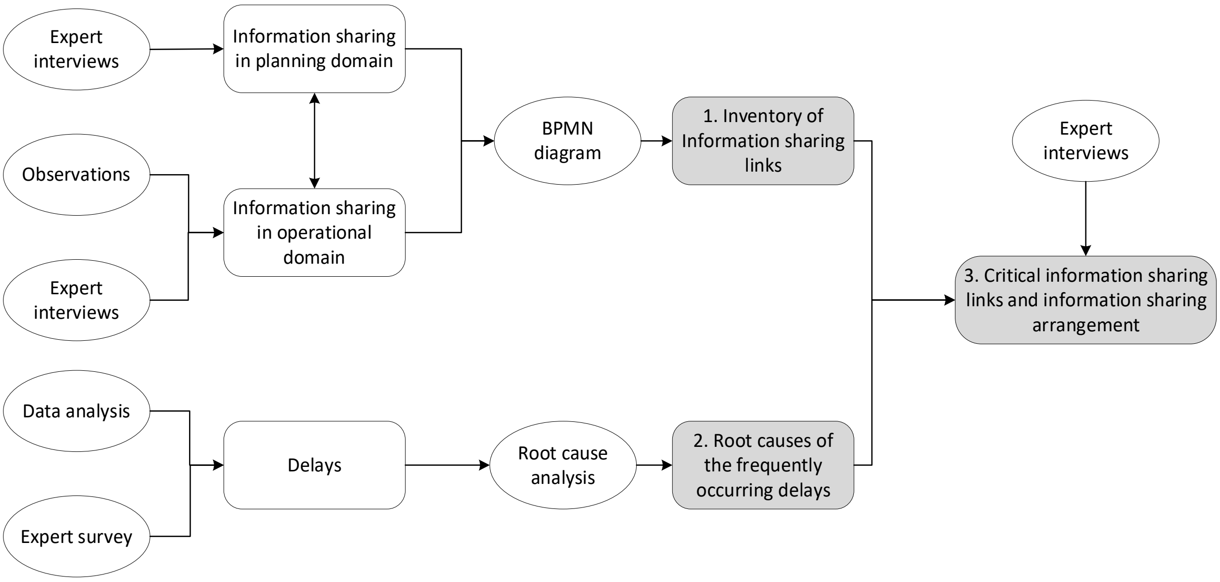

Figure 2.2. The proposed approach

Step1. Creation of an inventory of information sharing links between actors. The first step involves identifying and mapping information sharing links between the NC actors, which is done following diagramming standards, such as Business Process Modelling Notation (BPMN). The main source for this step is the port's guidelines for navigation, service provision and messaging, internally as well as with the client vessels. The formal modelling requires a synthesis of these guidelines and validation with experts from different service providers. This step is particularly important because not all the information sharing links, especially bilateral communications, are officially documented in information procedures and are often difficult to track.

Step 2. Identification of root causes of frequently occurring delays. This step investigates the frequently occurring delays and identifies parts of the process where delay mitigation is needed the most. This includes quantitative analysis, based on port call data, as well as qualitative analysis, through root cause analysis, which helps identify the events that may have occurred before the delay and may have caused the registered delay. For example, a case that is registered as a towage delay regards an earlier delay in terminal operations which keeps the assigned tugboats busy for longer periods. This, in turn, propagates on the tugboats' later assignments. This step leads to the identification of those delays that require action. Also, it identifies the first activities at which potential future delays can be signalled, which is an important input for delay mitigation.

Step 3. Identification of critical information sharing links. In this step, we combine the findings of the above two steps and associate the information sharing links related to each delay. For each delay, we investigate (1) what kind of signalling information is needed for the initial notice of a delay, (2) who can produce this information and (3) which actors should be updated. In a case of a towage delay, for instance, we investigate "who notices the delay first?", "what kind of information is needed from which actors to notice the occurrence of the delay?" and once the delay is certain "who needs to be updated?". By re-constructing the chain of events from the root cause until the delay, various opportunities for communication and management action can be considered. As far as information links occur between the same parties and/or concern the same subject, links can be grouped. These groups form the arrangement for sharing of critical information. As the design of these measures is situation (i.e. port) dependent and often relies on latent knowledge about the planning of execution of processes, it is advisable to work with local experts from the HM for instance.

Below we describe the approach in more detail, demonstrating it at the same time for the Port of Rotterdam.

2.5 Case study

In this section, we discuss the application of the approach to the Port of Rotterdam. The Port of Rotterdam is the largest port in Europe, hosting almost 30,000 sea-going vessels each year. A recent study reported the Port of Rotterdam as the most efficient port among ports of 17 different countries (de Oliveira, You and Coelho, 2021). The port of Rotterdam (PoR) is a landlord port. In a landlord port, the Port Authority owns the port areas and infrastructure and leases them to companies responsible for their own business. The HM is a division in the Port of Rotterdam authority in charge of rules and regulations for the use of the waterways in and around the port area. In the Port of Rotterdam, multiple public and private actors operate the NC's services.

2.5.1 Inventory of information sharing links

We distinguish information sharing in the planning domain from that in the operational domain. For the planning domain, we conducted semi-structured interviews with the planning departments of the NC actors in the period of October-December 2019. We interviewed seven experts and managers each from the planning departments of pilots, the tugboat company, the boatmen, a terminal, the HCC, a liner vessel agent, and the Port Authority itself. We asked the experts to explain the communications involved in delivering their services to incoming and outgoing vessels. For the operational domain, five semi-structured expert interviews and field observations were conducted in the same period. The interviewees were a pilot, tugboat captain, a boatman, a VTS operator and a policymaker at the Rotterdam Port Authority. For field observations, the authors took part (for a day) in the services of a pilot, a boatman and a tugboat captain, documenting the actual communications between the actors and asking experts to explain the information sharing guidelines that apply during the operations. After we derived the information sharing links, we validated the results with experts. An overview of the information sharing links between the actors of the NC is shown in Figure 2.3. A detailed explanation of these information sharing links is provided below.

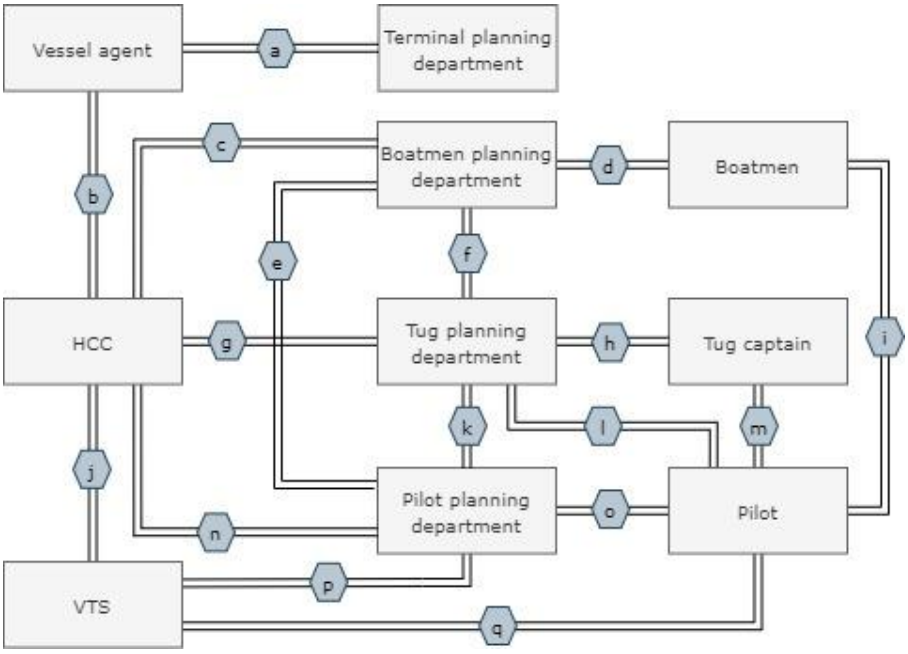

Figure 2.3. Information links between actors of the nautical chain (BPMN conversation diagram)

According to the process description above, we distinguish different purposes of information sharing in chronological order as follows.

Vessel agent's updates regarding terminal planning [a, b]: The agent is responsible for sharing the vessel and voyage information with the HCC and the terminal planner. Agents provide static details to the HCC, like the vessel's draft and the required number of tugboats. In addition, depending on terminal and voyage plan, vessel agents send multiple updates regarding changes in the ETA and ETD; still, reported estimated times are not always accurate (Parolas, Tavasszy and Kourounioti, 2017). The information exchanged between terminal planning and HCC is shared via the vessel agent.

Port traffic planning prior to vessel arrival and departure [j, p]: Before vessel arrival and departure, the HCC exchanges information with the VTS for port traffic planning. The VTS is also linked to pilot planning, to communicate vessel arrival and departure to pilot planners. To assure safety of the port, extra attention is paid on planning the visit of the deep-draft, tidal-bound, and dangerous cargo carrying vessels.

Planning of nautical service providers [c, g, n, e, f, k]: The boatmen planning, the pilot planning, the tugboat planning and the HCC are all linked to each other, to share information regarding the proposed ETA and ETD of planned vessels. They individually plan the deployment of their resources and, upon request, modify their plans together. Multiple communications via phone, E-mail, or very high frequency (VHF) radio may be needed when a nautical service provider is not available at the requested time.

Deployment of nautical service providers by their planning departments [o, h, d]: The pilot planning, tugboat planning and boatmen planning share the details of the next scheduled assignment with the boatmen crew, the tugboat captain and the pilot. Vice versa, updates of ongoing operations are shared from the boatmen crew, the tugboat captain and the pilot with their planning departments.

Vessel’s manoeuvring [i, m, q]: When nautical service providers are all present at an assignment to provide their services, the pilot gives orders and exchanges information via VHF radio with the boatmen crew and the tugboat captain. In addition, the pilot and VTS operator continuously communicate regarding the vessel’s intentions and port traffic. Sometimes phone calls are also needed to make quick arrangements.

2.5.2 Root causes of more frequently occurring delays

Delays can have many causes, which many times are interrelated. A systematic understanding of the main causes of delays and their relations is needed, to make sure that we address as many delays as possible and the need for information sharing is thus minimized. The technique of root cause analysis helps to achieve that purpose. To identify root causes of main delays in the PoR we analysed port call data and conducted further interviews. We used a database of registered vessel delays by the HM, which also identifies which service was delayed and for how long. We obtained data regarding delays between October 2019 and 2020, involving in total approximately 28,300 sea-going voyages. We analysed the data to identify direct causes of delays and the probability of occurrence of each individual cause, based on equation (1).

$$\text{Probability of occurance of delays due to cause } i = \frac{\text{Number of registered delays due to cause } i}{\text{Total number of delays}} \tag{1}$$

Figure 2.4 (a) and (b) show the direct causes of delays for incoming and outgoing voyages, respectively. In both cases, delayed towage accounts for most of the delays. The second main cause of delay for incoming voyages is congestion and, for outgoing voyages, it is delayed terminal operations, followed by congestion and delayed pilotage. Mooring operations are almost always on time for both incoming and outgoing voyages.

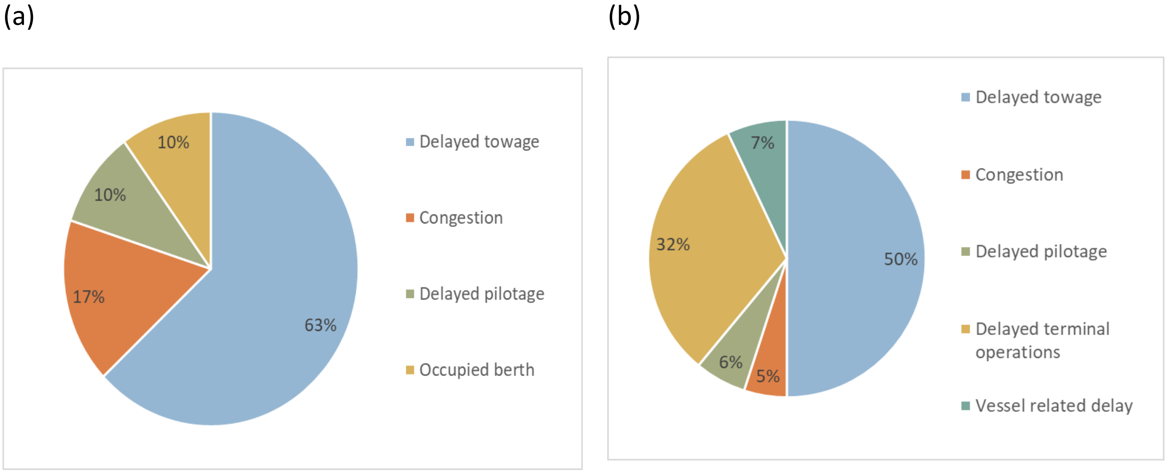

Figure 2.4. Direct causes of delays for (a) incoming and (b) outgoing voyages

The above-mentioned delays include only direct causes of delays and not the root causes of these delays. For example, a delay is registered as delayed pilotage when a vessel has to wait for the pilot, either because the pilot is not available at the requested time and rescheduling is needed, or because the pilot arrives with a delay to the scheduled assignment. The latter case may occur when the previous assignment of the pilot was delayed, or when a pilot is required with different qualifications than originally requested. This example shows that the root causes behind the direct causes of delays vary. Hence, it is important to identify them first to tackle them individually. Identifying such indirect causes is done by root cause analysis. We conducted two semi-structured in-depth interviews, with a policymaker at the HM department of the Port of Rotterdam and the VTS manager, in February 2020, asking them about potential root causes of delays. We asked what kind of delays can happen prior to the direct causes of delays shown in Figure 2.4 (a) and (b) In total, we identified no less than 45 root causes and illustrated in the cause-and-effect diagram of Figure 2.5. As there is no separate data regarding the frequency with which such root causes occur, we conducted expert surveys to identify the most frequently occurring causes of delays. We translated the cause-and-effect-diagram into a survey template and asked ten port actor experts to highlight the frequently occurring ones. The experts included a manager of the pilot organization, a tugboat company, the boatmen organization, the HCC, the ECT terminal, a pilot, a duty officer of the HM control centre, and a policymaker of the Rotterdam Port Authority. Importantly, the results of surveys showed a strong consensus about frequently occurring causes of delays. The most frequently occurring causes are highlighted in red in Figure 2.5 and listed below. In 16 of the 45 causes, there was complete unanimity about whether a root cause of a delay occurs frequently. For instance, all ten respondents agreed that capacity shortages of tugboats and pilots, and passages of large vessels are frequent causes of delays, while all ten respondents remarked that delays due to fog restrict vessels, technical problems do not happen frequently. We used a rather strict cut-off point of 90% consensus level, to determine frequently occurring causes of delays, i.e., when at least nine of the ten experts agreed. Accordingly, the following list resulted of frequently occurring root causes:

- (RC1) Delayed pilotage due to a pilot capacity shortage
- (RC2) Delayed towage due to tug capacity shortage
- (RC3) Delayed tug arrival to an assignment due to a delay of the previous vessel
- (RC4) Berth unavailability due to occupancy by an inland barge
- (RC5) Berth unavailability due to occupancy by a sea-going vessel
- (RC6) Terminal’s delay due to unfinished loading activities
- (RC7) Vessel’s delayed departure due to unfinished bunker activities
- (RC8) Fairway congestion due to peak demand
- (RC9) Fairway congestion due to passage of a large vessel.

Based on the identified frequently occurring root causes of delays, the next step is to identify the related information sharing actions. These are described in the next section.

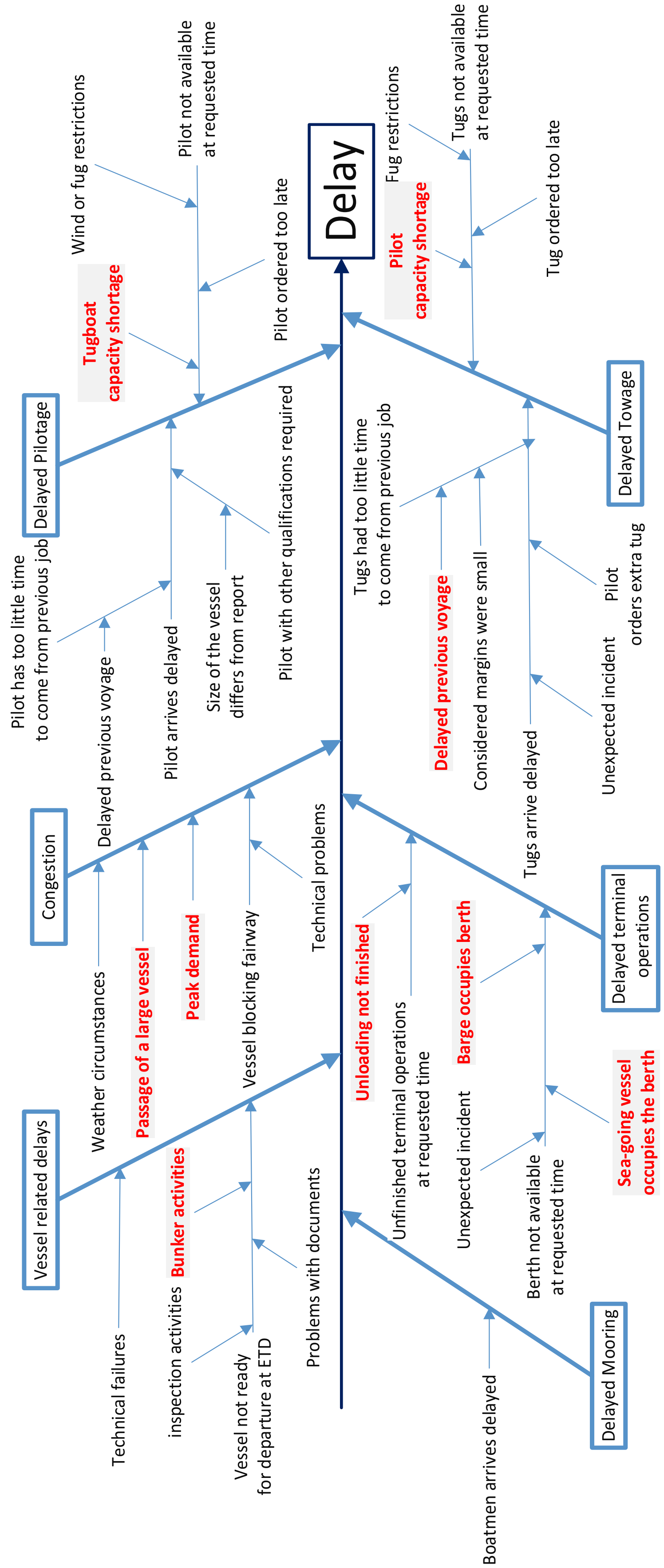

Figure 2.5. Cause-and-effect diagram of delays in the Port of Rotterdam

2.5.3 Critical information sharing links

We combine the findings of previous steps and complement them with an expert interview with a policymaker at the HM, to provide additional validation of critical information sharing links around frequently occurring root causes of delays. For each of the nine frequently occurring root causes, we asked three questions as follows: “Who notices a delay first?”; ”For the initial notice of a delay, what kind of information is needed and from which actors?”; “Which parties should be updated regarding the delay?”. For the frequently occurring root causes of delays, the following information sharing links were identified as critical.

(RC1) Delayed pilotage due to pilot capacity shortage: The initial notice of a shortage in pilot capacity depends on the information available to the pilot planner with regard to the demand for pilots and the available pilot capacity. Demand for pilot is submitted by the vessel agent to HCC [b]. Updated ETA of the vessel and demand for pilot is submitted from VTS to the pilot [q]. Pilot capacity is updated by pilots when they start and complete their assignments and update the pilot planner [o]. When the pilot planner notices that pilot capacity would be insufficient to respond to pilot demand, a request for a delayed ETA and ETD is sent to the HCC, the tugboat and the boatmen planning departments to inform them that the pilot’s arrival will be delayed [n, k, e].

(RC2) Delayed towage due to tugboat capacity shortage: The initial notice of a shortage in tugboat capacity depends on the information available to the tug planner with regard to demand for tugboats and the available tugboat capacity. Anticipated demand includes (a) the estimated number of tugboats, and (b) the estimated time of vessels at pilot station. The number of tugboats is indicated by the vessel agent or the pilot planner, and submitted to the tugboat planner [b, g, k]. The VTS operator registers the pilot station time and the tugboat planner estimates the time that the tugboats need to meet the vessel. The *final* number of tugboats is decided when the pilot is on board the vessel, and is discussed and agreed with the vessel captain. The pilot shares the required number of tugboats with the tugboat planner [l], after which the latter deploys the tugboats, informing the tugboat captain [h]. In cases where the tugboat planner notices that the available tugboat capacity is insufficient to respond to tugboat demand, and will cause a delay, an update is submitted to HCC, pilot planning and boatmen planning departments [g, k, f].

(RC3) Delayed towage due to delays in the previously served vessel: The initial notice of a delayed towage due to delays in the previous assignment depends on information available to the tugboat planner, submitted by the tugboat captain, who receives information on delays in the current assignment from the pilot [m]. The tugboat captain updates the tugboat planner on delays that occur during their assignment [h]. When the tugboat planner is certain that not enough tugboats are available to meet demand at the requested time, he sends a request for an updated time to the pilot planners [k]. Sometimes, the tugboat planner informs the pilot directly of the delayed tugboat arrival [l]. Sometimes, when the tugboat does not arrive on time at the scheduled assignment, the pilot calls the tugboat planning [l]. In case the tugboat is already in the proximity of the vessel, the tugboat captain directly contacts the pilot on board the vessel to inform the pilot about its delayed arrival [m].

(RC4) Berth unavailability due to occupancy by inland barge: The initial notice of berth occupancy by an inland waterways barge depends on the information available to the pilot, submitted by the VTS operator or the boatmen who are present at the quay waiting for the vessel’s arrival [q or i]. The pilot informs the tugboat captain [m]. When the delay is certain, the pilot, the tugboat captain and the boatmen inform their planning departments accordingly [o, h, d].

(RC5) Berth unavailability due to occupancy by sea-going vessel: Either the pilot onboard or the VTS operator notice that there is a delay due to the berth being occupied by a vessel.

Whoever notices this first, notifies the other [q]. The VTS informs the pilot of the incoming vessel regarding the delay so it can slow down if necessary [q]. The pilot on-board the delayed vessel calls his pilot colleague on-board the incoming vessel to discuss the details of the delay and possibilities of passing each other by manoeuvring in the port. One of the pilots must update the VTS operator of the decisions that are being made [q]. Next, the pilot updates the tugboat captain [m]. When the delay is certain, the pilot, the tugboat captain, and the boatmen crew inform their planning departments accordingly [o, h, d].

(RC6) Delayed terminal operations due to unfinished (un)loading activities: The initial notice of unfinished (un)loading activities depends on the information available to the pilot from the boatmen at the quay who receive information from terminal employees [i]. When the pilot notices the delay of the departing vessel, he informs the VTS and the tugboat captain [q, m]. If the occurrence of the delays is certain, the pilot, tug captain and boatmen inform their planning departments [o, h, d].

(RC7) Delayed departure due to unfinished bunkering activities: The initial notice of unfinished bunkering activities depends on information available to the pilot when he boards the vessel. When the pilot notices the delay, he informs the VTS, tugboat captain and boatmen [q, m, i]. When the delay is certain, the pilot, tug captain and boatmen inform their planning departments [o, h, d].

(RC8) Congestion at the fairway due to peak demand: The VTS operator is the first to notice a delay because of fairway congestion. Depending on the traffic, the VTS operator can decide to delay an incoming or outgoing vessel. The VTS operator updates the pilot [q]. Pilots of different vessels contact each other to discuss the traffic situations and any possibilities to pass each other. To inform VTS with regard to the decision being made, one of the pilots updates the VTS [q], the tugboat captain and the boatmen [m, i]. The pilot, tugboat captain and boatmen inform their planning departments [o, h, d].

(RC9) Congestion at the fairway due to passage of large vessels: The initial notice of delay depends on the information available to VTS regarding the current traffic in the port, and the planned arrivals and departures of the larger vessels (and possibly their delays). This information is shared with VTS by pilots [q]. The tug captain and boatmen also notify the pilot when they notice congestion in a port sector [m, i]. Pilots of vessels contact each other to discuss the traffic situation and the possibility of passing each other through manoeuvring. When it is certain there will be a delay, the pilot, tugboat captain and boatmen inform their planning departments [o, h, d].

The critical information sharing links (shown in brackets) allow delay mitigation for the frequently occurring root causes that meet with broad agreement from all the NC actors. We re-order the critical information sharing links in a number of distinct information sharing groups based on specific actors and information content (see Appendix 2.A). Together, these groups form the ‘arrangement’ for sharing critical information for delay mitigation. The arrangement further condenses and simplifies the required information sharing actions. The re-ordering of the critical information sharing links (see Appendix 2.A for the associations with each link) leads to the following groups:

i. **Sharing vessel information**: Information sharing between the vessel agent and the planning departments (pilot planning, tugboat planning and HCC and terminal planning) regarding the voyage order details and specifications such as ETA, ETD, estimated number of tugboats and designated berth.

ii. **Sharing joint planning information**: Information sharing between the pilot planning, tugboat planning, boatman planning departments and HCC regarding the updated ETA, ETD and their requests for delayed ETA and ETD.

iii. **Sharing deployment information:** Information sharing between the pilot, tugboat captain, and boatmen crew with their planning departments regarding the deployment information such as meeting point with the vessel, or estimated start and completion time of services.

iv. **Sharing assignment information**: Information sharing between the VTS, pilot, tugboat captain, and boatmen crew regarding traffic in port, (sailing speed and course) and the decisions and disrupting events that occur during the ongoing assignments.

v. **Peer-to-peer information sharing between the pilots:** Information sharing between the pilots of different assignments regarding delays and status of scheduled or ongoing assignments.

vi. **Sharing information of shared resources:** Information sharing from terminal planning, boatmen crew, and VTS with the pilot of the assignment that shares a resource (berth, fairway, tugboat) with another assignment. Figure 2.6 shows the parts of the information sharing arrangement and how they interact.

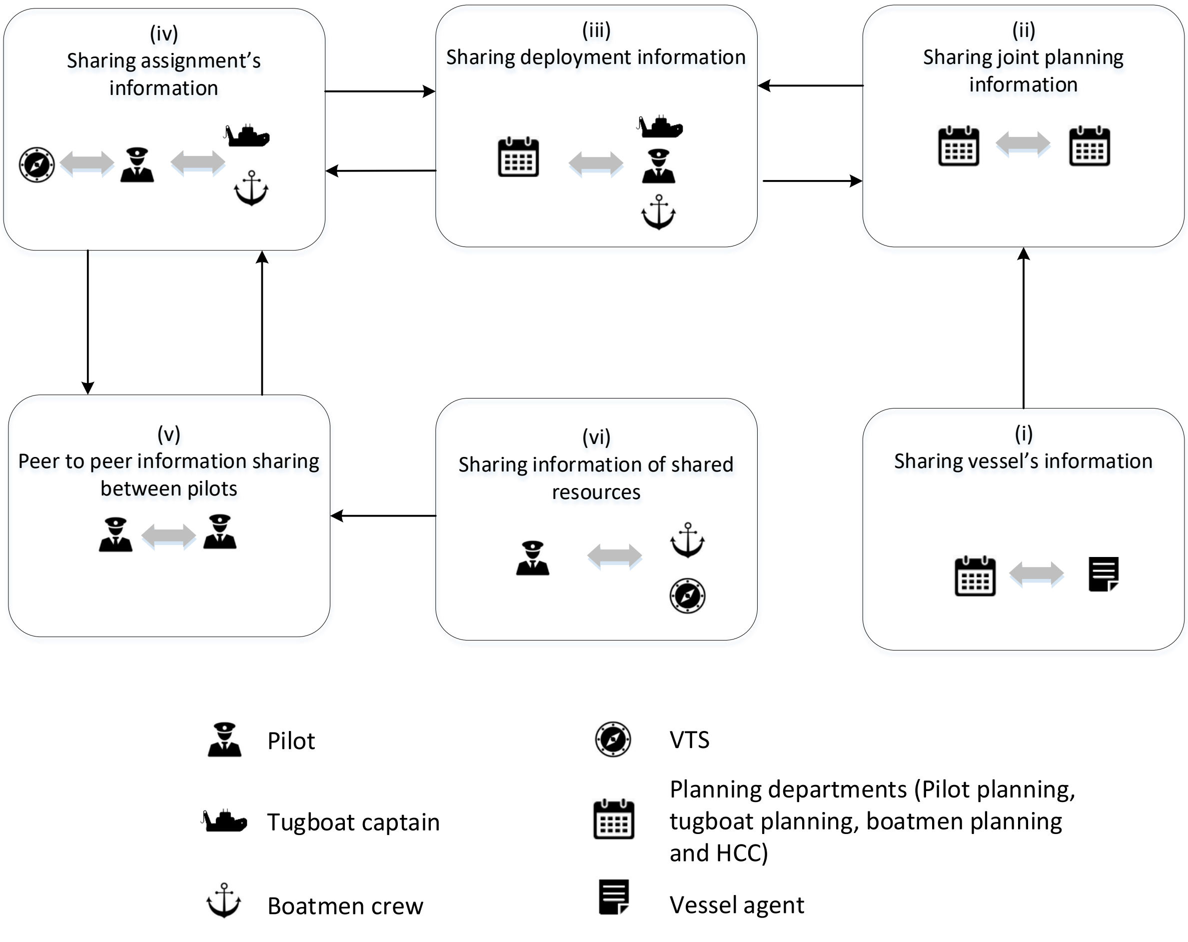

Figure 2.6. Information sharing arrangement for delay mitigation

The information available to each of the groups may depend on the information being submitted by other groups. Each group is represented with a box. Arrows indicate that the information that is available to the receiving box depends on the information being submitted from a sending box. For example, the availability of information of group (ii) depends on the information sent from groups (i) and (iii). These results are a steppingstone towards the creation of information systems for advanced operational information sharing between the actors for delay mitigation. The structural relationships between information sharing arrangements and the main root causes of delays, ensure consistency and support effective information sharing. The findings of our case study give rise to the following discussions, based on existing literature; they also have practical implications. These are discussed in the next section.

2.6 Findings

We highlight a couple of salient findings from our case.

Firstly, the analysis of root causes of frequently occurring delays shows that most of the service delays are a result of the high level of utilization of port infrastructure and resources, such as the fairway, pilots, tugboats, and berths, rather than technical issues or weather conditions. This appears to be the result of increased pressure on ports by ever larger vessels, visiting ports more frequently. In this regard, our study supports the findings of earlier studies regarding the need for a proactive role of ports in the port call process (Carbone and De Martino, 2003; Paixão and Bernard Marlow, 2003; Song and Panayides, 2008). As opposed to the current principle, whereby vessel visits are scheduled in fixed time windows, based on terminal planning only, and port actors have to react, ports can require vessels to call the port to arrange their just-in-time arrivals considering the availability of all port resources (Lind 2019). Such arrangements can help ports to plan their resources (e.g., pilots, tugboats and infrastructure) optimally and operate more efficiently. However, this also requires an understanding of the interdependencies as well as a certain level of 'partnership' to work.

Secondly, the expert surveys showed a very close agreement amongst experts on the root causes of delays. This suggests a high shared awareness of delay situations among the actors of the PoR. Operational support with information systems for better transparency is, however, indispensable. Our results constitute only a framework for the contents of information shared, and do not provide details about the information sharing processes themselves. Different operators may want to operationalize the arrangement in different ways. For example, one pilot may prefer first to communicate a delay to the pilot planning department, and then expect the latter to notify the tugboat and boatmen planning departments, and next they inform the tugboat captain and boatmen crew. Another pilot, however, may first want to communicate the delay to the pilot on the other vessel and then inform the tugboat captain and boatmen crew, expecting them to update their own planning departments. Lack of distinct information sharing guidelines for each delay case makes it difficult to track the information. Furthermore, multiple calls involving the same delays can be labour-intensive and confusing. Hence, one of the keys in mitigating port delays is designing specific information sharing guidelines for each delay case, so that each operator knows exactly what to do, who to contact and what information to share in each case. In designing such guidelines, we suggest paying particular attention to the needs of actors, because on-time information needs of different actors differ. For instance, in the Port of Rotterdam, on-time information for boatmen deployment can be inadequate for tugboat deployment, as the time needed for the tugboat dispatch is much longer than the time required for the boatmen crew. In addition, we suggest registering the necessary details in a delay database so that these causes are documented systematically and continuously and can be relied upon dynamically for studying the needs of the actors.

Thirdly, we find that in many cases, the pilot is the one who notices the delay first. Therefore, strengthening information sharing links from other parties to the pilot and vice versa can contribute enormously in mitigating delays. The former facilitates early notice of delays, while the latter helps avoid the propagation of delays, by helping others to adapt their tasks and decisions. Consequently, we suggest adoption of digital solutions, investing in ICT developments and trainings to further connect pilots to the other actors.

Fourthly, drawing conclusions about the responsibility of individual actors in the occurrence of delays is not easy. The statistics of the PoR showed that more than half of the delays are associated with delayed towage. We argue that this situation indicates the vulnerable position that the tugboat company finds itself in, with regard to information sharing within the NC, rather than issues with towage operations *per se*. Take, for instance, descriptions of 2.5.3 for the delayed towage due to a shortage in tugboat capacity (RC2). For the initial notice of tugboat capacity shortage, the tugboat planner depends on two pieces of information: the expected number of tugboats and the estimated arrival at the meeting point. These two pieces of information are submitted by two different actors, the pilot planner and the VTS.

When either information is missing or delayed, that causes delays in the tugboat planning and hence their dispatch. The required number of tugboats for each assignment remains *estimated* until the pilot sends the final request for tugboats from the vessel, as agreed with the captain[1]. This disruption only leaves a small margin for the tugboat company to dispatch the required number of tugboats if the actual number deviates from the original estimate. Another case is when towage delays occur due to delays of the previous voyage (RC3). In this case, the tugboat planner depends on information submitted by the tug captain, while the tugboat captain must receive it from the pilot first. These examples show that depending on the timely submission of information from others increases the risk of towage being delayed.

Fifthly, our case findings show the minimal contribution made by the terminal of study in the NC's information sharing. In the PoR, boatmen on the quay or the VTS operator act on the terminal's behalf to update the NC actors on any disruptions or delays. This means that the information regarding the completion of terminal operations may be imprecise. Actively involving the terminal in information sharing with the NC can significantly help improve the distribution of updated quality information. Similarly, the terminal is not involved in the updates about delays and about decisions made by the NC. Since the efficiency of the terminal is significantly affected by ETA uncertainty (Thoben and Wortmann, 2013), linking the terminal to the NC's information can benefit the terminal. Considering the benefits of further involvement of the terminal in information sharing of the NC, we argue that there is a significant opportunity for the mutual benefit of both the terminal and the rest of the NC actors, that has so far not been fully exploited.

Finally, our results confirm and reinforce the existing literature on interdependencies in ports. Earlier studies reported that the processes which different port actors carry out are interdependent and these interdependencies impact the ways port actors interact (Vitsounis and Pallis, 2012). The authors identified three types of interdependencies: serial (precedence of a process), reciprocal (mutual resource exchange among processes) and pooled interdependency (sharing a resource between processes). Our results show that these interdependencies not only exist in port processes, but also in information sharing for the provision of these processes. Take, for example, information sharing groups (i), (ii), (iii), where there is a serial interdependency. Sharing deployment information depends on the information being shared among the planning departments for joint planning. The information for the joint planning itself depends on the availability of vessel information. In other words, some information groups are antecedents to the subsequent information groups. Groups (iii) and (iv) provide an example of a reciprocal interdependency, where an information recipient processes the information, makes a decision and sends it back to the initial sender. For example, information on which planning departments base their decision depends on the information being shared with them by operational actors. Once a decision has been made, the information is sent back to the operational actors. Groups (iii), (iv) and (v) have pooled interdependency. In pooled interdependency, the information available to a group depends on the information shared from multiple groups. As such, the availability of information in group (iv) depends on information from two other groups (iii) and (iv). The existence of a variety of interdependencies complicates the identification of the actors' information needs. This complexity indicates that it is unlikely that the actors' information needs can be met in the absence of clear

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[1] It should be clear that, in most ports, the pilot is just the transmitter of the request for tugboats, while the decision on the number of tugboats belongs solely to the ship's master.

information guidelines. Therefore, it is necessary to design information sharing guidelines systemically. Moreover, we note that most information sharing links are inter-organizational, challenging information sharing even further by presenting organizational barriers. Our empirical findings substantiate the position of Talley et al. (2019, 2020) on the importance of these relationships. For facilitating information sharing practices in the ports, it may be interesting to investigate the actors' inter-organizational relationships as a pre-condition for information sharing.

2.7 Conclusions and future research directions

The paper proposes an approach that systematically studies information sharing in port to help mitigate delays in service times. It helps to identify which information is critical to be shared and with whom. We apply the approach to the case of PoR. The results provide insights into port delays and their relevance in terms of information sharing. Nine frequently occurring delays were identified. To facilitate early notice of delays and avoid their propagation, critical information sharing links were specified. Based on the approach and its application, we identified opportunities for improvements and suggested recommendations for practice. The main findings are the following:

- Delays occur mainly due to increased pressure on ports and the over-utilization of port resources. Managing this pressure requires proper planning of port resources by, first of all, ensuring the just-in-time arrival of ships, based on the port’s resource availability. This means that ports need to adopt a more proactive role in the port call process, as opposed to the current principle in which ETAs are extremely inaccurate, time windows are based on terminal planning only, and port resources cannot be planned until the vessels arrive at the port

- Information sharing links are inter-dependent and inter-organizational. The sender of the information itself receives information from an earlier sender and often requires additional information from multiple senders to make decisions. This interdependency creates complexity in identifying from whom to obtain the information and who to inform next. The presence of Inter-organizational links complicates information sharing even more. These complexities imply that, for improving information sharing, ports have to design operational information sharing guidelines fitting into their specific context.

- Neither the causes of the delays nor the measures to mitigate them must be seen in isolation. The port services form a complex system that needs to be approached systematically. Accordingly, delays that are attributed to one actor may be mitigated by facilitating information sharing among the rest of the actors.

- Results showed the critical position of pilots, the vulnerable position of tugboat companies, and the minimal contribution of the terminal in information sharing. Considering these positions is essential for the effective design of information sharing guidelines. We identified a significant potential opportunity to improve information sharing that is as yet unexploited.

These findings provide input for addressing the key port management challenges regarding the facilitation of information sharing, currently on the agenda of port policymakers. Adoption of these recommendations can ultimately help port efficiency improvements. This also leads us to the following suggestions regarding the future extension of our work. Firstly, the scope of this paper is limited to the ‘*what* and *whom’* questions of information sharing, and does not include *how* and *when* the information must be shared; something that future research can look into. Future research can also investigate whether digital solutions can overcome practical challenges of information sharing. The question "whether the actors would be willing to share information considering the unequal distribution of costs and benefits, risks involved, lack of trust, and unwillingness to invest in infrastructure?" also merits further research. Secondly, our research can be extended by a further quantitative analysis of delays and their root causes. Here, we identified the frequently occurring causes of delays through expert interviews. The combined use of geographical position data and process logs of port actors could increase the accuracy of identifying root causes. Thirdly, we suggest measuring the impacts of improved information sharing on port delays and overall efficiency to help measure the magnitude of the impact. Finally, the approach presented here can and should be applied to other seaports. Repeated applications and their comparison can help generate generalized findings, noting that different ports in different contexts will undoubtedly affect the information sharing needs.

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Appendix 2.A

The following table re-orders the information sharing links across the nine root causes of frequently occurring delays and provides distinct information sharing groups.

Table 2.1. Critical information sharing links

Root Causes of delays	Information Link	From	To	Information group	Information content
RC1	b	Vessel agent	HCC	i	Updated ETA and ETD, vessel's information, ordered nautical services
	n	HCC	Pilot planning		
	o	Pilot	Pilot planning	iii	Estimated completion time of the ongoing assignment
	q	VTS	Pilot	iv	Updated ETA
	n	Pilot planning	HCC	ii	Requests for a delayed ETA or ETD
	k	Pilot planning	Tugboat planning		
	e	Pilot planning	Boatmen planning		
RC2	b	Vessel agent	HCC	i	Updated ETA and ETD, vessel's information, the estimated number of tugs
	g	HCC	Tugboat planning		
	k	Pilot planning	Tugboat planning		
	l	Pilot	Tugboat planning	iv	Updated ETA, Final number of required tugboats
	h	Tugboat planning	Tugboat captain	iii	Deployment information
	g	Tugboat planning	HCC	ii	Requests for a delayed ETA or ETD
	k	Tugboat planning	Pilot planning		
	f	Tugboat planning	Boatmen planning		

RC3	m	Pilot	Tugboat captain	iv	Updates on the ongoing assignment, estimated completion time
	h	Tugboat captain	Tugboat planning	iii	Estimated completion time of the ongoing assignment, updates on delayed arrival
	l	Pilot	Tugboat Planning		
	k	Tugboat planning	Pilot planning	ii	Request for a delayed ETA and ETD
RC4	q	VTS	Pilot	vi	Updates on berth unavailability and estimated availability time
	i	Boatmen	Pilot		
	m	Pilot	Tugboat captain	iv	Updates on the ongoing assignment
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		
RC5	q	VTS	Pilot	vi	Traffic information, updated ETA and ETD
		Pilot	Pilot	v	Updates on sailing and manoeuvring information, possibility of overtaking
	m	Pilot	Tugboat captain	iv	Updates on the ongoing assignment
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		
RC6	i	Boatmen	Pilot	vi	Updates on the completion of time of terminal operations
	q	Pilot	VTS	iv	Updates on the ongoing assignment
	m	Pilot	Tugboat captain		
	i	Pilot	Boatmen		
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		

RC7	q	Pilot	VTS	vi	Updates on the completion time of bunkering operations
	m	Pilot	Tugboat captain		
	i	Pilot	Boatmen		
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		
RC8	q	VTS	Pilot	vi	Traffic information, updated ETA and ETD
		Pilot	Pilot	v	Updates on sailing and manoeuvring information
	q	Pilot	VTS	iv	Updates on the ongoing assignment and decisions made by pilots
	m	Pilot	Tugboat captain		
	i	Pilot	Boatmen		
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		
RC9	q	VTS	Pilot	iv	Traffic information, updated ETA and ETD
	m	Tugboat captain	Pilot		
	i	Boatmen	Pilot		
		Pilot	Pilot	v	Updates on sailing and manoeuvring information
	o	Pilot	Pilot Planning	iii	Updates on the ongoing assignment and estimated completion time
	h	Tugboat captain	Tugboat planning		
	d	Boatmen	Boatmen planning		

3 Organizational potentials for relationship and information sharing

This chapter conceptualizes the link between inter-organizational relationships and information sharing between the port actors. To this end, it operationalizes the partnership model, which was originally proposed for the supply chains, for the port context. The applicability of the model is tested for the port of Rotterdam. Data was collected using desk research, expert interviews and surveys amongst all port actors.

Section 3.1 provides context regarding the actors' relationships in the port. Section 3. 2 extends the review of the literature. Section 3.3 briefly explains the port call services and actor organizations. Section 3.4 suggests a new partnership model in a port context. Section 3.5 implements the proposed model for a case for the Port of Rotterdam (PoR). Section 3.6 discusses the findings and the managerial implications. Finally, section 3.7 concludes the study and presents future research directions.

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3.1 Introduction

Ports are busier than ever. The number and size of vessels calling at ports are growing (Lind *et al.*, 2020). Vessels' waiting time in ports is increasing which is an indication that the ports are struggling to handle this growing demand (UNCTAD, 2021). Currently, cargo vessels could spend up to 40% of their port time waiting for port services (Slack *et al.*, 2018). Waiting times increase fuel consumption, CO_2 emissions, and the risk of collisions (Pratap *et al.*, 2019). To cope with this growing demand, ports need to improve their efficiency in providing their services and be able to accommodate more vessels in shorter times.

As has become clear in recent years, information sharing is becoming a central strategy for transforming ports into smart, efficient, and green ports (Shaw, Grainger and Achuthan, 2017). During a port call, various services including traffic management, pilotage, towage, mooring are offered by several port actors, including the harbour master, the pilot organization, the tugboat company, the boatmen organization. Information sharing regarding the availability of the resources and adjustments to the initial plans are instrumental to synchronize services and together create a seamless and robust chain of services. The benefits of information sharing are extensive and there is a general consensus on connecting the port actors to share information (Ahmad *et al.*, 2021).

Sharing information is greatly facilitated by means of new developments in Information and Communication Technologies (ICT) such as the Internet of Things (IoT), blockchain, and cloud computing (Parola *et al.*, 2020). These days, many ports are equipped with ICT platforms that connect the port actors to exchange information; we refer to Heilig et al. (2017) for an overview of information systems for ports. Clearly, the technology for sharing information is already available. However, the progress is still slow (Lind, Ward and Bergmann, 2020) and hampered by challenges of an inter-organizational nature (Nikghadam *et al.*, 2021). Sensitive information may need to be shared with multiple parties across organizations and adjusted multiple times. Therefore, information sharing may be costly and risky for port actors. As such, it is necessary to address the extent to which port actors are willing to take on the challenge with others.

Literature shows that information sharing across organizations is an attribute of their business relationships (Cheng, 2011). Information sharing is enabled through strong, cooperative relationships (Heaver, 2015) while, conversely, weak relationships limit the exchange of sensitive information. Therefore, in ports too, it is essential to investigate port actors' relationships to assess their information sharing potentials. Literature also presents various examples of studies that looked into port actor relationships. These studies focused on cooperative relationships and report its benefits. De Martino et al. (2008, 2013) highlight the benefits of cooperative relationships regarding service quality, efficiency and innovation. Talley et al. (2014) introduce the concept of *port service chain*, as a service network for the provision of port services. Their study demonstrates that ports with cooperative relationships are more effective than non-cooperative ones (Talley, Ng and Marsillac, 2014). An implicit assumption of these studies is that port actors would be willing to engage in cooperative relationships if it is beneficial for the port collective. This assumption is questionable, as in most of the major ports today, actors are self-governed organizations that act aligned with their own business interests, avoiding actions and decisions that are not in line with these interests, even if the collective benefits.

In short, despite the strong aspiration to enhance information sharing and promote cooperative relationships in the literature, the important question "*How willing are the port actors to engage in* *cooperative relationships?"* is overlooked. What is missing is the perspective of the individual port actors in their cooperative relationships, a gap which is also acknowledged by Talley, Ng and Marsillac (2014). In this paper, we address this gap by investigating the port actors potentials in these aspects. We present a first approach for port managers and policy makers to assess port actors' inter-organizational relationships and information sharing potentials.

In the following, we develop an extension and application of the Lambert (2008) partnership model by operationalizing it for the actors involved in port calls. Next, we present an application of the model for the case of the port of Rotterdam. We identify the port actors' potentials for inter-organizational relationships in general and more specifically for information sharing. This leads to recommendations which support policy-makers in designing effective development strategies for smart, efficient and digitalized ports.

This chapter is organized as follows. Section 3.2 extends the review of the literature that addresses actors' relationships in the port call context. Section 3.3 briefly explains the port call services and actor organizations. Section 3.4 suggests a new partnership model in a port context. Section 3.5, implements the proposed model for a case for the Port of Rotterdam. Section 3.6 discusses the findings and the managerial implications. Finally, section 3.7 concludes the study and presents future research directions.

3.2 Literature review

There is an extensive body of literature that studies the relationship between the organizations within a port. Two main streams of literature exist: one stream has focused on the relationship between terminals and the other on the relationship between the Port Authority and terminals.

Most of the attention has been paid to the relationship between the terminals of a port. Many studies support the cooperative relationships of terminals and highlight the cost-saving benefits of their cooperation (Song, 2002; Lee and Song, 2017). They argue that cooperation between terminals allows idle resources of one terminal, like quay cranes, berthing and stacking locations to be used by the other when there is a shortage of resource. This cooperation for resource sharing in turn results in shortening berthing time and dwelling time, reducing costs, improving facility utilization and service level (Budipriyanto *et al.*, 2015). However, despite all the benefits, the development of long-term cooperative relationships between terminals is restricted by a variety of barriers such as, lack of trust and commitment, resistance to change, incompatibility of operating and strategic goals, lack of resources, strategic considerations (Van Der Horst and De Langen, 2008; Yuen and Thai, 2017). As a result of their highly competitive market environment, they compete with each other to be shipping companies' choices (Munim and Saeed, 2019). Their competition can be beneficial in some aspects, however. For example, this competition results in innovation and entrepreneurship as competing parties constantly aim to improve their services. The most widely accepted argument in favour of the competition within organizations of a port is that it prevents monopolistic power of actors such as high tariffs (Theys *et al.*, 2010).

The other stream of literature, that investigates the inter-organizational relationships within a port, focuses on the relationship between the Port Authority and terminal. This topic has been of particular interest because the policies set by the Port Authority determine the entry rules of terminals into the port and the competition amongst them (Grifoll, 2019). For example, long-term leases encourage terminals to invest more in development strategies. While, it limits the entry of new terminals to the port and the innovations they could have brought (Heaver, Meersman and Van De Voorde, 2001). The competition level between terminals is a very important consideration for Port Authorities in their vision for the future. When it is not entirely clear if the operating terminals will stay in the port, it is very difficult to set such a vision for the port (Ishii *et al.*, 2013). Therefore, the strategic relationship between the Port Authority and terminals of a port is very important for both terminal and the Port Authority. The relationship between the Port Authority and terminals is compared to the buyer-supplier relationship in supply chains. This comparison is used to investigate whether the parties have an incentive to cooperate (Zheng *et al.*, 2020).

In the literature, the investigation of relationships of organizations within a port is mostly focused on terminals and the Port Authority, ignoring other actors including pilot organizations, tugboat companies, and boatmen organizations. Even few studies that considered these actors, did not treat them as self-governed organizations but approached them as resources that can be pooled and centrally optimized (Talley, Ng and Marsillac, 2014). For example, Abou Kasm et al. (2021) presents a mathematical model which enables optimal allocation of the pilotage and towage resources to servicing the vessels.

The approaches which are based on pooling resources centrally can only apply to traditional centralized port structures where port actors, hence, their resources and their decisions are managed by a central Port Authority. However, since the decentralization reform, a large diversity of port governance structures has emerged (de Oliveira, You and Coelho, 2021). Among them, the landlord port structure is found to be the dominant and most effective port structure for large and medium-sized ports (Zheng and Negenborn, 2014; Tseng and Pilcher, 2017). In a landlord port structure, instead of the Port Authority having public control over planning and operations, self-governed public and private port actors are in charge of diverse roles and responsibilities such as pilotage, towage, and mooring services (Cui and Notteboom, 2018). Examples of ports with a decentralized structure are Port of Rotterdam, Barcelona, Vancouver, and Auckland (The World Bank, 2007). This decentralized structure necessitates acknowledging the port actors’ perspectives and taking them into account for proposing feasible development strategies.

In summary, while the extant literature considers the Port Authority and terminals in port actors' relationships, it does not recognize all relevant port actors and their unique self-organizational properties. Without having a clear understanding of these actor's perspectives, it is impossible to determine the precedents of their relationships, such as information sharing realistically. In the next sections, we address this gap by proposing and demonstrating an approach for assessing the potential strength of relationships between port actors. Below we first define the scope of the research.

3.3 The port call; services and actors

In this section, we briefly present the scope of this study and describe the services and actors involved in the port call process.

Ports provide a variety of *nautical-technical* services to vessels calling the port. These nautical services include traffic management, pilotage, towage and (un)mooring and cargo operations; these are offered respectively by the Harbour Master (HM), the pilot organization, a tugboat company, a boatmen organization, and a terminal.

Incoming vessels request a berth from the terminal they wish to visit and plan their voyage after the terminal's confirmation. When the vessel departs from its origin, it submits an administrative clearance request to the HM's office of the destination port. Upon the HM's confirmation, the pilot organization, tugboat company, and boatmen organization receive the vessel's estimated time of arrival (ETA) so that they can plan accordingly. When the vessel arrives at the port, it asks for operational clearance from the HM. If the traffic at the port permits, with the guidance of HM, the vessel takes the pilot on board. Under the pilot's command, the vessel starts sailing through the channels. Where tug assistance is needed, the tugboats connect and tow/push the vessel to the designated berth. Once there, boatmen help moor the vessel. When the vessel is safely moored, the incoming voyage is completed and the terminal can start with cargo handling operations.

For outgoing vessels the sequence of nautical services starts upon the completion of cargo operations; prior to that, the vessel asks for administrative clearance from the HM. If the clearance is given, the pilot organization, tugboat company, and boatmen organizations are updated regarding the estimated time of departure (ETD) so that they can plan accordingly. When the traffic of the port allows, the pilot comes on board, tugs are connected, boatmen get ready to unmoor and the vessel leaves the berth. When tug support is no longer needed the tugboats disconnect. Once the vessel has left the port area, the pilot leaves the vessel and returns to the pilot station. Finally, the vessel notifies the HM that it has successfully departed. Figure 3.1 shows a simplified visualization of the nautical chain (NC) services for incoming vessels.

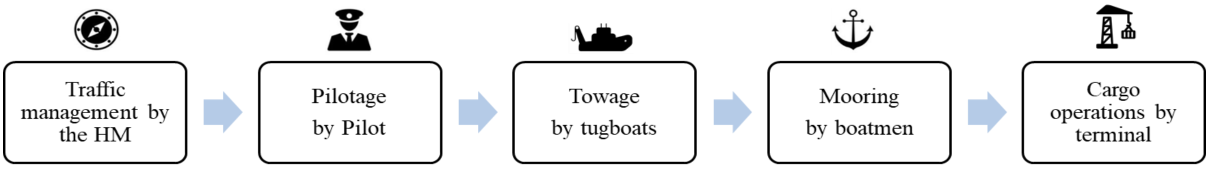

Figure 3.1. The nautical chain (NC) services for an incoming vessel

The above descriptions of NC services show the necessity for the actors to have relationships and share information about their plans and execution of their assignments, such that they meet at an agreed time at the agreed place (Lind, Ward and Bergmann, 2020). Take, for example, the case of an outgoing vessel that is delayed due to unfinished cargo operations, while the pilot, tugboat, and boatmen are ready and waiting to serve the vessel. The tugboats which are ready according to the initial plan may decide to take their next assignment in the meantime, instead of waiting idle. However, they may not be able to be back at the time the delay has been resolved and terminal operations have completed. Communicating such decisions helps others to adjust their plans accordingly, but also bares the risk of being disagreed with and facing repercussions. The related challenge in our research is to investigate how willing they are to share the most updated and sometimes sensitive information and decisions. In the next section, we present an approach to address this question.

3.4 Assessing the relationship and information sharing potentials in ports

In this section, we present our approach to assess the potential strength of relationships and willingness to share information by port actors. We build on the original partnership model of Lambert (2008), which we introduce in section 4.1. Next, we extend and operationalize the approach for the context of the port's NC services.

3.4.1 The partnership model

The relationship between organizations, and hence the attributes of their relationship, vary. The supply chain literature suggests four possible types of cooperative relationships between organizations: Arm's length relationship, Type 1, Type 2, and Type 3 partnerships (Lambert, 2008). When two organizations have an arm's length type relationship, they conduct transaction-based business without having a sense of shared commitment. This type of relationship helps two organizations meet the daily needs of their business and the relationship terminates when the exchange ends. In the literature Type 1, 2, and 3 partnerships are also named coordination, cooperation, and collaboration, respectively.

- In Type 1 partnerships (coordination), the organizations explicitly identify each other as partners. They share tasks- and project-related issues and they coordinate their activities and planning on a limited basis usually conducted on an ad-hoc basis between individuals. There are low or no joint investments, technological developments, and personnel exchanges. Trust is limited and commitment to each party is transaction- or project-based.

- Type 2 partnerships (cooperation) go one step further than coordination of their activities. Here, parties integrate their activities. Multiple units and functions within organizations are involved in the partnership. The parties may jointly invest in their own low-value resources and technologies.

- In Type 3 partnerships (collaboration), two organizations are operationally integrated. The partnership extends to almost all levels including strategic and tactical levels in both organizations. Activities in the partnership are a significant part of business for both parties. Both parties are committed to each other's long-term success, at all levels. The parties jointly invest in high-value resources such as personnel, technologies, and Research and Development (R&D) activities.

Several models have been proposed in the literature that investigate the inter-organizational relationships (Mohr and Spekman, 1994; Tuten and Urban, 2001; Lambert, 2008). Among these models, we chose the partnership model proposed by Lambert (2008) due to its specificity and simplicity in terms of evaluating the factors that influence organizations' relationships. Although the original model is suggested for supply chains, it can be applied by analogy for port studies. Literature provides several studies that argue that the port sector shares common features of supply chains - like relationships between organizations (Bichou and Gray, 2005; Panayides and Song, 2008). Take, for example, buyer-supplier relationships. In a similar way as supply chains, in ports, organizations provide services that are used by others. The former can be seen as suppliers of services for the latter. A clear example of this buyer-supplier relationship is the relationship between the terminal and the Port Authority (Zheng *et al.*, 2020). Later, we show that the model can be operationalized well for the port using this reasoning.

Lambert's partnership model states that the strength of the relationship between organizations will depend on two types of indicators: *drivers* and *facilitators*. Drivers are the compelling reasons for organizations to develop a relationship with others. Drivers are primarily classified into four categories: cost efficiency, customer service, flexibility, and profit stability. Facilitators are elements of the corporate environment that support the relationship between two parties. Facilitators are classified into four main categories and five additional factors. The main categories are compatibility, management philosophy, mutuality, and similarity; additional factors are shared competitors, physical proximity, exclusivity, prior experience, common end-users.

The assessment of drivers and facilitators is done by means of a survey, as follows (see Appendix 3.A and 3.B for drivers and facilitators, respectively). Respondents are asked to score items under each category on a Likert scale (from 1 to 5), answering to what extent the relationship with the other party contributes to each category. For drivers, if the respondent scores 3 or higher on a driver category, one more question needs to be answered, i.e., whether the factor is a competitive advantage for their business. If the answer is yes, one extra point is added to the score of that category. The total score of drivers is the sum of scores assigned to the four categories. Hence, the total score of drivers ranges between 4 and 24. Once we assessed the surveys, if the two parties have dispersed scores for drivers, the lower score is used to determine the potential relationship type because the relationships are only as strong as their weakest commitment. Similarly, facilitator scores are recorded on a Likert scale (from 1 to 5), indicating to what extent parties match in terms of facilitator categories. Respondents are asked whether the relationship is facilitated by means of each factor. The answers are assessed by Yes/No scoring 1 or 0. The total facilitators' score is the sum of all four categories and five additional factors. Total facilitators score ranges between 4 to 25.

The partnership model assesses drivers and facilitators based on Figure 3.2, to determine the relationship potential. When there are both high drivers and facilitators (above 16), the model recommends a stronger relationship, namely Type 2, 3 partnerships. In cases where there are low drivers or low facilitators, the partnership potentials are also low and there is a potential for a Type 1 partnership or arm’s length relationship. When drivers' scores are very low (below 8) the potential is so low that the partnership is not seen as worthwhile to pursue.

Figure 3.2. Relationship potential based on drivers and facilitators score (Lambert, 2008)

		Driver score		
		Low (8-11 points)	Medium (12-15 points)	High (16-24 points)
Facilitators score	Low (8-11 points)	Arm’s length	Type 1	Type 2
	Medium (12-15 points)	Type 1	Type 2	Type 3
	High (16-25 points)	Type 2	Type 3	Type 3

3.4.2 Operationalization of the partnership model for the NC

In this section, we adapt, operationalize and apply the Lambert (2008) partnership model to the NC. We follow the main four categories of drivers (cost efficiency, customer service, flexibility, and profit stability) and facilitators (corporate compatibility, management philosophy, mutuality, and similarity) and operationalize these to match the business scope of the port actors. Table 3.1 presents drivers and facilitators of the relationships in the NC supplemented by examples for each category. For constructing this table we are inspired by the earlier studies where the NC actors' interests are presented and discussed (Talley, 2019; Talley and Ng, 2022).

Table 3.1. Drivers and facilitators of the relationships in the NC

Drivers	**Facilitators**
Cost efficiency	**Corporate compatibility**
Reducing material costs and Information handling costs, Saving personnel costs and service costs, Reducing information handling costs, Improving managerial efficiencies	Keeping commitments, Seeing employees as long-term assets, Valuing external stakeholders, Commitment to partnership ideas, Willingness to change
Customer service	**Management philosophy**
On-time delivery of services, Better tracking of movements, Improving ordering processes, Shortening turnaround times, Shortening waiting times, Improving operational processes	Organizational structure, Degree of top management support, Types of motivation used, Importance of teamwork, Degree of employee empowerment
Flexibility	**Mutuality**
Flexibility in rescheduling due to the vessel's delays, actors' delays, and extreme weather conditions	Management skilled at two-sided thinking, taking the perspective of the partner organization, mutual respect, expressing goals and sharing expectations, having a longer-term view, willing to share financial information
Profit Growth	**Similarity**
Growth in profit, growth in the number of contracts, Market share stability	Financial strength, Relative market share in their respective industries, Productivity, Technological sophistication
	Additional factors
	• Shared competitors • Physical proximity • Exclusivity • Prior successful experience • Having the same end-user

3.4.3 Identifying information sharing potentials

As relationship types differ, attributes of the relationship differ as well. In this study, we focus on information sharing as an attribute of relationships. While stronger relationships enable a more frequent exchange of critical information, it is limited in weak relationships. Based on the literature (Xu and Beamon, 2006; Lambert, 2008) the following information sharing guidelines are suggested:

- In arm’s length relationships, information sharing potential is limited and one-way, from one party to the other. Parties share only transactional information.
- In Type 1 partnerships, each party uses its own information system and shares the information with the other party at a task- or project-level. Communication is primarily one-way, from one to the other, and non-routine. Planning is done individually and shared with the parties on a project basis.
- In Type 2 partnerships, information sharing is two-way but unbalanced. When information sharing is unbalanced predominantly one party is the sender and the other is the receiver. Planning is usually performed individually and shared with the partner to eliminate conflicts. Each party has its own information sharing system rather than jointly using one. Information sharing is regular and includes critical information including strategic and tactical information.
- Type 3 partnerships enable the frequent exchange of critical information. Planning may be performed jointly and at multiple levels. Information sharing is two-way and balanced. The parties often have a joint customized electronic information system. Planning can reach up to strategic levels. Sharing critical information at all levels is facilitated. Namely; strategic, tactical, operational, and interpersonal levels.

Figure 3.3 summarizes the information sharing guidelines based on the relationships types.

Information sharing	Arm’s length	Type 1 partnership	Type 2 partnership	Type 3 partnership
Operational	✓	✓	✓	✓
Tactical		✓	✓	✓
Strategic			✓	✓
Two-way			✓	✓
Frequent			✓	✓
Balanced				✓
Join planning				✓
Joint information system				✓

Figure 3.3. Information sharing guidelines

In the next section, we describe the approach’s implementation in a case study.

3.5 Case study: The Port of Rotterdam

In this section, we present the implementation of the above model for the port of Rotterdam. The Port of Rotterdam is the largest port in Europe with almost 30,000 sea-going vessel calls per year. The Port

Authority owns and develops port infrastructure and leases it to the private sector. This makes the Port of Rotterdam a so-called ’landlord’ port. The HM is part of the Port Authority and is responsible for ensuring the efficient flow of traffic through the port on behalf of the government. Whereas the HM is public without financial concerns, other actors are private. Terminal operations, towage and mooring services are carried out by specialized private organizations. Pilotage has been private since 1988.

The required data were collected by means of desk research, expert surveys, and expert interviews.

- We carried out desk research to get insight into the port operations and current state of information sharing as practiced currently (Nikghadam *et al.*, 2021; Port of Rotterdam, 2021).
- Expert surveys were conducted based on instructions of the Lambert (2008) partnership model as presented in Section 4.1 (for example, see Appendix 3.A and 3.B). Interviewees were representatives of the actor organizations: the HM, pilot organization, tugboat company, boatmen organization, and container terminal.
- Surveys were complemented with semi-structured interviews for validation and further elaboration and have taken place during 2019-2020. The experts participating included a senior policy maker at the HM Department of the port of Rotterdam, a senior maritime pilot, a former director of a tugboat company, an operational manager of the boatmen organization, and a quality supervisor of the largest (ECT) container terminal.
- The final results were validated by a policy maker at the HM of the port of Rotterdam.

In the next sections, we report the results in detail.

3.5.1 Relationship potential

Based on the described method in section 4.1, we determine the relationship potentials. We discuss the results for each pair so that all relationships can be systematically covered.

Pilot and Boatmen organizations: the relationship between pilot and boatmen organizations has the potential to be the strongest relationship in the Port of Rotterdam. Both parties believe that the relationship is beneficial in terms of all four categories of drivers. Additionally, with all the similarities in their corporate compatibility and management philosophy, their cooperation is highly facilitated. Considering their high drivers (17 and 20 for the pilot and boatmen organizations respectively) and facilitators score (18), their relationship potential is as strong as the Type 3 partnership. The following quote of a pilot illustrates how employees of these two organizations see each other:

“The boatmen are the eyes and ears of pilots.”

Pilot organization and the HM: both the pilot organization and the HM scored high on drivers (13 and 16 respectively) , with slightly higher drivers score for the HM. From their perspective, the relationship benefits their flexibility and customer service. These two aspects are the most important drivers for them, rather than financial aspects like cost efficiency or profit growth. The facilitator score for their relationship (14) showed that the corporate environment is relatively supportive with lots of similarities in their cultural and managerial aspects. Therefore, their relationship potential is a Type 2 partnership.

Pilot organization and tugboat company: the relationship between the pilot organization and the tugboat company can be one of the strongest relationships of the NC. Their equally high drivers score (15) indicates that their drivers are mutual. Improvements in customer service, flexibility and customer service are the most important drivers for both parties. With all the similarities in their corporate compatibility and management philosophy, their cooperation is adequately facilitated (15). Therefore, their relationship potential is a Type 2 partnership.

Boatmen organization and terminal: the drivers of boatmen organization are found to be considerably higher compared to the terminal (22 and 15). From the boatmen organization's perspective, its relationship with the terminal is advantageous in almost all four categories. If the terminal's drivers score was equally high, the relationship potential could have reached up to a Type 3 partnership. However, the terminal’s drivers score is medium. As quoted by the terminal representative:

“On-time and smooth mooring services are essential for the terminal. Yet, the mooring services are not the main determinants of terminals' success. The terminal’s business scope extends to cargo operations. Hence, costs and profits associated with boatmen's services are relatively insignificant for the terminal.”

Survey results show that their corporate environment is quite supportive as their facilitator is scored moderately high (11). Hence, their relationship potential is a Type 2 partnership.

The HM and tugboat company: the overall drivers score for both parties is found to be medium (14 and 12 for the HM and tugboat company respectively). From the tugboat company’s perspective, improvements in flexibility and customer service are the main drivers. One of the reasons raised by respondents was as the following:

“The HM is involved with making decisions regarding the location of tugboat’s resting stations in the port, which directly impacts the tugboat company’s cost efficiency and flexibility in its daily practice”.

For the HM too, the relationship with the tugboat company contributes to improvements in customer service and flexibility. Yet, considering their business dissimilarities and incompatibilities reflected in their facilitators score (11), their relationship potential is a Type 1 partnership.

The HM and boatmen organization: the drivers of boatmen organization in its relationship with the HM is found to be moderately high (15), mainly for flexibility and profitability reasons. However, the drivers of the parties are not equal. Although the HM acknowledges that the relationship has an impact on customer service and flexibility, the overall drivers score (11) is still relatively low. Therefore, despite the reasonably high drivers score (14) for the boatmen organization, their potential relationship is Type 1 partnership.

The HM and terminal: both the HM and the terminal scored equally low in the drivers (7 and 8 for the HM and terminal respectively). This means that from the both parties perspectives the benefits of relationship are rather insignificant. Respondents explained the low drivers score for both parties in view of the fact that the HM is in the public domain, whereas the terminal performs in the business domain as the following:

“The HM’s main interests are regarding the safety of the port. The terminal's main interests, namely cost efficiency and profitability, relate to its business relationship with shipping lines.”

Also, considering their low facilitators score (7), which is an indicator of the dissimilarities in their business characteristics, the development of a strong relationship becomes even less likely. Therefore, their potential relationship type is arm’s length.

For the remaining relationships, i.e., tugboat company and boatmen organization, tugboat company and terminal, pilot organization and terminal, the drivers' score of either of the actors or both are found to be very low (Below 8). As such, the relationship potential is so low that it is not necessary to proceed with the model (Lambert, 2008). We illustrate the actor's relationships with a network in Figure 3.4. Nodes of the network denote actors of the NC and links denote the relationship potential between the actors. The thicker the link, the stronger the relationship potential. The shading gradient of the link denotes the disparity of drivers score. The darker end of the link is the actor with the higher driver score. When the drivers score is equal for both parties the link is solid.

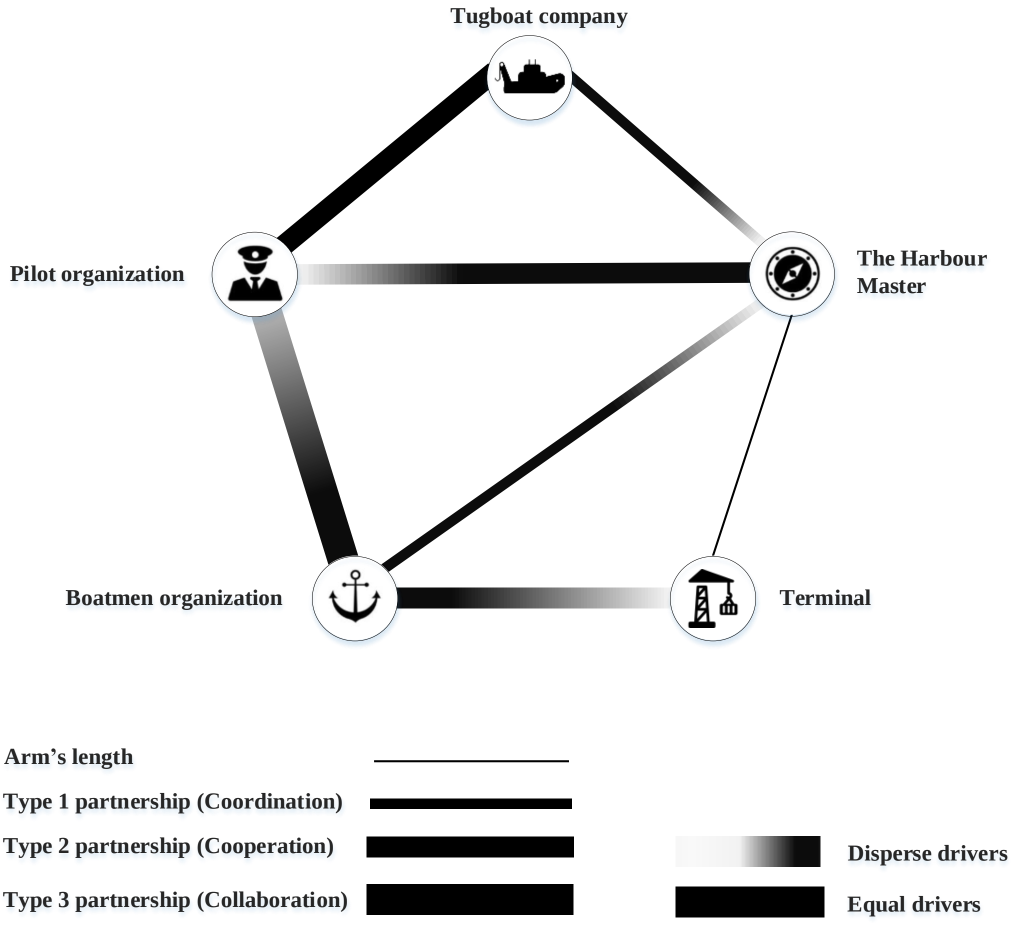

Figure 3.4. Relationship potentials in the NC of the Port of Rotterdam

3.5.2 Information sharing potential

In this section, we discuss the implications of the above findings for information sharing in the port of Rotterdam. First, we take the previous section's findings, the relationship potentials, and match them with the information sharing guidelines presented in section 3.4.2. Accordingly, we derive the information sharing potentials.

The Type 3 partnership potential between the pilot and boatmen organizations allows the highest level of information sharing. Employees at all departments can be expected to engage in a two-way, balanced, and frequent exchange of critical information including their strategic and tactical decisions. The relationship is so strong that it enables the integration of some activities for the pilot and boatmen. The Type 2 partnership potential between the pilot organization and HM, pilot organization and tugboat company, and boatmen and terminal enables a frequent two-way exchange of strategic and tactical information between the parties. The Type 2 partnership supports individual planning with the exchange of information for joint modifications of their plans, based on the request of the other party. A stronger partnership Type 3 would have allowed them to strive for a joint planning arrangement. Yet joint planning is not supported by their relationship potentials.

The uniquely strong partnership potential of the terminal with the boatmen organization enables terminal's information sharing between these two only. Direct communication by the terminal to pilots could have helped better planning, yet, their potential is limited. The type 1 partnership potential between HM and tugboat company, and the HM and boatmen organization, supports mostly one-way sharing of information. There is low or no potential for sharing sensitive information. The arm's length relationship potential between HM and terminal enables only low-level transactional information sharing. This means that information sharing can be very limited and critical information, at a tactical level for instance, is not enabled. Therefore, in the absence of measures to motivate both parties, further information sharing seems unlikely. For example, further exchange of information between the HM and terminal would have allowed to pool data and help provide more accurate estimates regarding the arrival and departure times to each other. We find, however, that the current relationship potential between them would not support this level of information sharing.

In summary, the results show that different pairs of actors have different information sharing potentials, varying widely from no information sharing to two-way frequent exchange of critical information.

3.5.3 Current information sharing practice

In this section, we investigate the current state of information sharing as practiced in the port of Rotterdam. Next, we will confront them with the information sharing potential as identified above. This comparison provides an indication of the feasibility of new information sharing opportunities.

The required data were collected by means of desk research and complemented with expert interviews from the HM of the Port of Rotterdam (For details see (Nikghadam *et al.*, 2021). First, the NC services were mapped; next, all information exchanges for planning and execution of the processes were identified.

When a vessel notifies its arrival or departure, the HM forwards the information to the tugboat company, the pilot- and the boatmen organizations for the planning of the NC services. The pilot organization, tugboat company and boatmen organization plan individually, to prepare for serving the vessel at the vessel's requested time. If either of them cannot deliver its service, an updated ETA or ETD is proposed. Multiple exchanges of information between the actors may be needed to agree on the proposed time. The common information system currently in use for these two-way communications is developed and owned by the pilot organization. During the execution of services, the pilot exchanges information with the tugboat and boatmen continuously and communicates regularly with the HM to inform the voyage details and be updated about the traffic.

Not all the actors communicate directly for the execution or planning of their operations. For instance, the tugboat company and boatmen organization do not exchange information in their daily operations. The terminal does not systematically exchange information with the HM. The information submitted by the vessel (agent) in the PCS is provided separately to the HM and the terminal in strictly separated domains (public and private, respectively) and not exchanged between the HM and terminals. Hence, the information that the terminal obtains is from the vessel itself and it is not received from the actors and not shared with them. Two-way exchange of planning information between the HM and terminals would have allowed to pool information and provide more accurate estimates. As we established above, however, the information sharing potential between them would not support this level of information sharing. The only information sharing of the terminal is its link with the boatmen organization. The boatmen act as an intermediary between the terminal and pilot organization. For example, when the berth of an incoming vessel is occupied with another vessel or the cargo operations are delayed for an outgoing vessel, the boatmen at berth acquire the expected times of terminal operations from the terminal employees and inform the pilot. Direct information sharing between the terminal and pilot organization could help to improve the planning, but currently there is no potential for such level of information sharing.

Figure 3.5 illustrates the information sharing as currently practiced in the Port of Rotterdam. The nodes indicate the actors and the arrows indicate the information sharing between them. The comparison of the current information sharing in practice with the information sharing potentials, presented in 3.5.2, shows a perfect match between the two. This means that in the Port of Rotterdam, where there is potential, the corresponding level of information sharing is practiced. This supports the idea that relationship potentials are an important precondition for information sharing. We discuss our findings further in the next section.

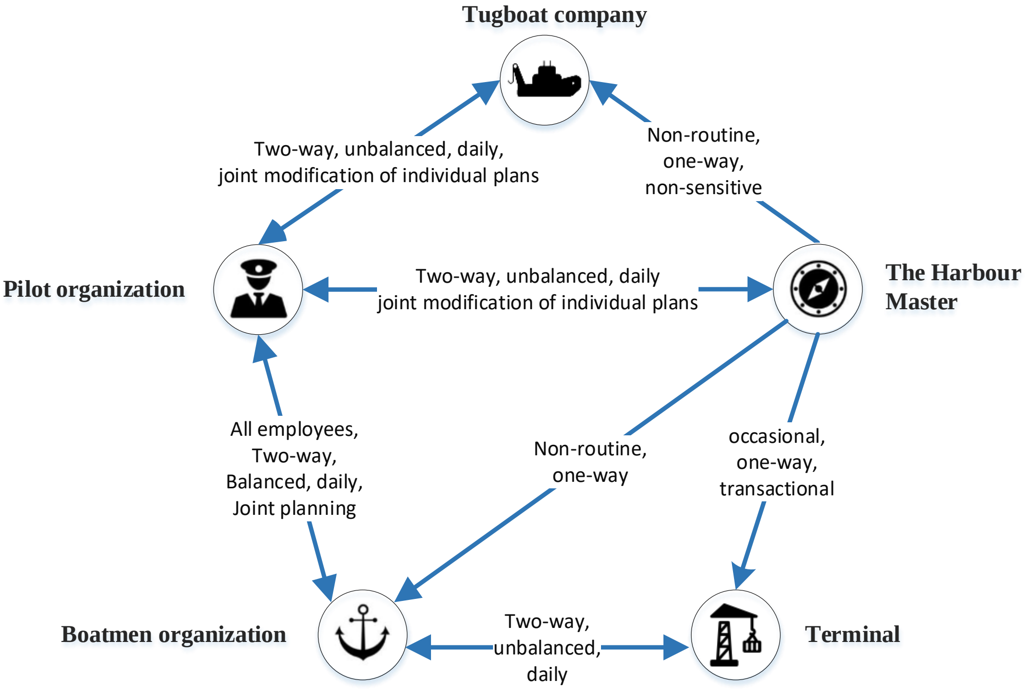

Figure 3.5. Current state of information sharing in the NC of the Port of Rotterdam

3.6 Discussion and managerial implications

The implementation of the model to the Port of Rotterdam gives rise to several implications for practice. Based on the extant literature, the following discussions emerge.

Firstly, our results show that the relationship potentials within the port vary substantially. While some pairs have the potential of reaching a Type 3 partnership, some pairs' potential is very limited. This means that not all the actors are willing to engage in strong relationships and the network of actors relationships is not composed of fully connected and equally strong relationships. These findings complement the current literature on port studies, which discusses cooperative strategies for ports without the distinction between the relationship type and actors involved (Lee and Song, 2017). The existing literature on port relationships is binary, characterizing actor relations as either cooperative or competitive (see the literature review section). We argue that, instead, a full spectrum of inter-organizational relationships, namely coordination, cooperation and collaboration, must be considered together with their unique attributes. Adding this distinction reduces the risk of counterproductive incentive design and policy-making for ports.

The diversities in relationship potentials are directly relevant for information sharing. Our findings show that information sharing between different actors is not equally facilitated. They vary from no direct information sharing to the frequent sharing of critical information. Therefore, we argue that it is unrealistic to assume that information can and will be exchanged equally well within the port. As a result, port digitalization efforts and the application of ICT tools for information sharing can only be effective if the differences in information sharing potentials are acknowledged. This point has remained substantially unexplored so far, despite the extensive literature on information sharing in ports (Fruth and Teuteberg, 2017). In this regard, our findings also suggest a need for tailored information-sharing strategies that fit closely to the actors' information sharing potentials. Questions to address in the future include *how* ICT tools should be designed and developed to support these diversities, and *which* information should be shared by *whom, how* and *when.*

The comparison of the current state of information sharing in practice, for the case study, with the information sharing potentials shows a perfect match between the two. It shows that when the potential allows, information sharing is practiced. Consequently, in order to advance information sharing practices it is necessary to approach this as an attribute of relationships and promote the relationships first, rather than targeting the information sharing on its own.

Relationships are not static. They can to be promoted to stronger relationships to enable more advanced information sharing. Various measures may need to be introduced to achieve this. The measures can be designed considering each pair's drivers and facilitators. For the illustrative case of the HM and tugboat company, this would imply the following. To promote the relationship, from the existing Type 1 partnership to Type 2 partnership, the HM that is the least motivated party should be incentivized. Measures should address customer service and flexibility for the HM, as cost efficiency and profit are not the dominant drivers for the HM in its relationship with the tugboat company.

Finally, our results provide an empirical validation of an important implicit assumption in the literature. Previous studies have highlighted the positive impact of cooperative relationships between the pilot organization and tugboat company on port effectiveness (Talley, Ng and Marsillac, 2014). Their implicit assumption was that these two actors are willing to cooperate. Our results confirm that considering their

Type 2 partnership potential, both parties have a strong willingness to engage in a cooperative relationship.

3.7 Conclusions and future work

In this study, we present an approach to assessing the relationship potentials between port actors. This topic is highly relevant to determining the potential for information sharing between the actors, which is at the core of port digitalization efforts. This is the first study that presents an approach that can be used by the port managers to assess the relationship and information sharing potentials.

We put forward an extension of Lambert's partnership model for ports. Our study shows that the partnership model of Lambert can be operationalized well for this problem. A first application of the approach was carried out for the port of Rotterdam. The different drivers and facilitators applied well to the port actors and can be assessed using surveys and interviews.

We arrived at a number of empirical findings, which gave rise to several managerial implications. We found that the relationship potentials vary strongly between port actors, which implies that also the potential for information sharing is unequal. This means, some actors are more willing to engage in stronger relationships and advanced information sharing than others. Based on this, we argue that port digitalization efforts and application of ICT tools for facilitating information sharing can only be effective if this diversity is acknowledged. Therefore, as opposed to the current binary approach in the literature, a full spectrum of inter-organizational relationships and their unique attributes must be considered when addressing port information sharing.

Further research could develop in different directions. Firstly, the data collected for this case study were obtained by interviewing single respondents from each organization, considered elite informants. The use of multiple respondents might generate different and possibly also more robust results. Secondly, this study has implemented and demonstrated the partnership model for one case, the Port of Rotterdam. Implementing the approach on new case studies and carrying out comparative studies or panel studies could help track the success factors of different port-cases and port structures, even as they develop through time. Thirdly, we note that actual relationship levels cannot be assessed with this model. Therefore, this approach could be complemented with models that assess the actual relationships within the port. Finally, this study could also be framed using action research to support the next steps to implement future cooperative relationships in ports.

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Appendix 3.A. Assessment of Drivers for Organization A in its relationship with Organization B

Drivers are motivations of your organization to engage in the appropriate level of business relationships with the service providers. Please fill in the boxes, answering the questions considering the following scale.

Very low	Low	Medium	High	Very high
①	②	③	④	⑤

Cost Efficiency

To what extent organization A's relationship with organization B reduce costs or improves asset utilization for organization A? such as;

① ② ③ ④ ⑤

- reducing service costs
- reducing information handling costs
- improving managerial efficiencies

If you marked cost efficiencies in the shaded area, respond to this question. If not, skip.

Do you think that the above-mentioned aspects are substantial competitive advantages for organization A?

No □ Yes □

Customer Service

To what extent does organization A's relationship with organization B improve the service provided to the vessel by organization A? such as;

① ② ③ ④ ⑤

- On time delivery of services
- Better tracking of movements
- Improving ordering processes
- Shortening turnaround times
- Shortening waiting times
- Improving operational processes

If you marked cost efficiencies in the shaded area, respond to this question. If not, skip.

Do you think that the above-mentioned aspects are substantial competitive advantages for organization A?

No □ Yes □

Flexibility

To what extent does organization A's relationship with organization B improve flexibility for organization A? such as;

① ② ③ ④ ⑤

- Flexibility in rescheduling due to vessel's delays
- Flexibility in rescheduling due to service provider's delays
- Flexibility in rescheduling due to extreme weather conditions

If you marked cost efficiencies in the shaded area, respond to this question. If not, skip.

Do you think that the above-mentioned aspects are substantial competitive advantages for organization A?

No □ Yes □

Profit Growth

To what extent organization A's relationship with organization B increase profit for organization A? such as;

① ② ③ ④ ⑤

- Growth in profit
- Growth in sales volume
- Market share stability

If you marked cost efficiencies in the shaded area, respond to this question. If not, skip.

Do you think that the above-mentioned aspects are substantial competitive advantages for Organization A?

No □ Yes □

Appendix 3.B. Assessment of facilitators for organization A in its relationship with Organization B

Facilitators are the factors which provide a supportive environment for the growth and maintenance of a partnership. Please fill in the boxes answering the questions considering the following scale.

Very low	Low	Medium	High	Very high
①	②	③	④	⑤

Corporate Compatibility

To what extent organization A and organization B are similar in terms of cultural and business related aspects? such as;

① ② ③ ④ ⑤

- Keeping commitments
- Seeing employees as long-term assets
- Valuing external stakeholders
- Commitment to partnership ideas
- Willingness to change

Management Philosophy

To what extent organization A and organization B are similar in terms of management philosophy? such as;

① ② ③ ④ ⑤

- Organizational structure
- Degree of top management support
- Types of motivation used
- Importance of teamwork
- Degree of employee empowerment

Mutuality

To what extent organization A and organization B have the skills for a mutual relationship? such as;

① ② ③ ④ ⑤

- Management skilled at two sided thinking
- Management skilled at taking the perspective of other organization
- Management skilled at expressing goals and sharing expectations
- Management having a longer-term view
- Management skilled at mutual respect
- Management willing to share financial information

Similarity

To what extent Organization A and Organization B are similar in terms of power ?such as;

① ② ③ ④ ⑤

- Financial strength
- Relative market share in their respective industries
- Productivity
- Technological sophistication

Do organizations A and B have shared competitors that tend to unite their efforts?	Yes ☐	No ☐
Are the key players in organizations A and B are in close physical proximity to each other?	Yes ☐	No ☐
Is there a willingness to deal exclusively with the partner?	Yes ☐	No ☐
Do organizations A and B have prior experience with successful partnerships?	Yes ☐	No ☐
Is the vessel a high-value end-user for organizations A and B?	Yes ☐	No ☐

4 Cooperation of the service providers by joint resource deployments: An impact analysis

This section explores the potential impact of cooperation between the service providers, empirically. We present an assessment using a port simulation model where the exchange of information has been made explicit. Cooperation is modelled as information exchange between the pilot organization and tugboat company for the deployment of pilots and tugboats.

First, section 4.2 provides a brief overview of the literature on cooperation among port actors. The vessel services and the associated modelling requirements are presented in Section 4.3. Next, the simulation model is designed and explained in Section 4.4. In Section 4.5, the experiments and the results are presented. In Section 4.6, the findings are discussed followed by the conclusion and future research directions.

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4.1 Introduction

Worldwide, the number and size of vessels calling at maritime ports are increasing (UNCTAD, 2021). This growing demand is putting pressure on port resources and infrastructures. Increasing vessel waiting times indicate that the ports struggle to handle this pressure (IMO, 2020). Ports aim to improve their performance by serving more vessels in shorter times (Talley and Ng, 2013, 2018), but achieving this goal is challenged by the complexity of operations. Many large ports have complex in-port navigation requiring pilotage and towage services offered by the pilotage and towage service providers. Recent port call statistics show that vessels spend up to 60% of their time in port waiting to be served (Nikghadam *et al.*, 2021). If these services are not available upon request, vessels incur high costs of waiting times.

Service providers can improve their services by expanding the capacity for their critical resources, such as personnel and fleet (Notteboom, Pallis and Rodrigue, 2022). However, resource capacity expansions are constrained, as they typically require high capital investments. Service providers can also improve their dispatching capabilities by better scheduling their existing resources. Pilotage planning (Wu, Jia and Wang, 2020) or tugboat scheduling (Wei *et al.*, 2020) are some examples (Wei *et al.*, 2020; Wu, Jia and Wang, 2020). Considerable effort has been made to improve individual service providers' performance. However, the pursuit of performance improvements in a cooperative manner has been remarkably limited.

Cooperation can take many forms (Huo, Zhang and Chen, 2018). But, a short definition of cooperation in our context was given by Talley et al. (2014): when parties work together toward a common goal rather than merely maximizing their own objective, they are cooperating. In ports, providers of the same service can cooperate by resource sharing. For example, terminals of a port can cooperate by sharing their berth and crane, which enables the idle resources of one party to be used by the other when needed, resulting in improved asset utilization overall (Gharehgozli, Roy and De Koster, 2016). However, resource sharing is not applicable to providers of different services, such as pilotage and towage service providers, who utilize different types of resources. In the literature, cooperation of service providers for different services is modelled by pooling and centralized planning of the resources (Talley, Ng and Marsillac, 2014). However, pooling resources may not also be applicable to practice considering the organizations’ business boundaries, particularly in decentralized ports, a dominant port model in major ports today, where the service providers are not governed centrally (The World Bank, 2007). Here, cooperation for the *deployment* of resources could be a promising alternative. But little is known about the operational strategies that the cooperating parties should adopt. This is the first gap that we aim to address.

The second gap is that research has focused on the benefits of cooperation for the port as a whole, while the impact on individual service provider performance has been overlooked. A crucial condition for the development of cooperation is to demonstrate its positive impact on all the cooperating parties (Van Der Horst and De Langen, 2008). For example, if cooperation would shorten the waiting time for one service provider and lengthen it for the other, even when the total waiting time reduces, this cooperation is less likely to be accepted. Therefore, considering service providers' perspectives for designing mutually beneficial strategies is vital. The third gap is that, so far, existing work has only theoretically discussed the potential benefits of cooperation between service providers, while there is no empirical study to back up such benefits quantitatively. This gap is also pointed out by Talley et al. (2014), yet it has remained unaddressed so far.

This study addresses the three gaps mentioned above. It contributes to the literature by exploring a cooperation strategy between vessel service providers that takes their perspective into account and quantitatively assesses the impact of the cooperation for the port and its service providers. To this end, we develop a simulation model in which information sharing between the service providers is explicitly modelled. The advantage of the simulation model, as opposed to the existing analytical models in the literature, is that it considers the common dynamics and stochasticity of the port operations, making it applicable to practice. We focus on services offered to vessels, and in particular on the effect of cooperation at the tactical and operational levels. We apply the model for the case of the port of Rotterdam. The results provide new empirical evidence about the magnitude of the impacts of cooperation.

The remainder of the paper is organized as follows. We provide a brief overview of the literature on cooperation among port actors in Section 4.2. The vessel services and the associated modelling requirements are presented in Section 4. 3. Next, the simulation model is designed and explained in Section 4.4. In Section 4.5, the experiments and the results are presented. In Section 4. 6, the findings are discussed followed by the conclusion and future research directions.

4.2 Literature review

Below we review the literature for studies on cooperation in ports and zoom in on cooperation between vessel service providers. Later we investigate the modeling approaches in these domains.

Ports provide a variety of services to vessels. In the literature, these services classify into two categories: cargo services and vessel services (Notteboom et al., 2022). Cargo services are offered for cargo transhipments through loading, unloading, and storage by terminal operators. The other category, vessel services are offered for the safe and timely maneuvering and positioning of vessels at sea and thorough harbour channels. Pilotage, towage, and (un-)mooring services are some examples. Both of these categories have been researched in the literature for understanding, measuring and improving the port's performance (Bichou, 2007). Cooperation was deemed to improve the performance of ports in providing both of these services. However, research has been predominantly on the cooperation of terminals for cargo services rather than cooperation between pilotage and towage service providers for vessel services. Although our focus is on vessel services within a port, we briefly summarize related literature on cargo services to discuss the impacts of cooperation for vessel services.

The literature shows that cargo services offered in a port improve through the cooperation of terminals. Terminals cooperate mainly by sharing resources such as quay cranes, berths, and stacking locations. According to Song (2002) and Lee et al. (2017), this cooperation improves their asset utilization and profitability. In fact, given the increase in cargo transhipment volumes in the past decade and the resulting pressure on terminal capacity, resource sharing has been instrumental in their performance (Pujats, Konur and Golias, 2021). Studies show that this form of cooperation has also helped shorten vessel waiting times (Budipriyanto *et al.*, 2015). Within the broader maritime transport system, cargo services benefit from the cooperation of ports with other parties, namely (i) freight forwarders (Heaver, 2010), (ii) shipping companies (Heaver, Meersman and Van De Voorde, 2001), (iii) inland transport companies (Song, 2002), and other ports (Woo, Pettit and Beresford, 2011; Cheon, Song and Park, 2018). According to these studies, much of the benefits of cooperation can be attributed to improved information sharing among the parties.

Concerning the research on vessel services, limited attention is paid to the cooperation of service providers. Instead, most of the literature is on the optimization of vessel services individually. For example, Kang et al. (2020) and Wei et al. (2021) investigated tugboat scheduling to minimize towage servicing times. Edwards et al. (2010) and Wu et al. (2020) looked into pilot planning to minimize pilotage waiting and transport times. Most of these earlier studies were deterministic, while recent studies such as Kang et al. (2020) considered time stochasticity. Despite the crucial role of service providers in determining the ports' performance, their cooperation has been remarkably overlooked. An important exception is a research by Talley et al, (2014). They introduce a mathematical model to argue that cooperation between vessel service providers should improve port performance. As the study was an analytical, empirical investigation of impacts would be useful to further substantiate their findings, broaden and potentially encourage its applicability to practice. The analytical approach also meant that the study did not address the dynamics and uncertainty that exists in port services.

Analytical approaches use mathematical expressions to describe the behaviour of the system. Optimization models and game theoretic approaches are some examples. Although elegant due to their mathematical tractability, these models provide a highly stylized representation of the system, which limits their application in practice. The many uncertainties and dynamics in port operations which were not included in these models have encouraged the growing implementation of simulation approaches (Ivanov, 2020). Existing simulation studies for cargo services include sustainable terminal management (Henesey, Notteboom and Davidsson, 2003), berth allocation (Yıldırım, Aydın and Gökkuş, 2020), terminal investments (Feng *et al.*, 2020) and crane scheduling (Gracia, Mar-Ortiz and González-Ramírez, 2019). Only one recent study used simulation for modeling the vessel services (Fransen and Davydenko, 2021). Including this latter study, no research has used simulation modeling to evaluate the impact of cooperation between vessel service providers.

In summary, the literature review shows that the cooperation among vessel service providers has largely been overlooked. The single exception concerns an analytical model, which leaves a clear research void for empirical investigations. We address this gap by means of a simulation model, with a case study for the port of Rotterdam. In following the services and the modelling requirements are described in more detail.

4.3 Vessel services: challenges and modeling requirements

The main indicator to measure port performance around vessel services is the waiting times of vessels (UNCTAD, 2021), mainly consisting of waiting time for pilotage and for towage. The deployment of resources, to minimize vessel waiting time, is challenged by several challenges that need resolution: the cost/service trade-off for individual service providers, the combinatorial problem of scheduling of vessels and service providers, and the stochasticity in service time and requirements. We detail these below.

The first challenge relates to the trade-off between the waiting times and service providers' resource capacities. Pilotage and towage service providers each have their own resources and utilize them to deliver their services. Pilots have high salaries and the time to train them is long. Tugboats require a large capital investment and high maintenance costs. So, even though, the higher the service providers' resource capacity, it is more likely for them to deliver their services on time, high resource capacity is costly and requires high capital investments. Therefore, making better use of resources is also vital for their business.

Secondly, it is a complex challenge to determine the deployment of resources such that services are provided on time and resources are used efficiently. To understand this, we briefly describe the process at hand. Vessel services for larger incoming vessels start with pilotage. When the vessel arrives at the port entry, it requests a pilot. The pilot is deployed from the pilot station and moves to the vessel. After the pilot has boarded the vessel, they order the tugboats depending on the vessel's class and weather conditions. Towage services are obligatory for big vessels. After the vessel has safely sailed through the port and arrived at its berth, service providers can move to their subsequent assignments. Outgoing vessels also require pilotage and towage services. If either of these resources is unavailable, service providers and vessels have to wait. On a typical day, each service provider serves multiple vessels after each other. The order of these assignments and the transportation time between them determines how efficiently their resources are utilized. If a service provider successively serves incoming and outgoing vessels, the time needed for transporting between the assignments is quite short. However, when two outgoing or two incoming vessels are assigned to a service provider successively, the transport time between these assignments becomes much longer. The combined effect of resource deployments will result in a specific order of services and, consequentially, depending on the dynamics of the arrival process, waiting times for the vessel, and the service providers.

We illustrate this challenge with an example of two vessels. Assume two vessels are ready to be served in the port: vessels A and B. Vessel A is an incoming vessel with the expected towage duration of 40 minutes. Vessel B is an outgoing vessel with an expected towage duration of 50 minutes. The pilotage times for vessels A and B are 100 and 120 minutes, respectively, but let's focus on towage operations only for simplicity. Both of the vessels require two tugboats. These two tugboats are available at the port entry, where the transport time to the meeting point with vessels A and B would take about 5 and 20 minutes, respectively. Since the tugboat company's available capacity is sufficient to serve only one vessel, one of the vessels must be prioritized. One option is to serve vessel A first, where the tugboats are in close proximity and would be able to start the towage in 5 minutes. By prioritizing vessel A, vessel B must wait 50 minutes (5+40+5) to be served. In this order, vessels A and B's average waiting equals 27.5 minutes ((50+5)/2). Alternatively, vessel B can be served first, which requires 20 minutes of transport time for the tugboats to meet the vessel. This order would result in a waiting time of 75 minutes (20+50+5) for vessel B, resulting in an average waiting time of 47.5 minutes ((75+20)/2). If the tugboats have to return to their base stations after completing their assignments, prioritizing vessel B would incur another transportation time of 20 minutes for each tugboat. This simplified example (Figure 4.1) shows that the individual service providers' performance and subsequent waiting times are quite different in different servicing orders.

However, if vessel B requests a pilot before vessel A, the pilot would be deployed to vessel B even though prioritizing vessel A would have been more efficient in terms of using free tugboats. In this example, if the tugboat company shares information about the tugboats' free capacity, the pilot organization could prioritize vessel A for deploying its pilots accordingly. This exchange of information for deploying resources in a cooperative manner can be beneficial for both vessel and service providers. Still, In many ports, resource deployments follow the simple rule of first-come-first-serve with very limited information sharing between the service providers (Nikghadam et al., 2021).

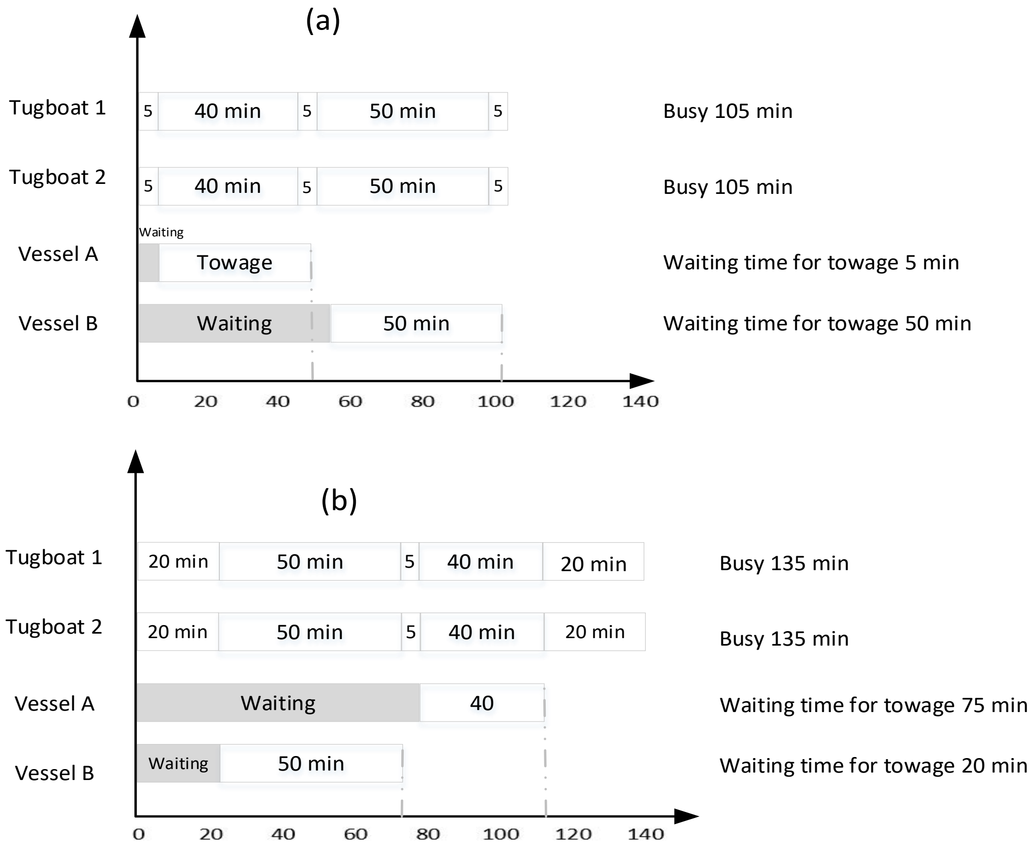

Figure 4.1. Effect of servicing order on vessel waiting times: (a) Vessel A served first (b) Vessel B served first

Another vital characteristic of port operations that affects the on-time delivery of port services arises from the dynamics and uncertainty of the processes. Dynamics indicates that not all vessels are ready simultaneously; some vessels may arrive or depart while the earlier vessels are getting the services. Uncertainty means that the vessel’s arrival time, departure time, service time, and requirements may change in practice. Despite modern developments such as single window information arrangements within ports, service providers are generally only updated approximately 6 to 3 hours before arrivals or departures, and updates are often unreliable (Veenstra and Harmelink, 2022). As a result, planning service deployment beforehand is not regarded as feasible and service providers are expected to be ready to act shortly after their services are requested.

According to the characteristics of port services mentioned above, a model that aims to study the performance of ports in providing vessels services needs to address the following requirements:

1. Consider the trade-off between the service providers' waiting times and resource capacities.
2. Define the correct sequence of operations for vessels and the service providers.
3. Explore different servicing orders for the resource deployment
4. Consider the dynamics and uncertainty in service times and requirements.
5. Include information sharing between the vessel and service providers.

4.4 The simulation model

4.4.1 Model outline

There exist a variety of simulation techniques, such as Discrete Event Simulation (DES), System Dynamics, and Agent-Based Modeling (ABM), each with its principal characteristics and use (Brailsford *et al.*, 2019). Given the requirements stated above, a Multi-Agent Discrete Event Simulation (MADES) model is preferred. Although this modeling technique has the inherent shortcoming of the hybrid modeling techniques, high modeling complexity, it enables addressing all the five requirements stated above. In our model, the pilot organization, tugboat company, and vessel are defined as agents of the ABM, whereas their process flows are modeled in Discrete Event Simulation (DES).

The schematic of the simulation model is shown in Figure 4.2. The base case (current state of the port) is shown with black-lined boxes and arrows, with messages annotated to the process steps. The sequence of operations is organized vertically in separate columns per actor. The cooperation scenario is indicated by red-lined boxes and arrows. The figures show that, in the new scenario, towage service providers inform pilots as soon as they reach peak demand. We explain the measure further in more detail.

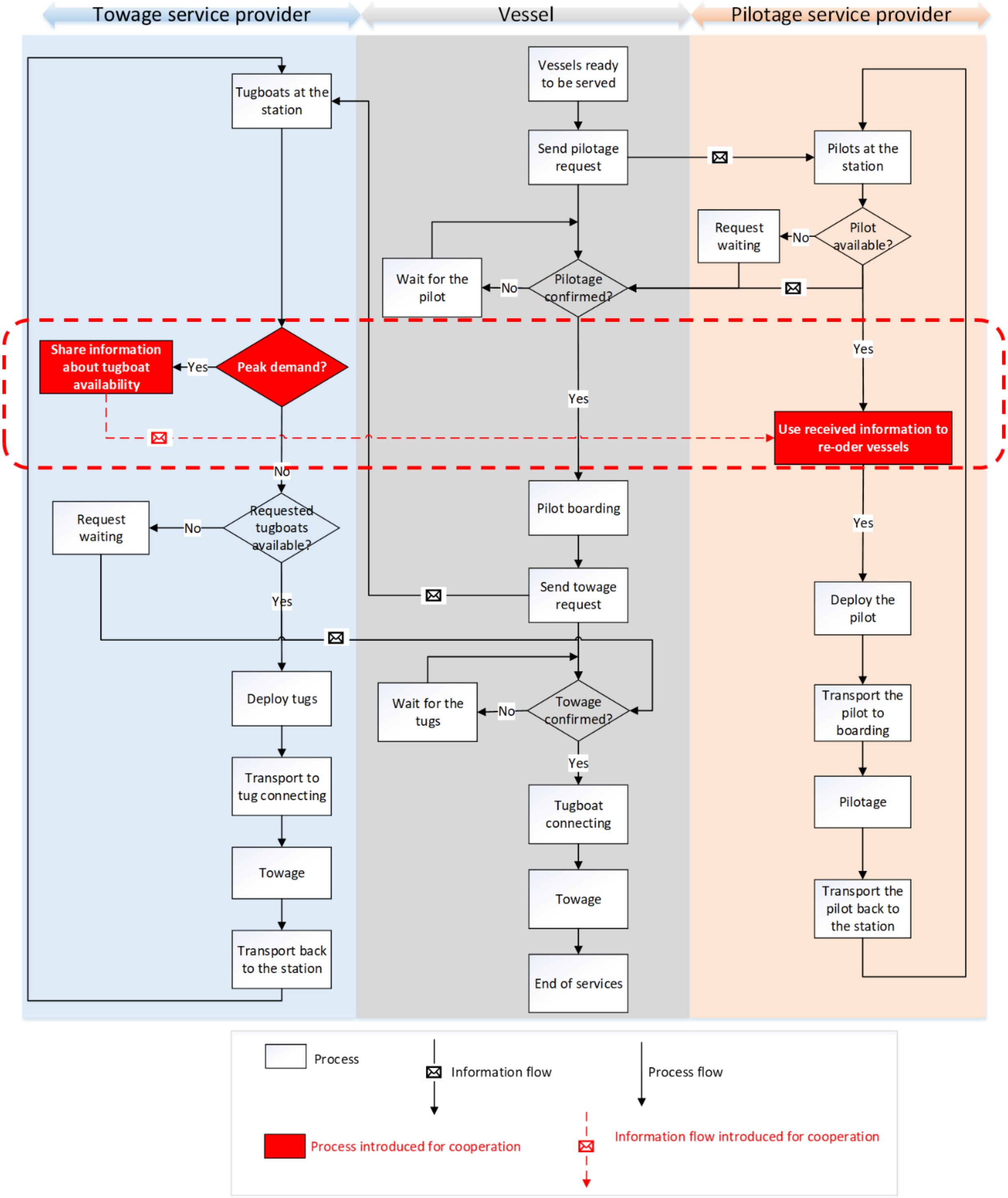

Figure 4.2. Schematic diagram of the simulation model

The model inputs, outputs, and simplifying assumptions are summarized in Table 4.1. Model parameters are the capacities of pilot organizations and tugboat companies. These two parameters are defined as the number of pilot crew members and the tugboat fleet size on duty at each moment. These parameters are free to choose and enable investigation of cooperation’s impact in various capacities. The average resource utilizations for the pilot organization and tugboat company are defined as the ratio of their resources’ busy time over total available time.

Table 4.1. Model attributes

Input data	Distribution of vessel arrivals per vessel class, mean, min and maximum sailing speeds per vessel class per river section, mean number of tugboats needed per vessel class per destination, pilotage requirements per vessel class, pilot resting stations, pilot boarding stations, pilot transport, tugboat resting stations locations, tugboat transport, tugboat meeting locations, sailing speed of pilot and tugboat, terminal's service time distributions per vessel class.
Outputs	Time series, mean and standard deviation of: Vessel waiting times for pilotage, vessels waiting for towage; pilotage lead times; towage lead times, Pilot organization and tugboat company's resource utilization.
Parameters	Pilot organization's capacity (crew on duty), Tugboat company's capacity (fleet on duty)
Scenarios	• Base case • Cooperative case (with information sharing for the cooperative deployment of resources)
Simplifying assumptions	• Pilots and tugboats are available 24/7. • A single type of pilot. • A single type of tugboat. • A single tugboat and pilot service organization.
Stochasticity	Vessel arrival, departure and terminal service times, vessel sailing speeds, pilotage and towage service times, pilot and tugboat transfer times
Validation	Expert (face validity) and statistical validity
Software	Anylogic 8.7.8

4.4.2 Implementation: the case of the Port of Rotterdam

The port of Rotterdam is the largest in Europe, with about 30,000 seagoing vessels calling the port annually. The Port of Rotterdam is a landlord port where the port authority acts as a regulatory body and as a landlord, while private companies carry out port services, including pilotage, towage, and cargo services. Historical port call data of the port of Rotterdam for two months (June-July 2017) was used as the data set (Verduijn, 2017). The data includes, among others, historical information about visiting vessels' classes, designated berths, the number of tugboats required, pilotage times, and turnaround times. A comparison of monthly and yearly data confirmed that this period is representative of yearly traffic (Verduijn, 2017). From this data, we derived the vessel arrival rates (avg. 74 vessels per day) and their distribution over different vessel classes. Vessel classes are determined by their length and draught, as shown in Table 4.2. Other model inputs, such as geographical inputs, including length of the river sections, berth locations, pilot and tugboat boarding, and resting stations, were obtained from the port's map and modelled accordingly. The pilot organization currently has 220 registered pilots. All these pilots are independent contractors that are registered with the pilotage association. They work based on different shifts and as per the pilotage requests. Thus, at any point in time, the available on-duty pilotage capacity is relatively small compared to the total registered pilots. The total number of tugboat fleets also varies throughout the year as the tugboat companies may decide to operate part of their fleet in nearby ports. We have established levels of pilotage and towage service providers crews and fleets on duty, using a recent survey report (Vermeulen, 2020). Port rules and regulations regarding the sailing speeds of different vessels, pilotage, and towage requirements per vessel class were obtained from the port call information guide of the PoR (Port of Rotterdam, 2021).

Table 4.2. Port call statistics for the period of two months (June-July)

	Class 1	Class 2	Class 3a	Class 3b	Class 4	Class 5	Class 6	Total
Length (m)	<120	120-200	200-300	200-300	>300	>300	>300	
Draught (m)			<14.3	>14.3	<14.3	14.3-17.4	>17.4	
Number	1750	2062	685	89	154	21	19	4780

The pilotage and towage service times, sailing speed of vessels through the harbour, and the required resources depend on the specific vessel class. Table 4.3 provides the modelled number of tugboats required in the PoR for each vessel class. The data show that all vessels required one pilot.

Table 4.3. Number of tugboats per vessel class

	Class 1	Class 2	Class 3a	Class 3b	Class 4	Class 5	Class 6
Required number of tugboats for incoming vessels	0	0	2	3	2	2	4
Required number of tugboats for outgoing vessels	0	0	2	2	2	2	3

4.4.3 Verification and validation

Model verification assesses whether the computerized model is implemented correctly, while model validation substantiates if the model is accurate enough for the model's intended purpose (Sargent, 2011). We verified the model by checking the output process logs and the animation while performing the test runs. This stage of verification included the tracing of event sequences, consistency checks (vessels, pilots, and tugboats used), and the analysis of collective statistics of processes.

For validation, we employed two techniques, expert and data validation. For expert validation, we approached a port operations expert, a senior policy maker at the port of Rotterdam Authority, and presented the model's animation to receive feedback on its face validity. Minor modifications were suggested, after which the model was revised and further data validation could be conducted.

For data validation, the simulation model was run for six months, and the output data was generated. A warm-up period of the model was set to two weeks, where no data was collected. We compared the pilotage lead time obtained from the simulation model with the sample historical data -- rather than the turn-around time, as this was used to calibrate the model. The data validation results (Table 4.4) showed that the deviation between the simulation's output and sample data was less than 5 % for all vessel classes except class 6, which represents the largest vessels. This class has particular service requirements, such as pilots with specific pilotage certification and port traffic rules, which typically cause extra waiting times in practice. Such certification requirements and traffic rules are not included in the model. In addition, due to the very irregular arrival of this vessel class (less than 0.5 % of the time), the simulation model still shows a comparably high deviation. Nevertheless, the simulation model outputs are highly accurate for other vessel classes. Therefore, the model is validated given that it performs satisfactorily in replicating the defined purpose.

Table 4.4. Data validation; comparison of average pilotage lead time; sample data versus simulation output

		Class 1	Class 2	Class3a	Class3b	Classs4	Class 5	Class 6
	Vessel Distribution	37%	43%	14%	2%	3%	0,5%	0,5%
Average pilotage lead time for Incoming vessels	Sample data (min)	200	176	168	242	167	192	430
	Simulation output (min)	201	175	174	231	164	199	330
	Deviation (%)	**0,9 %**	**0,8 %**	**3,5 %**	**4,8 %**	**2,4 %**	**3,4 %**	**26,4 %**
Average pilotage lead time for Outgoing vessels	Sample data (min)	165	129	125	124	131	158	174
	Simulation output (min)	162	134	128	131	132	164	230
	Deviation (%)	**1,8 %**	**4,0 %**	**2,6 %**	**5,1 %**	**0,5 %**	**3,9 %**	**24,0 %**

4.5 Experiments and results

This section presents the design and results of two sets of experiments: the base case and the cooperative case. First, we experiment with the current situation and refer to this as the base case. The base case experiments are carried out to improve our understanding of the current state of the port performance regarding vessel waiting times and the service providers’ resource utilization. To keep our case generic, we conduct experiments for various parameter combinations for pilot and tugboat capacity. Section 4.5.1 presents the design and results of the base case experiments. Next, we propose a cooperation strategy based on the insights gained from the base case. In section 4.5.2, we experiment with the cooperative case, compare it with the base case and analyze the performance enhancements.

4.5.1 Base case – no cooperation

This subsection presents the base case experiments. The data presented in Table 4.1 and Section 4.4.2 were used as input for the experiments. The experiments were carried out for a run length of 6 months.

First, we established a base level of reasonable capacities for the pilot organization and tugboat company. We varied the pilot organization’s capacity for randomly picked pilot team sizes between 40 and 80. We observed that if the pilot capacity value is reduced beyond 60, the vessels started lining up for the pilotage services with increasing waiting times. By increasing the pilot organization’s capacity, it is determined that a minimum of 76 pilots are required to reduce the average vessel waiting time to be below one minute. We conclude from the initial simulation experiments that the reasonable capacity range for the pilot organization is between 62 and 76 pilots. Next, similarly, we varied the tugboat company’s fleet capacity from 12 to 30. When the tugboat capacity was below 14, vessels experience strongly increasing waiting times for the towage, indicating that tugboat capacity was too small. Vessel waiting time for the towage became negligible when the the tugboat capacity was above 22. Therefore a reasonable capacity range for the tugboat company was found to be between 15 and 22.

In the next experiments, we focused on capacity combinations for the pilot organization and tugboat company within the reasonable capacity ranges. We selected five capacity points for each provider. Figure 4.3 illustrates the resulting waiting time of vessels from these 25 experiments.

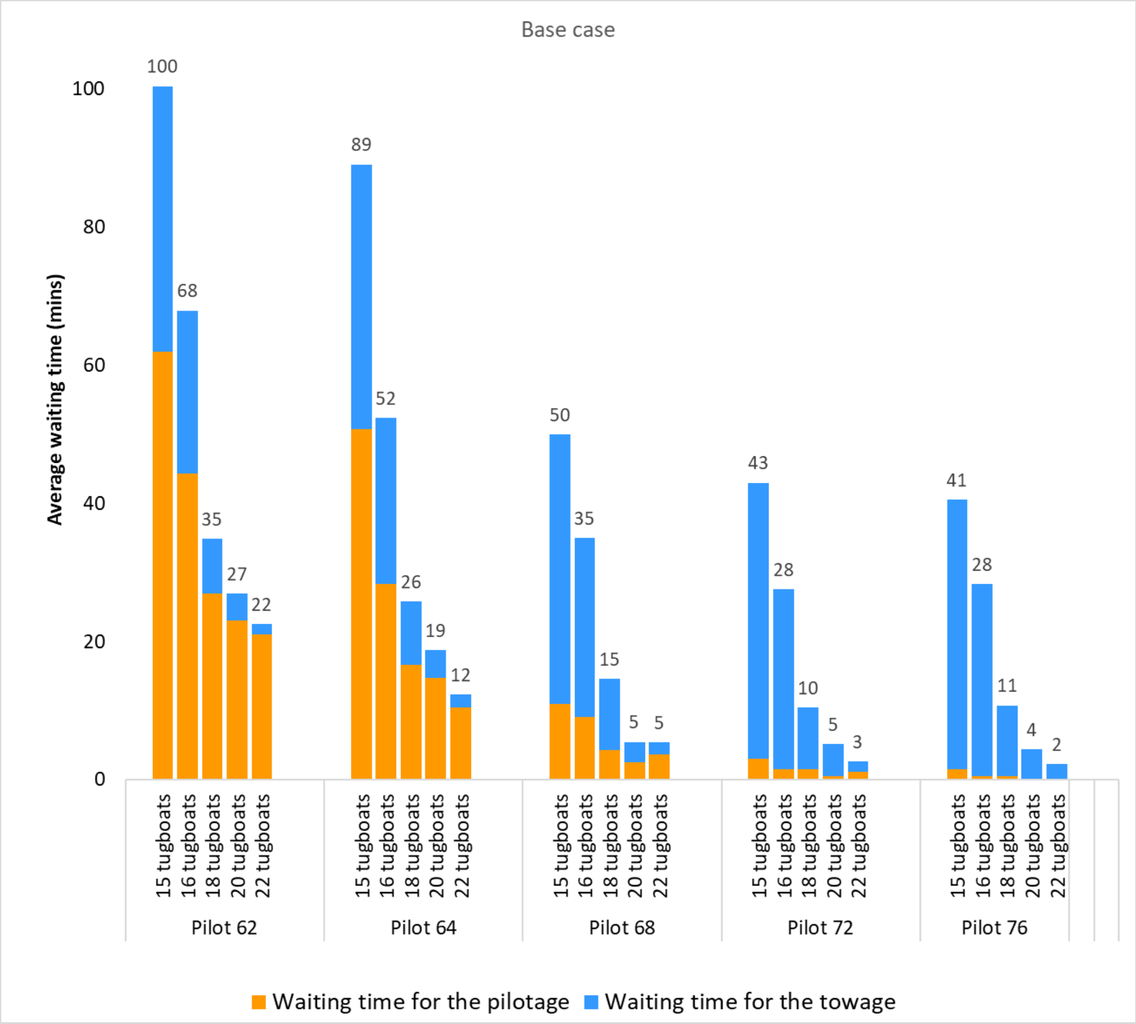

Figure 4.3. Average vessel waiting time for services under various capacities; base case

It is clear from Figure 4.3 that with the increase in resource capacities, the waiting time of vessels for the pilotage and towage decreases. As expected, the total vessel time is affected by the capacities of both the service providers, i.e., pilots and tugboats. Interestingly, however, the pilot organization's performance (Orange bars in the figure) is much more sensitive to tugboat capacity, than the reverse. For instance, when the pilot capacity is kept at 64, the vessel's average waiting time for pilotage ranges between 51 and 10 minutes respectively depending on the vessel's waiting time for towage service. While the performance of the pilot organization depends on that of the tugboat company, the reverse is not significant. For example, when the tugboat capacity is 15, waiting times for the towage vary only slightly between 38 and 44 minutes across different pilot capacities, although the waiting time for the pilotage varies between 2 and 62. This asymmetric dependency can be explained by the extra time pilots have to spend on board, waiting for the towage. As the pilotage boarding happens prior to the tugboat connecting, vessels and pilots incur additional waiting times while waiting for the towage services to start. Thus, smaller tugboat capacities will affect the pilot's performance by additional waiting times, affecting further pilotage services in subsequent assignments. In smaller pilot capacities, this dependency is found to be as big as 66%.

Next, we compare resource utilization and waiting times, per actor. Figure 4.4. (a) concerns the pilot organization, where cross marks indicate their average resource utilization and bars indicate the average waiting time for pilotage. Similarly, Figure 4.4. (b) shows the average resource utilization of the tugboat company and average waiting times for towage. In both, the error bars show the variation in waiting times for different capacities of the other service. The differences in error bars again indicate the asymmetric dependency discussed above.

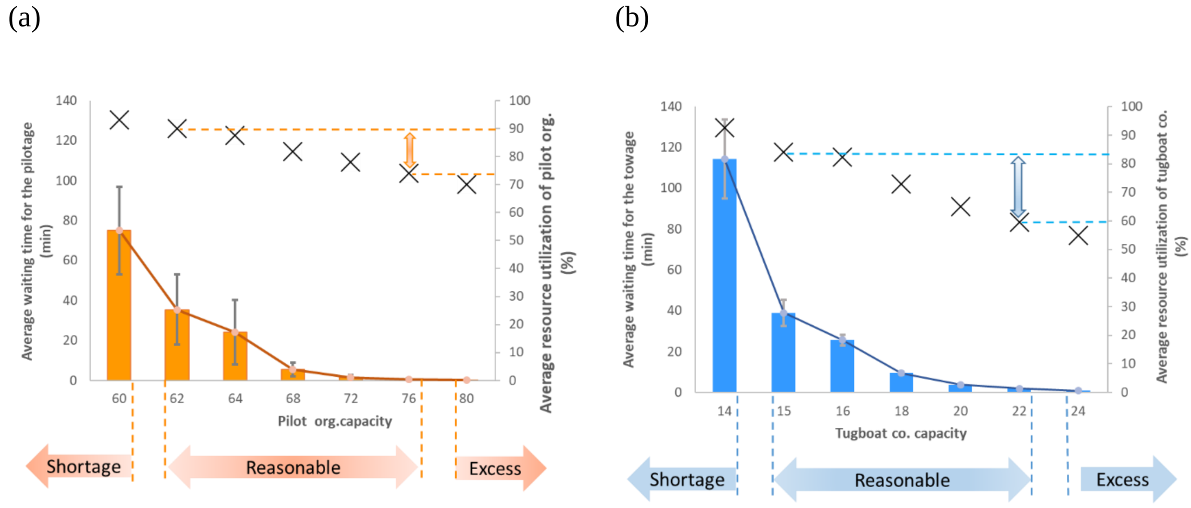

Figure 4.4. Average resource utilization for the pilot organization (a) and the tugboat company (b); both for the base case

Figure 4.4. (a) and (b) show that both resource utilization and waiting times vary more strongly for the tugboat company. Resource utilization for the pilot organization in the reasonable range is between 74% and 93%, while the tugboat company's resource utilization in the reasonable is between 60% and 86%. These figures show that waiting times can go up to almost 140 minutes for towage but are always less than 100 minutes for pilotage. In short, the experiments indicate a relatively low and relatively sensitive resource utilization for the tugboat company compared to that of the pilot organization, at nearly equal waiting times.

Given that, by definition, the resource utilization of an organization does not only depend on its resource capacity but also on the demand for the resources (Cachon and Terwiesch, 2006) we study the demand for pilots and tugboats in more detail. To investigate this effect, we set the pilot capacity to a sufficiently large number so that all the pilotage requests could be satisfied upon request; here, a value of 100. Figure 4.5. (a) shows the variation in demand for pilots on a random day. By analogy, we set the tugboat capacity to a sufficiently large number, in this case, 40, and obtained the demand for tugboats. Figure 4.5. (b) shows the variation in demand for tugboats throughout the same day. Note that the parameter values (100 and 40) are set for experimenting purposes and do not impact the outputs as long as they represent a situation of excess capacity. As the demand pattern of each day is quite unique due to the stochasticity of demand, we use the probability distribution for an overall impression. Figure 4.6

illustrates the probability distribution function of the demand for pilots and tugboats over the course of half a year.

A comparison of demand pattern snippets in Figure 4.5 shows that the peak demands for the pilots and tugboats do not necessarily occur at the same time. This observation can be explained by the fact that the demand for pilots depends on the number of vessels requiring a service, whereas for the tugboats it depends on vessels' sizes too. For instance, the arrival of several small vessels may create a peak demand for the pilots but not for the tugboats, while the arrival of a few big vessels still can create a peak demand for the tugboats.

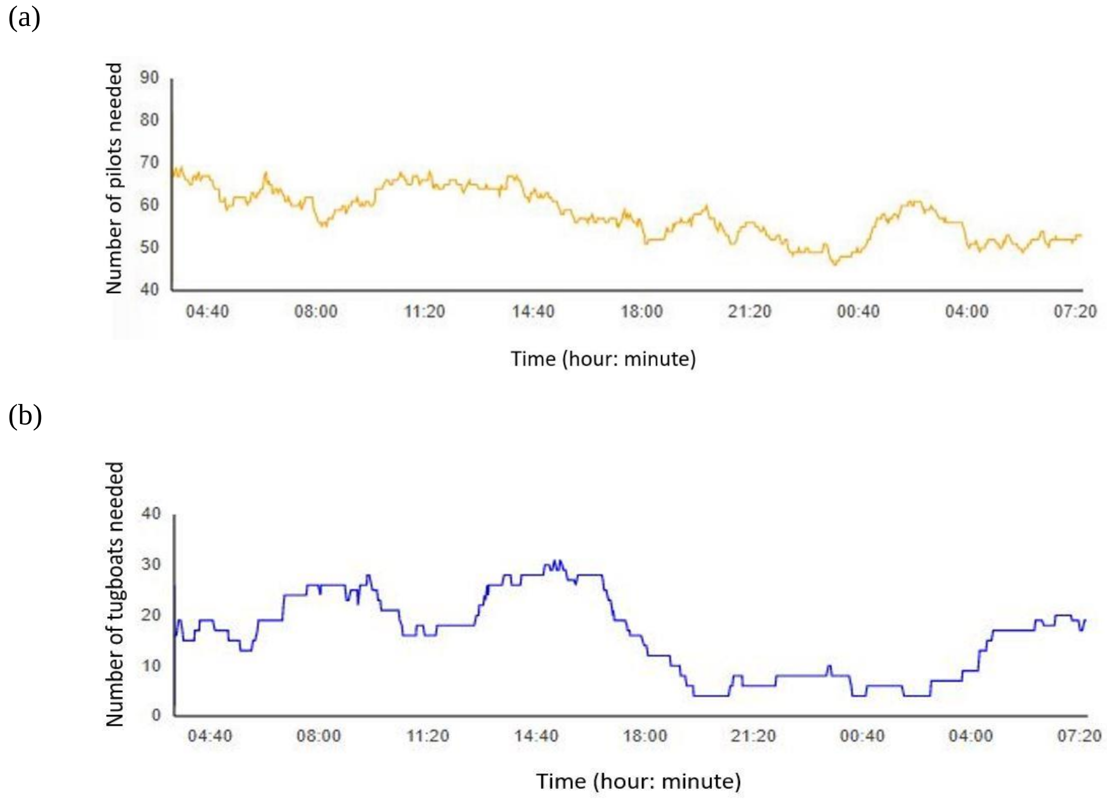

Figure 4.5. A snapshot of the demand for the pilots (a) and tugboats (b) in a (random) day

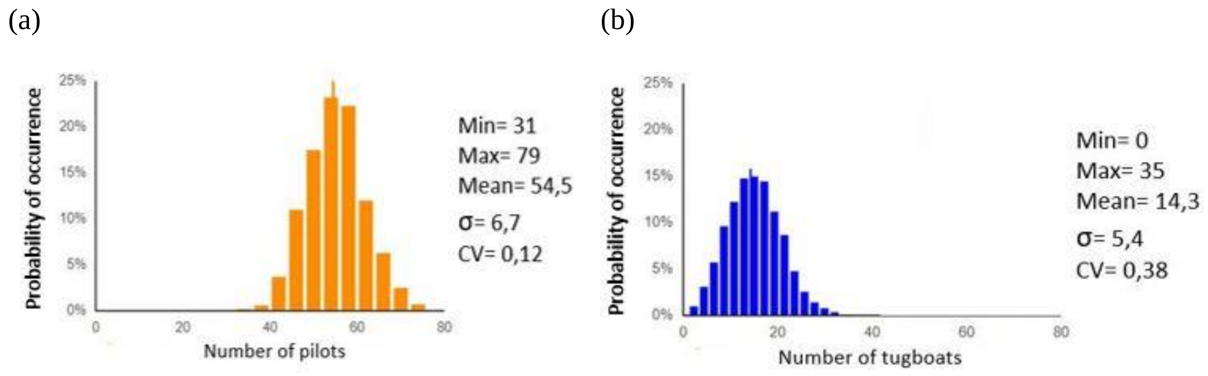

Figure 4.6. Distribution of demand for pilots (a) and tugboats (b)

Figure 4.6 (a) shows that the demand for pilots ranges between 31 and 71. The mean demand for pilots is 54 and the standard deviation is 6,7. The demand for tugboats ranges between 0 and 35 with a mean of 14 tugboats and a standard deviation of 5,4. The coefficient of variation CV measures the variability in distribution around the mean; for pilotage and towage these are 0.12 and 0.38 respectively. This shows that the demand for the tugboat company is three times more variable than the demand for pilots. This variability explains the earlier results regarding the lower average resource utilization for the tugboat company.

Translated into practice, the above implies that the towage is the more vulnerable and likely to become the bottleneck in peak demands, which also negatively impacts the pilot organization’s performance.

4.5.2 Cooperative case

Based on the insights gained from the base case, presented in section 4.5.1, we develop a cooperation strategy in this section and present the results of its assessment. Our aim is to define a solution that addresses the key problem of towage waiting times in peak demands.

We design the cooperation strategy inspired by the Theory of Constraints (Goldratt, 1990). The Theory of Constraints is a management paradigm that explores the performance improvements for systems where their processes are constrained by capacity. One way to improve such systems’ performance is to *subordinate the environment around the constraint by regulating the inputs and outputs of processes* so that the bottleneck can operate at maximum.

In our case, the port’s performance is constrained by towage, which becomes a bottleneck if overburdened. Subordinating the environment by adjusting the inputs to the constrained service can be done by adjusting the servicing order of vessels, which is now first-come-first-serve. In other words, while the towage service provider is the more vulnerable, the solution is upstream. We arrive at the following insights:

(1) Providing on-time towage services with unregulated inputs requires a large tugboat capacity, which is not cost-efficient from the tugboat company’s perspective. As fleets cannot be dimensioned only for peaks, long waiting times are inevitable with the current service rule.

(2) Waiting time for towage also negatively impacts the performance of the pilot organization. This performance dependency creates an incentive for the pilot organization to help shorten the vessels waiting time for towage.

Considering the above we propose the following cooperation strategy using information exchange: when the tugboats’ available capacity drops below a certain threshold, the tugboat company signals the pilot organization, sharing information about the current fleet capacity and location of tugboats. The threshold is defined as the percentage of the tugboat fleet capacity which is free for the next services. The pilot organization is asked to use this information to prioritize vessels with smaller towage requirements to temporarily reduce the peak demand for towage. This prioritization is based on the number of tugboats for each vessel, the proximity of the tugboats to be served, and the expected towage duration. For instance, vessels that require fewer tugboats for shorter towage durations and are close to where the tugboats finish their earlier assignments are prioritized. In the following, we experiment with the suggested strategy and report the results. We initially set the threshold free capacity to be 30%.

Figure 4.7 (b) shows the total waiting time of vessels in various capacity combinations for the cooperative case while Figure 4.7 (a) presents the results in the base case.

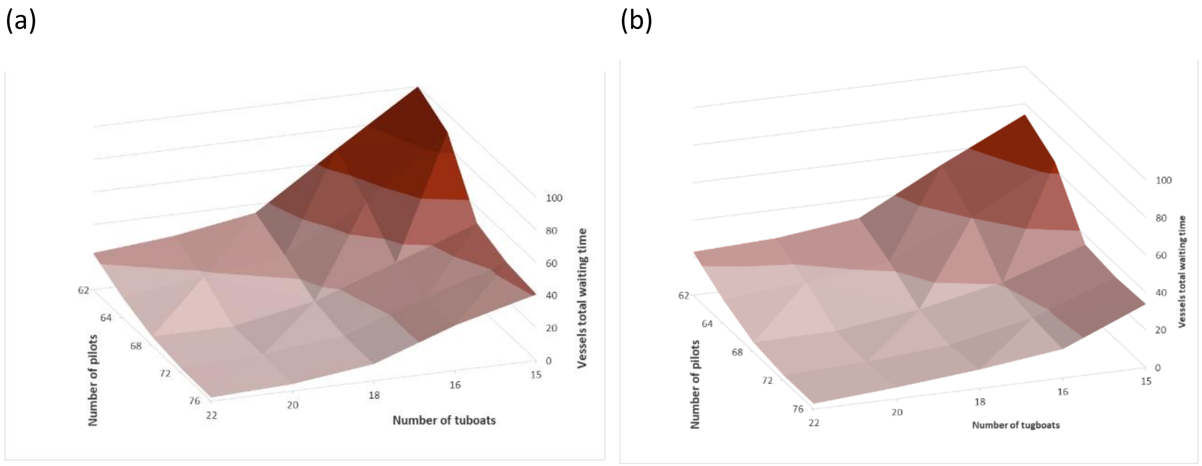

Figure 4.7. Total waiting time of vessels; base case (a) and cooperative case (b)

It is clear from the above figures that cooperation reduces waiting times considerably. As expected, tight capacity combinations give the highest gain. Next, as for the base case, we explore the waiting times for pilotage and towage services and present the results in Figure 4.8.

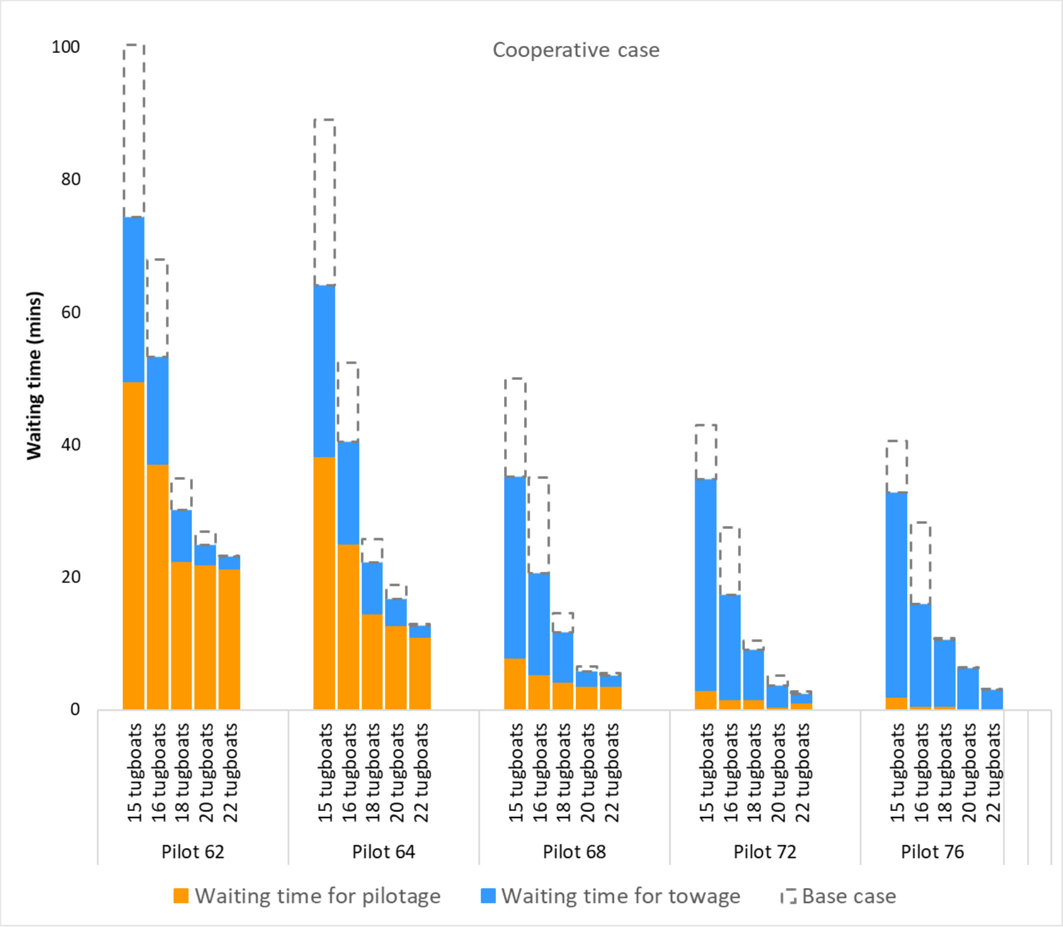

Figure 4.8. Vessels waiting time in various resource capacities; cooperative case

The comparison of Figure 4.8 and Figure 4.3 shows that the impact of cooperation depends on the service providers' capacity, reaching a 25% and 30% reduction in vessel waiting times for pilotage and towage, respectively. Again, time-savings are larger when the capacities are smaller. As the resource capacities increase, the vessel's waiting times as well as time-savings decrease.

As an example, in the capacity combination of 62 pilots and 16 tugboats, the average waiting time for the pilotage and towage is 25 and 12 minutes, respectively. These figures were 49 and 25 minutes in the base case (Figure 4.3), suggesting a time savings of 16% and 32 % for the pilotage and towage, respectively. In this capacity combination, these improvements from cooperation are equivalent to adding two more pilots. In bigger capacity combinations, e.g., 76 pilots and 20 tugboats, no time-saving are observed.

Figure 4.9 shows the impact of cooperation on individual service providers. It shows that cooperation is beneficial for both service providers. By cooperation, the frontiers of capacity-waiting times are shifted downwards for both, indicating a better utilization of their resources.

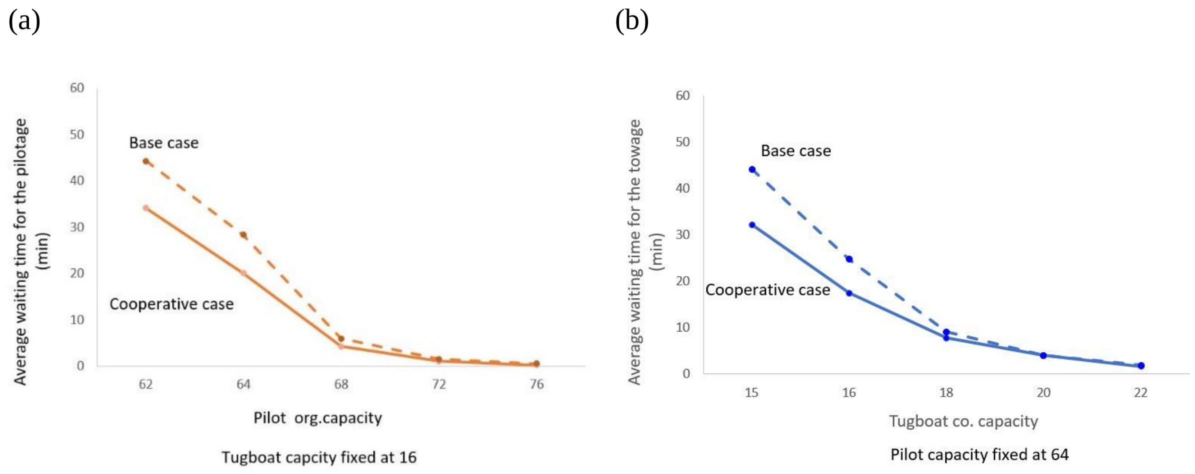

Figure 4.9. Average waiting time of vessels for the pilotage (a) and towage (b) in the base and cooperative case

In order to understand the impact of cooperation on each vessel class, we compared the average waiting time of each vessel class in the base case with the cooperative case in Figure 4.10. The pilotage and towage waiting times are presented in Figure 4.10 (a) and Figure 4.10 (b) respectively. As the cooperation strategy is in effect when vessels are waiting to be served, by better use of available resources, the average waiting time of all vessel classes reduces (e.g. 0-3 minutes for the pilotage and 0-9 minutes for the towage waiting times). However, these time reductions are bigger for some vessel classes than others. Note that the towage waiting time for vessel classes 1 and 2 in both cases is zero, as these two classes do not require towage assistance.

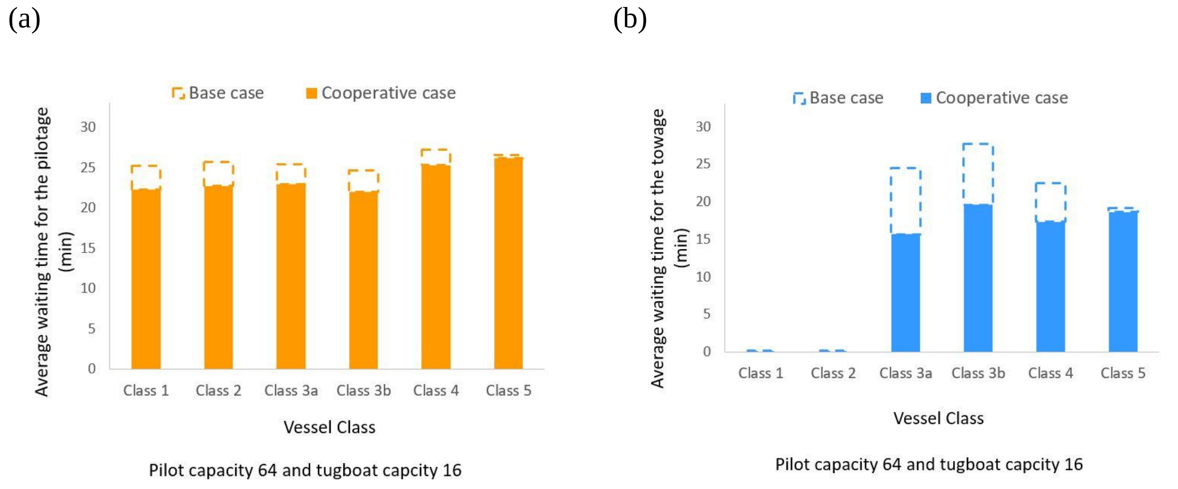

Figure 4.10. Comparison of the average waiting time of different vessel classes for the pilotage (a) and towage (b) in the base and cooperative case

4.5.3 Sensitivity analysis of threshold

In the above, the assumption was that the tugboat company informs the pilot organization when it reaches its 30% fleet capacity as the threshold limit. In this subsection, we conducted a sensitivity analysis to test the impact of the threshold limit on the experiment results i.e. waiting times. For this purpose, we conducted two more sets of experiments with threshold values of 65% and 100% and compared them with the results of the 30% threshold limit. The 65% threshold means that the cooperative deployment of resources starts when the available tugboat capacity reaches its 65% fleet capacity, while the 100% means the service providers always cooperate. Figure 4.11 shows the average waiting time of vessels in various thresholds when the pilot organization's capacity is fixed at 64. We chose this pilot capacity as an example. The observations were similar for other pilot capacities.

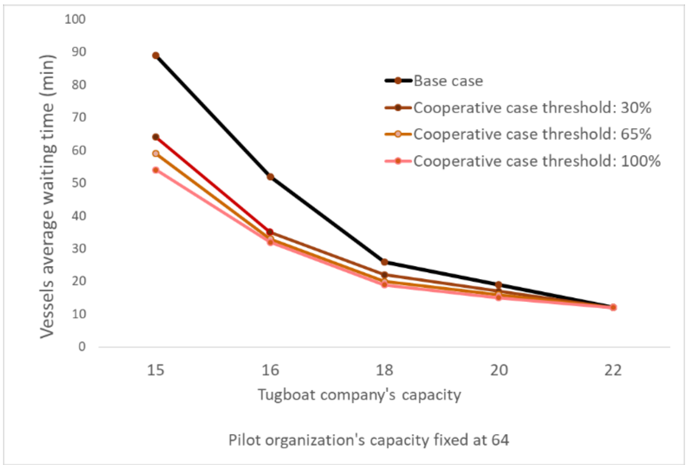

Figure 4.11. Sensitivity analysis of the cooperation thresholds

Figure 4.11 shows that the bigger the threshold values will result in smaller vessels' waiting times. This means that the earlier the cooperative deployment of resources starts, the bigger the positive impact. However, the improvement in the performance due to cooperation is higher when the threshold limit reaches from base case to 30% than from 30% to 65% and so on. This suggests that although the higher level of cooperation, i.e., 100% threshold, is most beneficial, the smaller levels of cooperation create a relatively greater impact on the performance improvements. Note that, as cooperation involve significant costs for information sharing, the threshold is an important parameter to fine-tune the cooperation.

4.6 Discussions and conclusions

This section summarizes the key findings and managerial insights from the simulation experiments, concludes the paper and suggests future research directions. The simulation of port vessel services provided by pilotage and towage, under stochastic arrivals of vessels of varying classes, revealed the following patterns of importance:

- The port's performance in providing on-time vessel services is constrained by towage, i.e., it becomes a bottleneck if overburdened. The pilot organization is able to offer on-time pilotage services (with less than 5 minutes of waiting time) with an average resource utilization of around 75%, while this figure is way smaller (around 60%) for the tugboat company. The lower average resource utilization for the tugboat company indicates that providing on time towage services requires a large tugboat capacity, which is not cost-efficient from the tugboat company's perspective. Therefore, the occurrence of longer waiting times for towage is more likely, making the towage service provider more vulnerable.

- Waiting time for towage is not only relevant for the vessels and the tugboat companies but also for the pilot organization. Our results show that at a fixed pilot capacity, the waiting time of vessels for the pilotage services depends on the towage waiting times and varies significantly. These results indicate that waiting time for towage negatively impacts the performance of the pilot organization. This dependency is highly relevant for practice given that it can create incentives for the pilot organization to help shorten the waiting times for towage. Yet, it has been widely overlooked in the literature. Port managers can emphasize this dependency to incentivize the pilot organization's involvement in the development of cooperation in ports.

- Peak demands for the pilotage and towage services typically do not occur at the same time. The demand for pilots depends on the number of vessels requiring a service, whereas the demand for tugboats also depends on vessel size. Making a distinction between these two is important when addressing peak demand for port services.

This study contributes to the literature in the following ways:

First, it takes the service providers' perspective into account, acknowledging their business boundaries, for proposing the cooperation strategy. The proposed strategy is based on information sharing for the cooperative deployment of resources in towage peak times. Towage peak times are signalled to pilots when fleet availability reaches a pre-specified threshold. The advantage of this strategy is that it is relatively simple and applicable in practice, even for modern decentralized ports with self-governed service providers. As such, it complements earlier studies in the literature, where cooperation between service providers involves the pooling of resources (Abou Kasm, Diabat and Bierlaire, 2021).

Secondly, it shows the mutuality of benefits for the individual service providers as well as the port as a whole by quantitatively assessing the impact. Our results show that cooperation is beneficial for the performance of the whole port as well as that of individual service providers. Ports can achieve time savings of up to 30% in total vessel waiting times. For the pilotage and towage service providers, the possible time savings are up to 25% and 30%, respectively. The added value of cooperation is bigger when resource capacity is lower. This provides empirical support to prior work (Talley, Ng and Marsillac, 2014) which argued that cooperation has positive impacts. Translating these time savings and improved resource utilizations into cost savings would be necessary for investment decisions and could be interesting grounds for further research. Finally, we acknowledge that cooperation requires a willingness from the parties to share information and adapt their independent practices. Our earlier work (Nikghadam, Rezaei and Tavasszy, 2022) confirms that both the pilot organization and the tugboat company are willing to engage in the proposed form of information sharing. The result that both parties improve their performance is an important incentive for their participation.

In summary, this study investigates the impact of cooperation between pilotage and towage service providers. Cooperation between these service providers is modelled as information sharing for the deployment of pilots and tugboats. The performance improvement is expressed by a reduction in waiting times of vessels for services. We presented a generalizable simulation model of the port in which this information sharing is explicitly modelled. A first application of the model is shown for the Port of Rotterdam. The model can be adapted and used by other ports. Experiments with the base model, without cooperation, provided new insights for the design of an effective cooperation strategy. The results show that with cooperation all actors such as pilotage, towage and vessels - can achieve significant time savings of up to 30%. Highlighting this mutual benefit of cooperation can incentivize service providers to cooperate. This study is another call to move beyond ad-hoc synchronization of port operations towards a systematic cooperation.

The model still has some limitations which have to be considered when using the results in practice. Firstly, the influence of changes in towage requirements due to external conditions, such as the weather, is ignored. As the number of tugboats required for serving vessels, in practice, is sensitive to visibility and wind, we expect that considering weather conditions and increasing the variability for tugboat demand will increase the need and positive impacts of cooperation. Future research may explore this argument further by considering different weather conditions. Probably this will make the cooperation more attractive for practice. Secondly, heterogeneity in service demands and the related specialisations of tugboats and pilots are disregarded. Future research could add more detail to the simulation model by including the pilot specialisations and tugboat's bollard pull force to explore the analysis of benefits in practice. Finally, our analysis focuses on the impact of cooperation in terms of time savings, as this is the major driver for the value of nautical services to vessels. Translating these time savings into cost savings would be necessary for investment decisions and could also be interesting ground for further research

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5 Joint scheduling of vessels and service providers in the port call process

This chapter formulates a mathematical model for join scheduling of vessels and service providers. We test objective functions based on the best overall port capacity utilization, a minimal level of service, the best overall port capacity utilization, and the currently prevailing first-come-first-serve approach. We demonstrate the application of the model using the data from the Port of Rotterdam.

First, section 5.1 introduces the background. Section 5.2 reviews the literature on scheduling vessel services. Section 5.3 briefly specifies the problem characteristics and assumptions on which the model is built. Section 5.4 presents the mathematical formulation of the model. Section 5.5 presents the solution of the model for a numerical example and discusses the findings. Section 5. 6 concludes the chapter.

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S. Nikghadam, R. Vanga, J. Rezaei, L. A. Tavasszy, “Proactive joint scheduling of vessels and service providers in the port call process”, Manuscript under review.

5.1 Introduction

As trade is increasing and maritime traffic is growing, ports are getting busier, bigger vessels are calling at ports more frequently, occupying more services for longer (UNCTAD, 2022). As a result, the usual practice of accommodating all vessels on a first-come-first-serve basis is becoming increasingly challenging to maintain. Generally, when confirming requests from vessels for arrival or departure, ports will assume that services like pilots and tugboats will be available at the requested time. This way of working is now putting increasing pressure on ports and their service providers. In peak times, it becomes difficult for service providers to serve vessels according to their requests. Peak demands can reach up to 200% and 600% of low demands for pilots and tugboats (Nikghadam *et al.*, 2023). During peak times, a lack of preparation has negative implications for the use of resources. Service providers need to hurry to deliver their services, and may have to wait the rest of the time. In addition, vessels that sail full speed to arrive at the port may need to wait to be served, if resources are not available, idling at anchorage or at terminals, occupying space, burning fuel, and creating more congestion. Therefore, the traditional unscheduled way of working has disadvantages from a safety, environmental and economic perspective.

As ports are experiencing more traffic, their awareness is increasing of the need to optimize the port call process. Port call optimization (PCO) is one of the initiatives to this goal of maritime stakeholders (IMO, 2020). PCO refers to the efficient planning of the port call process to reduce vessel waiting times at ports. It aims to ensure that all relevant parties facilitate an efficient port call, from the moment vessels depart from their previous port of call until they arrive at their destination port, complete their cargo operations and leave the port again. The reported benefits of PCO are numerous. Besides the cost saving benefits and environmental sustainability of the slow steaming experienced by the vessels and shipping companies, PCO also benefits the other actors in the port including the terminal, port authority, and service providers (IMO, 2020). It leads to the timely port services, more efficient use of the service providers' resources, improved terminal planning, reductions in greenhouse gas emissions, and shortening the waiting times of vessels at ports (IMO, 2020). Analysis undertaken by Maritime Strategies International shows that the CO_2 emission savings are around 10-11 % annually (ABS, 2020). For an example of a container ship calling at the Port of Rotterdam, apart from significant fuel savings, PCO can lead to a reduction of 15% of the call time (IMO, 2020). The proactive involvement of ports to guide timely arrival and departure of vessels is an important component of PCO. If the port authority can assess a vessel's *requested time*, prior to actual arrival or departure, and provide them with feedback based on resource availability, vessels can slow down to arrive just-in-time (JIT) when resource availability is guaranteed. This requires vessels to arrive and depart when all the required resources such as pilots, tugboats and boatmen are readily available, based on the eventual *scheduled time*, when service providers have confirmed their availability. One of the key challenges which ports face in the implementation of PCO is determining the time based on which they can guarantee resource availabilities. It is challenging because a full service schedule must be created for multiple service providers. Also, the servicing sequence of vessels must be decided based on expected arrivals and available resources. Therefore, ports need tools to help them simultaneously schedule vessels and service providers.

Until recently the scheduling literature in the port context has focused on individual port resources, like tugboat and pilot scheduling under fixed vessel arrival times. For example, Wei et al. (2020), determine tugboat schedules such that the time tugboats travel back and forth between their assignments are minimized. Pilot scheduling studies minimize pilotage service, repositioning and delay costs for pilot organizations see e.g. (Wu, Jia and Wang, 2020). The only study that has recently considered pilotage and towage services together to schedule vessels is by Abou Kasm et al. (2021). Their results showed that significant improvements can be obtained by the scheduling of vessels given service providers' resource constraints. Interestingly, however, the study assumed that vessels are already waiting to be serviced. Thus they will always experience a waiting time. This will put more pressure on the resource scheduling process than with pro-active scheduling, where incoming vessels can slow down to arrive at their scheduled times. In addition, their study involved some non-trivial assumptions, which made it difficult to apply the model to larger and busy ports. Here, there is an increased chance of waiting times for vessels during the services, when successive services are needed. Also, because of the stronger spatial dispersion of port, the time taken by service provider's resources to move between assignments may show large variations. Finally, the objective of scheduling was limited to minimizing the longest waiting times, while alternative scheduling strategies could also be interesting. Especially a strategy to minimize total waiting times would, by definition, provide more relief to the overall port, and deserves to be studied. Especially in busy ports, the effect of this strategy on overall throughput is expected to be relevant.

In short, especially for large and busy ports, appropriate tools are lacking to design joint and proactive port call schedules for vessels and service providers. Our study addresses this gap. We propose an extended optimization model and study alternative objectives, testing these for the illustrative case of the large and busy port of Rotterdam. The remainder of this paper is organized as follows; Section 5.2 reviews the literature. Section 5.3 briefly specifies the system on which the model is built. Section 5.4 presents the mathematical formulation of the model. Section 5.5 presents the solution of the model for a practical example and discusses the findings. Sections 5.6 concludes the paper.

5.2 Literature review

The question of efficient scheduling of resources for port vessel services has been addressed by several scholars. The decisions considered by these studies include tactical capacity decisions as well as operational deployment decisions for the service providers (Lee and Song, 2017). Their scheduling objectives are diverse, including minimizing the sum or maximum of port stay time, waiting time, handling time, service completion time, or delayed departures of vessels. One of the pioneering scheduling studies was on tugboats fleet management by Jaikumar and Solomon (1987). This study minimizes the number of tugboats required to serve a given number of vessels in the port. Later tugboat scheduling studies aim at minimizing a variety of objectives such as the latest completion time of all services, total waiting time of vessels, or total towage operation costs including repositioning and penalty costs (Ilati, Sheikholeslami and Hassannayebi, 2014; Wang *et al.*, 2014; Wei *et al.*, 2021). A variety of modelling techniques, such as integer programming, mixed integer programming (Kang, Meng and Tan, 2020), and mixed integer nonlinear programming (Wang et al 2012) has been proposed. Various heuristic or metaheuristic approaches have been developed (Wang *et al.*, 2014), some focused on towage services for container terminals and others on inland barge operations (Zhen *et al.*, 2018). While earlier tugboat scheduling studies were deterministic, the latest one incorporates various uncertainties (Kang, Meng and Tan, 2020). The objective of this study was to minimize the total towage time. In another study, Wei *et al.*, (2021) argue that as the towage requests of vessels are prone to change, it is unrealistic to assume that all towage requests are known. They propose a model that dynamically updates tugboat schedules as new towage request arrives.

Unlike the extensive research on tugboat scheduling, pilot scheduling studies are limited. This limited attention may be because pilot organizations are less efficiency driven than tugboat companies (Nikghadam, Rezaei and Tavasszy, 2022). Pilot organizations in many ports are associations of self-employed pilots that have a monopolistic position and a public mandate to provide pilotage services. Two out of three pilot scheduling studies focus on minimizing costs for the pilot organization. Wu et al. (2020) proposed a model in which they minimize the total pilotage costs which consist of delay, service and repositioning costs (Wu, Jia and Wang, 2020). Jia et al. (2020) integrate pilot scheduling into vessel traffic management. Their model schedules pilots, considering the utilization of fairways, anchorage areas and terminal basins as constraints of the model. Similar to Wu et al. (2020), their model minimizes the total pilotage delay, service and repositioning costs. Additionally, they consider the costs of unsatisfied vessel service requests (Jia, Wu and Meng, 2020). Besides these cost minimization models, Lorenzo et al. (2021) propose a model that configures extended breaks for pilots given their off-day preferences and labour regulations.

In the above-mentioned resource scheduling studies, the attention was on the supply side of the port services. The vessel arrivals and departures were fixed, and the decision to be made was to determine which resource to be deployed to which vessel, to achieve a specific objective. The objectives were related to the service providers' interests such as maximizing tugboat utilization, minimizing (total or maximum) towage service times or minimizing total pilotage costs. However, there has been limited attention to the demand side of the services, concerning vessel scheduling. A recent study by Abou Kasm et al. (2021) provides a vessel scheduling model, which considers pilot and tugboat resource capacity constraints. Their model shows that vessel scheduling is beneficial for resource utilization and customer satisfaction. However, the model has some limitations which are particularly relevant for larger, busier ports. First, the waiting times between subsequent services are ignored. In large ports, these waiting times can be significant. In the Port of Rotterdam, for instance, 63% of the incoming vessels wait for towage, after the pilot has boarded with waiting times up of to 40 minutes (Molkenboer, 2020). A second limitation is that the repositioning times of pilots and tugboats between assignments are assumed to be constant. However, in larger ports, this time is highly variable as the spatial dispersion of assignments also varies. A third issue closely related to the above is the discretized treatment of time in their model. An advantage of a discrete representation of time is that it reduces the complexity of the solution approach. However, as inter-service waiting times and variations in repositioning times are introduced, time intervals in the optimization need to be very short, which again increases complexity. A continuous time approach is much more refined, increases the solution space and gives more accurate results. Such a model has not yet been studied in this context, however.

Given the above-mentioned gaps in the literature, our study contributes with an optimization model which schedules vessels and service providers. The model is continuous in time and considers inter-service waiting times and sequence dependent repositioning time of resources. In the next section the system is described which is the basis for the modelling problem.

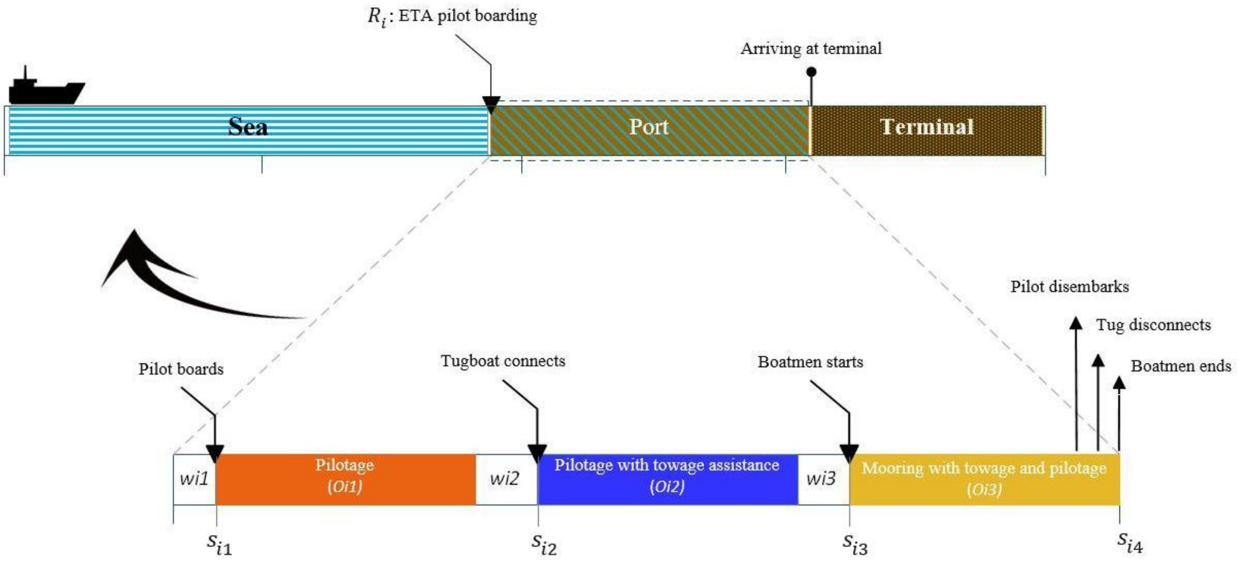
5.3 Problem definition

In this section, we further explain the characteristics of the problem and present the details of operations, services, service providers, and resources.

Consider that V vessels are calling the port at any point in time. They can be either incoming or outgoing vessels. Incoming vessels enter the port from the sea and sail toward their allocated berth. Outgoing vessels are located at berth, sail out of the port, and travel towards their next destinations. Both these sets of vessels may require assistance while travelling through congested, often narrow channels, thus requiring the assistance of services such as pilotage, towage, and mooring for safe passage. Different service providers offer these services, namely pilot organization, tugboat company, and boatmen organization. Each service provider has several resources to provide their service. We assume that each service provider has only one primary type of resource. Pilots, tugboat fleets, and boatmen crew are considered the main type of resources for the pilot organization, tugboat company, and boatmen organization, respectively. We also assume that these resources, namely pilots, tugboat fleet, and boatmen crew, are homogeneous. As such, we simplified the use of pilotage certificates and tugboats bollard pull, since we don’t expect them to significantly alter the conclusions drawn from our findings.

Each vessel, either incoming or outgoing, goes through j operations. The sequence of operations for incoming and outgoing vessels is illustrated in Figures 5.1 (a) and (b), respectively.

(a) Incoming vessel



(b) Outgoing vessel

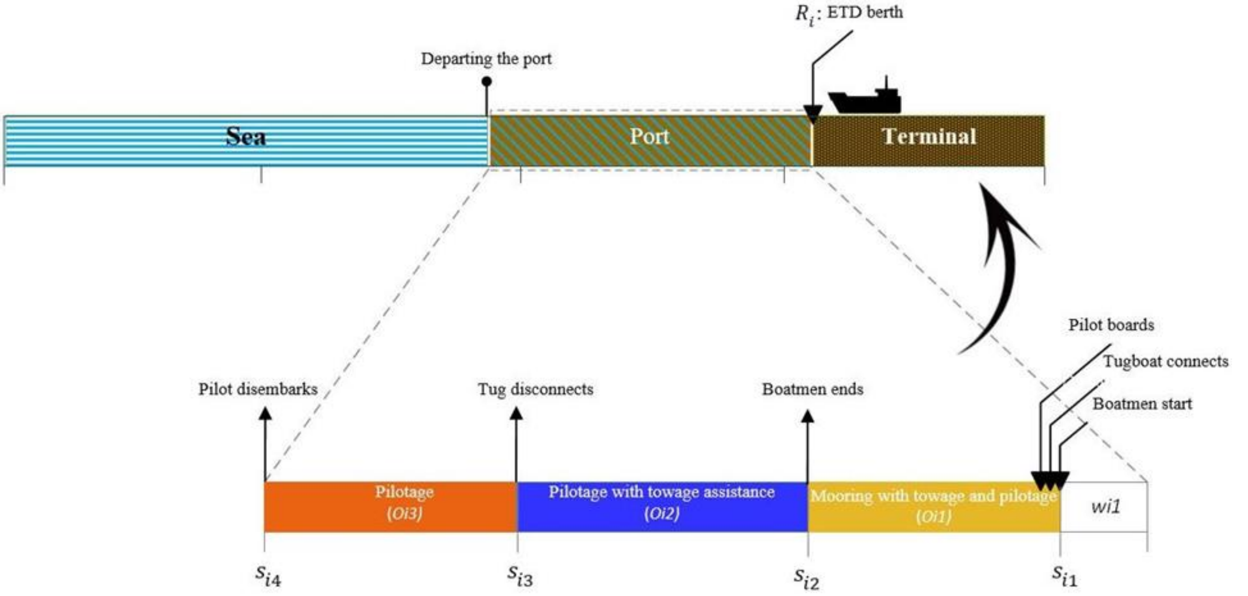


Figure 5.1. The sequence of operations for (a) incoming and (b) outgoing vessels

For an incoming vessel, the sequence of operations is as follows: When an incoming vessel is still at sea, the vessel (agent) sends an estimated time of arrival at the pilot boarding place, also called ETA-pilot boarding place. This time is the requested starting time (R_i) for incoming vessels. When the vessel arrives at the port, the vessel's captain starts communicating with the pilot organization to take a pilot on board for pilotage. A pilot sails from its station to the boarding place to board the vessel. After the pilot has boarded the vessel, the vessel enters the harbour. This operation between the pilot on boarding and tugboat engagement is considered operation 1 of incoming vessels. Next, the pilot and the vessel's captain command the tugboats to provide towage services. The number of tugboats required typically depends on the vessel size. Tugboats sail from either their station or previous assignments to connect to the vessel for towage. The tugboats tow/push the vessel until it reaches its designated berth. This is considered as operation 2. Once the vessel arrives at its berth, boatmen start their service to help moor the vessel, which begins operation 3. Only after the completion of this operation, the services of an incoming vessel are considered complete, and the assigned pilot, tugboats, and boatmen are released for their subsequent assignments or can move back to their respective stations. Note that, during the successive operations, the resources of earlier operations remain occupied. Figure 5.1 (a) illustrates the sequence of services for incoming vessels.

Outgoing vessels request their servicing start time by sending an Estimated Time of Departure time from their current berth, called ETD berth. This time is the requested starting time (R_i) for outgoing vessels. If the service providers confirm the requested time, the servicing can begin at the requested time. The unmooring operation is carried out when the pilot, the required number of tugboats, and the boatmen team are ready. Unmooring is operation 1 of an outgoing vessel. This operation is done by boatmen, with towage assistance, and under the pilot's command. With the completion of the unmooring operation, the boatmen will be released, and operation 2 will start. During operation 2, the vessel manoeuvres through harbour with the tugboat's assistance, still under the pilot's command. When tugboat assistance is no longer needed, the tugboats disconnect, and operation 3 starts, where only the pilot is on board to help the vessel to sail out of the port. Operation 3 continues until the vessel is out of the port, and the pilot disembarks the vessel to go to its next assignment (or station). With the pilot disembarkation and completion of operation 3, the service for the outgoing vessel will end. Note that, unlike the services for an incoming vessel where resources are seized successively at the start of their respective operation, all resources are occupied at the start of the operations for the outgoing vessels, and they are released after the completion of their respective operations. Figure 5.1 (b) presents the sequence of operations for outgoing vessels.

The operation times of a vessel refer to the duration of the travelling time in reaching its berth (incoming vessel) or in reaching sea from its berth (outgoing vessel) and are typically estimated from past data and considered as known. In the Port of Rotterdam, for instance, the maximum allowed sailing speed for each vessel class and historical data are used to estimate the operation times (Verduijn, 2017). Operation times of different vessels differ depending on several factors, such as vessel size and berth location. The time that operation j of vessel i takes is denoted mathematically as O_{ij}. This time enables the service providers to approximate their service start time. For example, the boatmen team assigned to an incoming vessel would expect the vessel arrival time as $s_{i3} = R_i + O_{i1} + O_{i2}$, where, s_{i3} is the estimated time of starting mooring operations for the incoming vessel, $\mathrm{R_i}$ *is the* vessels' requested time, and O_{i1} and O_{i2} *are the* durations of operations 1 and 2 for vessel i, respectively. Each operation is assumed to be non-pre-emptive, which means that each operation O_{ij} cannot be interrupted once it starts.

For example, the boarded pilot can only leave the occupied vessel to serve another once the service ends. This is almost always the case in reality.

The sequence of operations for both types of vessels is fixed and known (see Figures 5.1 (a) and (b)). Vessels with pilotage exceptions are excluded in this study since the vessels without a pilot are not allowed to take tugboats either. Further, we assumed that each vessel required one pilot and one boatmen team. However, its towage requirements vary in number. Bigger vessels may require up to 4 tugboats, while smaller vessels do not require towage assistance. In the case of smaller vessels, the number of tugboats needed is assigned zero (An example is presented in the next section).

Service providers are individual companies that perform services with their resources. We assume that the pilot organization, tugboat company, and boatmen organization have P identical pilots, T identical tugboat fleet, and B identical boatmen crew, respectively. Each resource may serve multiple vessels successively during the scheduling period but not simultaneously. For example, one pilot cannot serve two vessels simultaneously. Initially, each resource is assumed to start from its station (denoted as $c)$ and has to return to its station or travel to its next assignment after completing the current one. Each resource can only make one complete tour by starting from its own stations and returning there finally. Sub-tours are not allowed (See Figure 5.2). The resources that are not assigned to any assignment can stay at their stations. The transportation time to and from its station is considered explicitly. Each resource may finish its assignment in one vessel and start serving the next. The repositioning time between the assignments is significant, and they are indicated by D_{ik}^{p}, D_{ik}^{t}, D_{ik}^{b} for pilot, tugboat, and boatmen, respectively. The repositioning time between the assignments is shorter for the pilot and tugboats if the resource serves a different type of vessel type (incoming, outgoing) in succession. Alternatively, when a resource successively serves two incoming (or two outgoing) vessels, the transportation time becomes much longer. For example, when a pilot is assigned to two incoming vessels successively, the pilot has to travel back to the port entry after disembarking the first vessel, to start its next incoming assignment. Thus, based on the current and next assignment combinations, each resource might travel in five ways (incoming – incoming, incoming – outgoing, outgoing to outgoing, incoming to station, outgoing – station). However, for the boatmen, as their assignments are always at the berth, such sequence dependency is typically not significant.

The challenge is that in peak times the port can only grant some of all the requested times (R_i). During peak demand, when the service providers are not readily available, the port may suggest a new scheduled starting time (s_{i1}). This implies that the scheduled starting time of vessel i has a deviation of $w_{i1} = s_{i1} - R_i$ from the requested time. After operation 1 starts with the deviation, w_{i1}, there is still a possibility of facing deviations in the next consecutive operations (referred to as w_{i2} *and* w_{i3}). Since the vessels' starting and operations times define the service providers' assignments and their repositioning durations between them, the model needs to schedule the vessels and service providers simultaneously. A port may pursue different optimization strategies in this scheduling. We formulate and explore three separate strategies as objective functions as the following:

- **Strategy (I)**: Minimizes the total sum of deviations of scheduled from requested times [Min Sum]
- **Strategy (II):** Minimizes the maximum of deviations of scheduled from requested times [Min Max]
- **Strategy (III) :** Minimizes the deviation of the scheduled from the requested starting time [FCFS]

Note that these objective functions represent alternative strategies for ports. Hence, they are not multiple objectives of a single model. Multi-objective optimization is suitable for modelling problems where several conflicting objective functions need to be considered simultaneously. In this study, we explore three scheduling strategies and understand their trade-offs among them to determine the best strategy. Strategy (I) focused on minimizing the total sum of $w_{i1} + w_{i2} + w_{i3}$ for all vessels. Strategy (II) minimizes the maximum of $w_{i1} + w_{i2} + w_{i3}$ for all vessels. Strategy (III) minimizes the total sum of w_{i1} for all vessels focusing only on starting the services as soon as possible, disregarding the inter-service waiting time of vessels i.e. $w_{i2} + w_{i3}$.

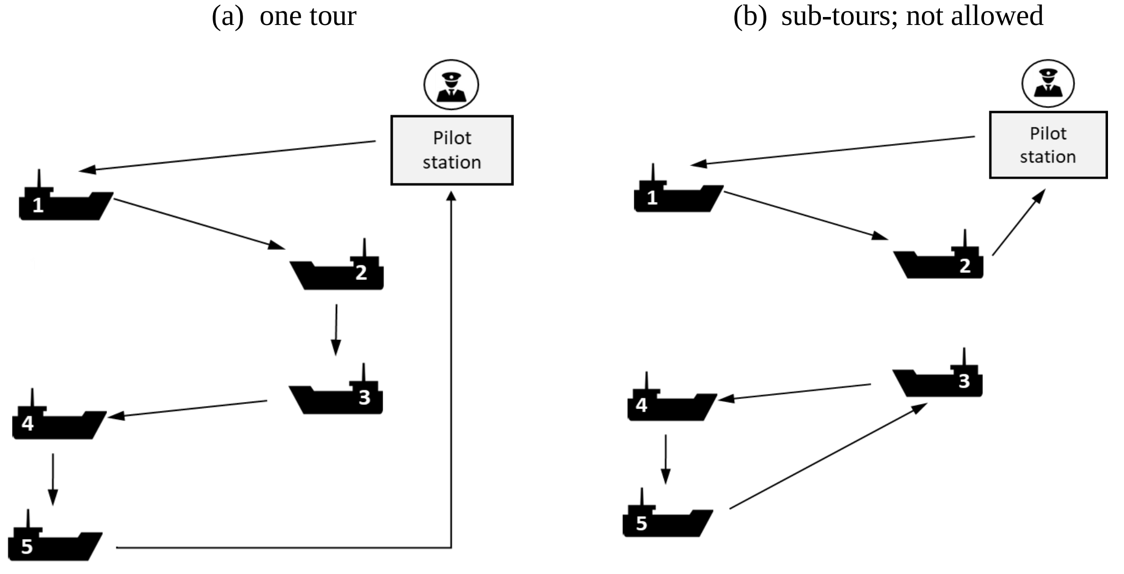


Figure 5.2. The sequence of pilot repositioning for serving five vessels; (a) a correct tour starting and ending at station (b) includes sub-tours which is not allowed.

5.4 Mathematical formulation

In this section, we formulate the problem described in Section 5. 3 as a Mixed Integer Linear Programming Model (MILP). The sets, decision variables, and parameters used in the formulation are presented below. The problem has characteristics similar to the Hybrid Flow Shop Scheduling Problem (HFSP) and Vehicle Routing Problem (VRP). The vessel scheduling part of the problem is identical to the HFSP problem with three stages and sequence-dependent setup times (Kis and Pesch, 2005). Vessels are taken as jobs, operations as stages, and resources as the number of machines in each stage. Similar to the jobs in the HFSP, each vessel has to go through these three fixed stages sequentially. Scheduling service providers is similar to the VRP (Dantzig and Ramser, 1959). Resources are taken as vehicles that have to travel to their customers, here vessels. Each resource starts at its station, serves vessels one after the other, and returns to its station. The repositioning time of resources is also considered.

Sets:

$i,k\text{: }Vessels, i,k \in V, V = \left\{V^{in} \cup V^{out}\right\}$, *where* $|V|$ *indicates the number of vessels*

$J\text{: }set\ of\ operations\ , j = \{1, \dots, J\}, J = 3$

$P\text{: }Pilots, p = \{1, \dots, P\}$

$T\text{: }Tugboat\ fleet, t = \{1, \dots, T\}$

$B\text{: }Boatmen\ crew, b = \{1, \dots, B\}$

$C\text{: }Stations, c = \{c^p, c^t, c^b\}$, *where* c^p, c^t , c^b *indicate pilot, tugboat and boatmen stations respectively.*

Decision variables:

$s_{ij}\text{: }The\ scheduled\ starting\ time\ of\ operation\ j\ of\ vessel\ i$

$s_{i4}\text{: }The\ scheduled\ completition\ time\ of\ the\ last\ operation\ of\ vessel\ i$

$w_{ij}\text{: }The\ deviation\ between\ the\ scheduled\ and\ requested\ time\ of\ j\ th\ operation\ of\ vessel\ i$

$$x_{ijp}^{p}\text{: }\begin{cases} 1\ \ if\ pilot\ p\ is\ assigned\ to\ operation\ j\ of\ vessel\ i \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$$y_{ikp}^{p}\text{: }\begin{cases} 1\ \ if\ pilot\ p\ transports\ from\ i\ to\ k;\ i,k \in V\ \cup \{c^p\} \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$$x_{ijt}^{t}\text{: }\begin{cases} 1\ \ if\ tugboat\ t\ is\ assigned\ to\ operation\ j\ of\ vessel\ i \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$$y_{ikt}^{t}\text{: }\begin{cases} 1\ \ if\ tugboat\ t\ transports\ from\ i\ to\ k; i,k \in V\ \cup \{c^t\} \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$$x_{ijb}^{b}\text{: }\begin{cases} 1\ \ if\ boatmen\ b\ is\ assigned\ to\ operation\ j\ of\ vessel\ i \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$$y_{ikb}^{b}\text{: }\begin{cases} 1\ \ if\ boatman\ b\ transports\ from\ i\ to\ k;\ i,k \in V\ \cup \{c^b\} \\ \qquad\qquad\qquad 0\ otherwise \end{cases}$$

$z_i^p\text{: }The\ order\ which\ vessel\ i\ is\ served\ by\ its\ pilot\ (Auxilary\ variable\ for\ subtour\ elimination\ )$

$z_i^t\text{: }The\ order\ which\ vessel\ i\ is\ served\ by\ its\ tugboat(s)\ (Auxilary\ variable\ for\ subtour\ elimination)$

$z_i^b\text{: }The\ order\ which\ vessel\ i\ is\ served\ by\ its\ boatman\ (Auxilary\ variable\ for\ subtour\ elimination)$

(Input) Parameters:

$O_{ij}\text{: }The\ duration\ of\ operation\ j\ of\ vessel\ i$

$N_i\ \ \text{: }The\ required\ number\ of\ tugboats\ for\ vessel\ i$

$D_{ik}^{p}\text{: }The\ duration\ of\ repositioning\ time\ of\ pilot\ p\ from\ i\ to\ k;\ i,k \in V\ \cup \{c^p\}$

$D_{ik}^{t}: The\ duration\ of\ repositioning\ time\ of\ tugboat\ t\ from$ i to k; $i,k \in V\ \cup \{c^{t}\}$

$D_{ik}^{b}: The\ duration\ of\ repositioning\ time\ of\ boatman\ b\ from\ i\ to\ k;\ i,k \in V\ \cup \{c^{t}\}$

$D_{c^{p}k}^{p}: The\ duration\ of\ repositioning\ time\ of\ pilot\ p\ from\ the\ pilot\ station\ (c^{p})\ to\ vessel\ k$

$D_{c^{t}k}^{t}: The\ duration\ of\ repositioning\ time\ oftugboat\ t\ from\ the\ tugboat\ station\ (c^{t})\ to\ vessel\ k$

$D_{c^{b}k}^{b}: The\ duration\ of\ repositioning\ time\ of\ boatman\ b\ from\ the\ tugboat\ station\ (c^{b})\ to\ vessel\ k$

$R_i: The\ requested\ starting\ time\ of\ first\ operation\ for\ of\ vessel\ i$
$(for\ incoming\ vessels\ that\ is\ ETA\ at\ pilot\ boarding\ place,$

$for\ outgoing\ vessels\ that\ is\ ETD\ at\ berth\ )$

Model:

$$Minimize \sum_{i\in V}\sum_{j=1}^{J} w_{ij} \tag{1}$$

Subject to

$$s_{i1} - R_i - w_{i1} = 0 \qquad \forall\, i \in V \tag{2}$$

$$s_{ij} + O_{ij} + w_{ij+1} - s_{ij+1} = 0 \qquad \forall\, i \in V, j = \{1,..,J-1\} \tag{3}$$

$$\sum_{p=1}^{P} x_{i1p}^{p} = 1 \qquad \forall\, i \in V \tag{4}$$

$$\begin{cases} x_{i1p}^{p} = x_{i2p}^{p} \\ x_{i2p}^{p} = x_{i3p}^{p} \end{cases} \qquad \forall\, i \in V, p = \{1,\dots,P\} \tag{5}$$

$$\sum_{t=1}^{T} x_{i2t}^{t} = N_i \qquad \forall\, i \in V \tag{6}$$

$$\begin{cases} x_{i1t}^{t} = 0 \\ x_{i2t}^{t} = x_{i3t}^{t} \end{cases} \qquad \forall\, i \in \{V^{in}\}, t = \{1,\dots,T\} \tag{7}$$

$$\begin{cases} x_{i1t}^{t} = x_{i2t}^{t} \\ x_{i3t}^{t} = 0 \end{cases} \qquad \forall\, i \in \{V^{out}\}, t = \{1,..,T\} \tag{8}$$

$$\sum_{b=1}^{B}\sum_{j=1}^{J} x_{ijb}^{b} = 1 \qquad \forall\, i \in V \tag{9}$$

$$x_{i1b}^{b} + x_{i2b}^{b} = 0 \qquad \forall\, i \in \{V^{in}\}, b = \{1,..,B\} \tag{10}$$

$$x_{i2b}^{b} + x_{i3b}^{b} = 0 \qquad \forall\, i \in \{V^{out}\}, b = \{1,..,B\} \tag{11}$$

$$2x_{i1p}^{p} - 1 \leq \sum_{k \in V\, \cup \{c^p\}} y_{ikp}^{p} + \sum_{k \in V\, \cup \{c^p\}} y_{kip}^{p} \leq 2x_{i1p}^{p} \qquad \forall\, i \in V, p = \{1, \dots, P\} \tag{12}$$

$$\sum_{k \in V\, \cup \{c^p\}, i \neq k} y_{ikp}^{p} \leq 1 \qquad \forall\, i \in V\ \cup \{c^p\}, p = \{1, \dots, P\} \tag{13}$$

$$\sum_{k \in V\, \cup \{c^p\}, i \neq k} y_{ikp}^{p} = \sum_{k \in V\, \cup \{c^p\}, i \neq k} y_{kip}^{p} \qquad \forall\, i \in V\ \cup \{c^p\}, p = \{1, \dots, P\} \tag{14}$$

$$y_{iip}^{p} = 0 \qquad \forall\, i \in V\ \cup \{c^p\}, p = \{1, \dots, P\} \tag{15}$$

$$1 \leq z_i^p \leq |V| \qquad \forall\, i \in V \tag{16}$$

$$z_i^p - z_k^p + 1 \leq |V| * (1 - \sum_{p=1} y_{ikp}^{p}) \qquad \forall\, i, k \in V, i\ \neq k \tag{17}$$

$$2x_{i2t}^{t} - 1 \leq \sum_{k \in V\, \cup \{c^t\}, i \neq k} y_{ikt}^{t} + \sum_{k \in V\, \cup \{c^t\}, i \neq k} y_{kit}^{t} \leq 2x_{i2t}^{t} \qquad \forall\, i \in V, t = \{1, \dots, T\} \tag{18}$$

$$\sum_{k \in V\, \cup \{c^t\}, i \neq k} y_{ikt}^{t} \leq 1 \qquad \forall\, i \in V \cup \{c^t\}, t = \{1, \dots, T\} \tag{19}$$

$$\sum_{k \in V\, \cup \{c^t\}, i \neq k} y_{ikt}^{t} = \sum_{k \in V\, \cup \{c^t\}, i \neq k} y_{kit}^{t} \qquad \forall\, i \in V \cup \{c^t\}, t = \{1, \dots, T\} \tag{20}$$

$$y_{iit}^{t} = 0 \qquad \forall\, i \in V \cup \{c^t\}, t = \{1, \dots, T\} \tag{21}$$

$$1 \leq z_i^t \leq |V| \qquad \forall\, i \in V \tag{22}$$

$$z_i^t - z_k^t + 1 \leq |V|\ * (1 - \sum_{t=1}^{T} y_{ikt}^{t}) \qquad \forall\, i, k \in V, i\ \neq k \tag{23}$$

$$2 * \sum_{j=1}^{J} x_{ijb}^{b} - 1 \leq \sum_{k \in V\, \cup \{c^b\}, i \neq k} y_{ikb}^{b} + \sum_{k \in V\, \cup \{c^b\}, i \neq k} y_{kib}^{b} \leq 2 * \sum_{j=1}^{J} x_{ijb}^{b} \qquad \forall\, i \in V, b = \{1, \dots, B\} \tag{24}$$

$$\sum_{k \in V\, \cup \{c^b\}, i \neq k} y_{ikb}^{b} \leq 1 \qquad \forall\, i \in V \cup \{c^b\}, b = \{1, \dots, B\} \tag{25}$$

$$\sum_{k \in V\, \cup \{c^b\}, i \neq k} y_{ikb}^{b} = \sum_{k \in V + \{c\}, i \neq k} y_{kib}^{b} \qquad \forall\, i \in V \cup \{c^b\}, b = \{1, \dots, B\} \tag{26}$$

$$y_{iib}^{b} = 0 \qquad \forall\, i \in V \cup \{c^b\}, b = \{1, \dots, B\} \tag{27}$$

$$1 \leq z_i^b \leq |V| \qquad \forall\, i \in V \tag{28}$$

$$z_i^b - z_k^b + 1 \leq |V| * (1 - \sum_{b=1}^{B} y_{ikb}^b) \qquad \forall\, i, k \in V, i \neq k \qquad (29)$$

$$s_{i4} + D_{ik}^p \leq s_{k1} + M(1 - y_{ikp}^p) \qquad \forall\, i, k \in V, i \neq k, p = \{1, \dots, P\} \qquad (30)$$

$$\begin{aligned} s_{i4\ \forall\, i \in \{V^{in}\}} + s_{i3\ i \in \{V^{out}\}} + D_{ik\ i,k \in V, i \neq k}^t \\ \leq s_{k2\ k \in \{V^{in}\}} + s_{k1\ k \in \{V^{out}\}} + M(1 - y_{ikt}^t)_{\,i,k \in V, i \neq k} \end{aligned} \qquad t = \{1, \dots, T\} \qquad (31)$$

$$\begin{aligned} s_{i4\ \forall\, i \in \{V^{in}\}} + s_{i2\ \forall\, i \in \{V^{out}\}} + D_{ik\ \forall\, i,k \in V, i \neq k}^b \\ \leq s_{k3\ k \in \{V^{in}\}} + s_{k1\ k \in \{V^{out}\}} + M(1 - y_{ikb}^b)_{\,i,k \in V, i \neq k} \end{aligned} \qquad b = \{1, \dots, B\} \qquad (32)$$

$$w_{ij}, s_{ij}, z_i^p, z_i^t, z_i^b \geq 0 \qquad \forall\, i = \{1, \dots, I\}, j = \{1, .., J\} \qquad (33)$$

$$x_{ijp}^p, x_{ijt}^t, x_{ijb}^b \in \{0,1\} \qquad \begin{aligned} &\forall\, i, k \in V, \\ &j = \{1, .., J\}, \\ &p = \{1, \dots, P\}, t = \{1, \dots, T\}, \\ &b = \{1, \dots, B\} \end{aligned} \qquad (34)$$

$$y_{ikp\ i,k \in V \cup \{c^p\}}^p, y_{ikt\ i,k \in V \cup \{c^t\}}^t, y_{ikb\ i,k \in V \cup \{c^b\}}^b \in \{0,1\} \qquad \begin{aligned} &p = \{1, \dots, P\}, t = \{1, \dots, T\}, \\ &b = \{1, \dots, B\} \end{aligned} \qquad (35)$$

The objective function (1) formulates the scheduling strategy (I) and minimizes the total sum of deviation of the vessel's scheduled times from their requested times. The decision variable w_{i1} indicates the deviation from their requested starting time. The other decision variables, w_{i2}, and w_{i3} are inter-service waiting times, indicating the waiting time of vessels for operations 2 and 3, respectively. Alternatively, strategy (II) could be formulated as $Minimize\ \max_{i \in V} \sum_{j=1}^{J} w_{ij}$. This objective function minimizes the maximum deviation of vessels scheduled times from their requested times. Strategy (III) can be formulated as $Minimize\ \sum_{i \in V} w_{1j}$ which minimizes the sum of deviation of vessels scheduled starting times from their requested starting times.

Constraint (2) defines w_{i1}, which is the difference between the vessel's requested starting time and scheduled starting time. Constraint (3) assures that the sequence of operations for each vessel is respected. It also defines the inter-service waiting time between the operations. For example, starting time of operation 2 of an incoming vessel is equal to the sum of starting time of operation 1, the duration of operation 1, and the waiting time of the vessel to start operation 2. Thus, $s_{i1} + o_{i1} + w_{i2} - s_{i2} = 0$. Constraint (4) assigns one (and only one) pilot to the first operation of each vessel. Constraint (5) ensures that the assigned pilot remains assigned to the vessel until the completion of the last operation.

Constraint (6) assigns the required number of tugboats (N_i) to each vessel for starting the towage operations. Constraint (7) assigns tugboats to the second operation of an incoming vessel and ensures that the assigned tugboats remain assigned until the completion of the third operation. The term $x_{i1t}^t = 0$ ensures that no tugboat is assigned to the first operation of an incoming vessel. Constraint (8) assigns tugboats to the first operation of an outgoing vessel and ensures that the assigned tugboat remains engaged until the completion of the second operation. The term $x_{i3t}^{t} = 0$ means that no tugboat is assigned to the third operation of an outgoing vessel. Constraint (9) assigns one (and only one) boatman team to each vessel. Constraints (10) and (11) ensure that no boatmen are assigned to the first two operations of incoming vessels and the last two operations of outgoing vessels, respectively.

Constraint (12) assures sequential pilot assignments and specifies that if pilot p is assigned to vessel i, i.e., $x_{i1p}^{p} = 1$, then in its assignments, either i proceeds k or vice versa. It indicates that the assigned pilot must come from either the station or a vessel and move to either the station or another vessel after completing the current assignment. If pilot p is not assigned to vessel i ($x_{i1p}^{p} = 0$), then the constraint ensures that the pilot does not go from i to k, which implies that $\sum_{k\in V \cup\{c^p\}} y_{ikp}^{p} + \sum_{k\in V \cup\{c^p\}} y_{kip}^{p} = 0$. Constraint (13) ensures that each pilot repositions from i to k only once. Constraint (14) ensures that if pilot p repositions from i to k, then the next move will start from k. Constraint (15) ensures that pilot repositioning from i to i is not defined. Hereby, the diagonal elements of the matrix y_{iip}^{p} set to zero. Constraints (16) and (17) are sub-tour elimination constraints of the well-known Miller-Tucker-Zemlin formulation (Pferschy and Staněk, 2017). Together they ensure that each pilot makes only one complete tour. (See Figure 5.2). The pilot can only start from its station and return to its station after completing its assignments.

Constraint (18) ensures that if tugboat t is assigned to vessel i (i.e., $x_{i2t}^{t} = 1$), then the tugboat should be assigned to k, which either immediately succeeds or proceeds i. Constraint (19) ensures that each tugboat repositions at most one time from i to k. Constraint (20) ensures that if tugboat t repositions from i to k, the successive move will start from k. Constraint (21) ensures that tugboat repositioning from i to i is not defined and set to zero. Constraints (22) and (23) together define sub-tour elimination constraints of Miller-Tucker-Zemlin formulation for the tugboat (Pferschy and Staněk, 2017). They ensure that each tugboat makes only one tour starting from its stations and returning there. Constraint (24) ensures that if boatman team b is assigned to the vessel i (i.e., $\sum_{j=1}^{J} x_{ijb}^{b} = 1$), then, the boatmen team is either repositioned from k or will proceed to it. Constraint (25) ensures that each boatman team repositioning from i to k is performed at most once. Constraint (26) ensures that if the boatmen team has repositioned from i to k, the successive move will start from k. Constraint (27) ensures that the boatmen repositioning from i to i is set to zero. Constraints (28) and (29) together define sub-tour elimination constraints of Miller-Tucker-Zemlin formulation for the boatmen (Pferschy and Staněk, 2017). They ensure that each boatman makes only one complete tour starting and returning from its stations.

Constraint (30) determines the starting time of operations given the completion time of the earlier assignment of a pilot and the corresponding repositioning time to the next assignment. Constraint (31) determines the starting time of operations given the completion time of the towage assignment and its repositioning time to its next assignment. Constraint (32) determines the starting time of operations given the completion time of the boatmen's assignment and its repositioning time to its next assignment. Constraints (33)-(35) specify the nature of decision variables.

The HFSP with more than two stages and multiple machines in each stage is a known NP-hard problem (Oğuz et al., 2004). Given that we modelled the problem HFSP with three stages, with multiple machines at each stage, the problem of this study is NP-hard as well.

5.5 Application

In this section, we apply the model to a practical case and use it to study the effect of three scheduling strategies discussed earlier (section 5.3). Our analysis is based on historical data from the port of Rotterdam, the biggest port in Europe, with about 30000 seagoing vessels visiting annually. In the first subsection, we present input parameters extracted from our dataset. Further subsections will show the results from the application of the model to the case, and in the final subsection, we will discuss the key results.

5.5.1 Input Parameters

Table 5.1 shows the vessel-related input parameters of the case. We used the data obtained from the port call data of the port of Rotterdam on a random date and time (Verduijn, 2017). We considered an instance of 12 vessels, equivalent to a workload of approximately two hours in the Port of Rotterdam. The port serves 150 incoming and outgoing vessels per day ($75\, incoming + 75\, outgoing\ vessels\ per\ 24\ hrs \simeq on\ average\ 12\ vessels\ per\ two\ hours$). Specific information, such as the date and vessel's name, are removed from the table for confidentiality reasons. The vessels requested times (ETA-Pilot boarding place for incoming vessels and ETD-berth for outgoing vessels) and their operations times are obtained from the same dataset. The durations O_{i1}, O_{i2},and O_{i3} of each vessel are shown in Table 5.1. Column R_i represents the requested starting time of operation 1. The requested starting times of operations 2 and 3 for incoming vessels are calculated by equations $R_i + O_{i1}$ and $R_i + O_{i1} + O_{i2}$, respectively. For the incoming vessel 1, the requested ETA-pilot boarding time is $12{:}45$, the requested towage starting time is $13{:}45$ and the mooring starting time is $13{:}45 + 01{:}15 = 15{:}00$. Hence, the requested completion time of services is $15{:}00 + 0{:}30 = 15{:}30$.

Table 5.1. Input parameters of the case

Vessel	Movement type	The required number of tugboats	Requested Starting time	Operation times		
i		N_i	R_i	O_{i1}	O_{i2}	O_{i3}
v_1	in	3	12:45	01:00	01:15	00:30
v_2	in	2	12:45	01:00	00:50	00:30
v_3	in	2	12:45	00:50	00:50	00:20
v_4	in	2	13:15	00:50	00:55	00:30
v_5	in	0	13:15	00:30	00:30	00:20
v_6	In	2	13:15	01:00	01:15	00:30
v_7	out	0	13:30	00:20	00:30	00:40
v_8	out	0	12:30	00:20	00:30	00:55
v_9	out	2	12:50	00:30	00:40	00:50
v_{10}	out	2	13:00	00:30	00:40	01:00
v_{11}	out	0	13:10	00:20	00:30	01:00
v_{12}	out	0	13:15	00:20	00:40	01:00

In the selected time interval (12:00-14:00), the service providers' overall resource availability for servicing these 12 vessels is approximated as the following; 8 pilots and 10 tugboats, and 3 boatmen teams. To approximate the available capacity, we excluded 25% of their total capacity for shifting vessels and 15% for the scheduled breaks of the crew. The distribution of vessel movements in a day is approximately 37%, 37%, and 25% for incoming, outgoing, and shifting voyages, respectively. We assumed that at $12{:}00$, all the resources were based at their stations. The repositioning time (in minutes) for a pilot and tugboat, D_{ik}^{p} ,and D_{ik}^{t}, between two consecutive assignments are assumed to be as the following $\begin{array}{c|cc} & incoming & outgoing \\ \hline incoming & 0{:}50 & 0{:}30 \\ outgoing & 0{:}30 & 0{:}50 \end{array}$, $\begin{array}{c|cc} & incoming & outgoing \\ \hline incoming & 0{:}40 & 0{:}20 \\ outgoing & 0{:}20 & 0{:}40 \end{array}$ matrices, respectively. For example, if a pilot serves an incoming vessel consecutively, after completion of serving the incoming vessel at berth, it has to reposition to port entry which takes about 50 minutes. This repositioning time will be shorter if the pilot assigns to an outgoing vessel. The repositioning time between two consecutive assignments for a boatmen team is assumed to be always 20 minutes.

5.5.2 Results

This section presents the results of our experiments with input data from section 5.5.1 to compare the performance of each scheduling strategy. The proposed model (presented in section 5.4) is coded in Python and solved by the Gurobi Optimization solver version 9.5.1 (Santos, n.d.). The problem has 4305 binary variables and 193 continuous variables.

Strategy (I). [Min sum]

The [Min sum] objective function minimizes the sum of total deviations of scheduled times of vessels from their requested times. Table 5.2 presents the optimal solution obtained. The computational time was 2745 seconds. The results show that with the current combination of available resources (8 pilots, 10 tugboats, and 3 boatmen teams), only some vessels are served at their requested times, and the starting time of the others have been postponed. For example, the incoming vessel v_1 's requested ETA- pilot boarding place was $12{:}45$, but it can only get the service at $15{:}20$. Given the time its operations take, (as in Table 5.1). The scheduled starting time of towage and boatmen are 16:20 and 17:35, respectively, and the scheduled completion of services is $18{:}05$. The assigned resources are pilot p_1, tugboats t_1, t_2, t_3, and boatmen team b_3. This schedule suggests a deviation of 155 minutes from vessel v_1 's requested starting time, with no inter-service waiting time. As another example, the outgoing vessel v_8 is scheduled at its requested time. Pilot p_3 and boatmen team b_2 are assigned to this vessel, with no tugboats, given that this vessel does not require towage assistance.

Table 5.2. Vessels’ schedule based on strategy (i) [Min sum]

Vessel i	R_i	s_{i1}	s_{i2}	s_{i3}	s_{i4}	Assigned pilot p	Assigned tugboats t	Assigned boatmen team b
v_1	12:45	15:20	16:20	17:35	18:05	p_1	t_1, t_2, t_3	b_3
v_2	12:45	12:50	13:50	14:40	15:10	p_5	t_5, t_8	b_1
v_3	12:45	12:50	13:40	14:30	14:50	p_4	t_3, t_4	b_2
v_4	13:15	14:45	15:35	16:30	17:00	p_3	t_9, t_{10}	b_1
v_5	13:15	13:15	13:45	14:15	14:35	p_2	-	b_3
v_6	13:15	13:15	14:15	15:30	16:00	p_7	t_6, t_7	b_1
v_7	13:30	15:05	15:25	15:55	16:35	p_2	-	b_3
v_8	12:30	12:30	12:50	13:20	14:15	p_3	-	b_2
v_9	12:50	12:50	13:20	14:00	14:50	p_1	t_2, t_9	b_1
v_{10}	13:00	13:00	13:30	14:10	15:10	p_8	t_3, t_{10}	b_3
v_{11}	13:10	13:00	13:30	14:00	15:00	p_6	-	b_2
v_{12}	13:15	13:00	15:40	16:20	17:20	p_4	-	b_2

Table 5.3 shows the optimal schedule for each of the resources. For example, it shows that vessel v_1 is the second assignment of pilot p_1. As shown in Table, the pilot p_1, starts operations from its station, and serves the outgoing vessel v_9, and incoming vessel v_1 before returning to its station. Tugboat t_1 serves vessels v_{10} and v_1 consecutively. Each boatmen team serves four vessels. For example, the boatmen team b_1 serves vessels $v_9, v_2, v_6, and\ v_4$before they return to their station. The order of assignments for the pilots and tugboat shows that they are assigned successively to incoming and outgoing vessels to minimize the repositioning time. However, such a pattern is not observed for the boatmen team as their repositioning time is fixed. The last row of Table 5.3 shows the total repositioning time of pilots, tugboats, and boatmen. Later, we will compare them with the results of other strategies.

Table 5.3. Service providers' schedule based on strategy (i) [Min sum]

Pilots' schedule	
Pilot p	Order of assignments
p_1	c^p, v_9, v_1, c^p
p_2	c^p, v_5, v_7, c^p
p_3	c^p, v_8, v_4, c^p
p_4	c^p, v_3, v_{12}, c^p
p_5	c^p, v_2, c^p
p_6	c^p, v_{11}, c^p
p_7	c^p, v_6, c^p
p_8	c^p, v_{10}, c^p

Tugboats' schedule	
Tugboat t	Order of assignments
t_1	c^t, v_{10}, v_1, c^t
t_2	c^t, v_9, v_1, c^t
t_3	c^t, v_3, v_1, c^t
t_4	c^t, v_3, c^t
t_5	c^t, v_2, c^t
t_6	c^t, v_6, c^t
t_7	c^t, v_6, c^t
t_8	c^t, v_2, c^t
t_9	c^t, v_9, v_4, c^t
t_{10}	c^t, v_{10}, v_4, c^t

Boatmen team's schedule	
Boatmen b	Order of assignments
b_1	$c^b, v_9, v_2, v_6, v_4, c^b$
b_2	$c^b, v_8, v_{11}, v_3, v_{12}, c^b$
b_3	$c^b, v_{10}, v_5, v_7, v_1, c^b$

Total repositioning time of pilots	680 mins	Total repositioning time of tugboats	640 mins	Total repositioning time of boatmen	300 mins

Strategy (II). [Min max]

The computational time for the [Min max] strategy was 2 seconds. The Min max optimization problems have multiple solutions. Table 5.4 and Table 5.5 present one of the optimal solutions obtained. Table 5.4 shows that similar to strategy (I), only some of the vessels can be served at their requested times, resulting in the postponement of other services. Comparison of Table 5.4 and Table 5.5 with Table 5.2 and Table 5.3 show that the optimal schedule of the vessels and the service provided are different for these two strategies. A comparison of the repositioning times of Table 5.3 with Table 5.5 shows that the total repositioning time of tugboats and boatmen is equal in these two strategies. However, strategy (I) yielded a schedule where the repositioning time of pilots is shorter.

Table 5.4. Vessels' schedule based on strategy (II) [Min max]

$\boldsymbol{i}$	$\boldsymbol{R_i}$	$\boldsymbol{s_{i1}}$	$\boldsymbol{s_{i2}}$	$\boldsymbol{s_{i3}}$	$\boldsymbol{s_{i4}}$	Assigned pilot $\boldsymbol{p}$	Assigned tugboats $\boldsymbol{t}$	Assigned boatmen $\boldsymbol{b}$
v_1	12:45	13:45	14:45	16:00	16:30	p_1	t_1, t_2, t_3	b_3
v_2	12:45	13:40	14:40	15:30	16:00	p_4	t_6, t_{10}	b_2
v_3	12:45	12:50	13:40	14:30	14:50	p_3	t_7, t_9	b_3
v_4	13:15	14:45	15:35	16:30	17:00	p_6	t_5, t_6	b_1
v_5	13:15	13:15	13:45	14:15	14:35	p_8	-	b_2
v_6	13:15	15:20	16:20	17:35	18:05	p_5	t_4, t_7	b_1
v_7	13:30	15:20	15:40	16:10	16:50	p_3	-	b_1
v_8	12:30	12:30	12:50	13:20	14:15	p_6	-	b_1
v_9	12:50	12:50	13:20	14:00	14:50	p_5	t_5, t_6	b_2
v_{10}	13:00	13:10	13:40	15:30	17:00	p_7	t_4, t_{10}	b_1
v_{11}	13:10	13:35	13:55	16:00	17:20	p_2	-	b_3
v_{12}	13:15	15:20	15:40	16:20	17:20	p_8	-	b_3

Table 5.5. Service providers' schedule based on strategy (II) [Min max]

Pilots' schedule

Pilot p	Order of assignments
p_1	c^p, v_1, c^p
p_2	c^p, v_{11}, c^p
p_3	c^p, v_3, v_7, c^p
p_4	c^p, v_2, c^p
p_5	c^p, v_9, v_6, c^p
p_6	c^p, v_8, v_4, c^p
p_7	c^p, v_{10}, c^p
p_8	c^p, v_5, v_{12}, c^p

Tugboats' schedule

Tugboat t	Order of assignments
t_1	c^t, v_1, c^t
t_2	c^t, v_1, c^t
t_3	c^t, v_1, c^t
t_4	c^t, v_{10}, v_6, c^t
t_5	c^t, v_9, v_4, c^t
t_6	c^t, v_9, v_2, c^t
t_7	c^t, v_3, v_6, c^t
t_8	c^t, v_4, c^t
t_9	c^t, v_3, c^t
t_{10}	c^t, v_{10}, v_2, c^t

Boatmen team's schedule

Boatmen b	Order of assignments
b_1	$c^b, v_8, v_{10}, v_7, v_4, v_6, c^b$
b_2	c^b, v_9, v_5, v_2, c^b
b_3	$c^b, v_{11}, v_3, v_{12}, v_1, c^b$

Total repositioning time of pilots	760 mins	Total repositioning time of tugboats	640 mins	Total repositioning time of boatmen	300 mins

Strategy (III). [FCFS]

This section presents the results for strategy [FCFS] where the objective function minimizes the deviations of vessels' scheduled starting times from their requested times. The computational time was 564 seconds. Since the requested times of some vessels are the same, this strategy also may have more than one solution. Table 5.6 and Table 5.7 show one of the schedules obtained by this strategy for vessels and service providers, respectively. A comparison of the repositioning times of Table 5.3, Table 5.5, and Table 5.7 show that strategy (III) resulted in a schedule where the repositioning time for both pilots and tugboats is longer than strategy (I) and (II). Figure 5.3 compares and illustrates the repositioning times for the three strategies. The repositioning time of the boatman was equal to strategy (I) and (II) because the repositioning time of boatmen is not sequence dependent.

Table 5.6. Vessels' schedule based on strategy (III) [FCFS]

i	R_i	s_{i1}	s_{i2}	s_{i3}	s_{i4}	Assigned pilot *p*	Assigned tugboats *t*	Assigned boatmen *b*
v_1	12:45	12:50	15:35	16:50	17:20	p_1	t_1, t_2, t_3	b_1
v_2	12:45	12:50	15:10	16:00	16:30	p_4	t_8, t_9	b_1
v_3	12:45	12:50	13:40	14:30	14:50	p_7	t_7, t_{10}	b_1
v_4	13:15	15:20	16:10	17:05	17:35	p_2	t_6, t_{10}	b_3
v_5	13:15	13:15	13:45	14:15	14:35	p_6	-	b_2
v_6	13:15	14:45	18:00	19:15	19:45	p_3	t_1, t_5	b_1
v_7	13:30	15:20	15:40	16:10	16:50	p_7	-	b_1
v_8	12:30	12:30	12:50	13:20	14:15	p_3	-	b_1
v_9	12:50	12:50	13:20	14:00	14:50	p_2	t_2, t_9	b_3
v_{10}	13:00	13:00	13:30	14:10	15:10	p_5	t_3, t_4	b_2
v_{11}	13:10	13:10	13:30	14:00	15:00	p_8	-	b_1
v_{12}	13:15	15:05	15:25	16:05	17:05	p_6	-	b_2

Table 5.7. Service providers' schedule based on strategy (III) [FCFS]

Pilots' schedule	
Pilot p	Order of assignments
p_1	c^p, v_1, c^p
p_2	c^p, v_9, v_4, c^p
p_3	c^p, v_8, v_6, c^p
p_4	c^p, v_2, c^p
p_5	c^p, v_{10}, c^p
p_6	c^p, v_5, v_{12}, c^p
p_7	c^p, v_3, v_7, c^p
p_8	c^p, v_{11}, c^p

Tugboats' schedule	
Tugboat t	Order of assignments
t_1	c^t, v_1, v_6, c^t
t_2	c^t, v_9, v_1, c^t
t_3	c^t, v_{10}, v_1, c^t
t_4	c^t, v_{10}, c^t
t_5	c^t, v_6, c^t
t_6	c^t, v_4, c^t
t_7	c^t, v_3, c^t
t_8	c^t, v_2, c^t
t_9	c^t, v_9, v_2, c^t
t_{10}	c^t, v_3, v_4, c^t

Boatmen team's schedule	
Boatmen b	Order of assignments
b_1	$c^b, v_8, v_{11}, v_3, v_7, v_2, v_1, v_6, c^b$
b_2	$c^b, v_{10}, v_5, v_{12}, c^b$
b_3	c^b, v_9, v_4, c^b

Total repositioning time of pilots	770 mins	Total repositioning time of Tugboats	660 mins	Total repositioning time of boatmen	300 mins

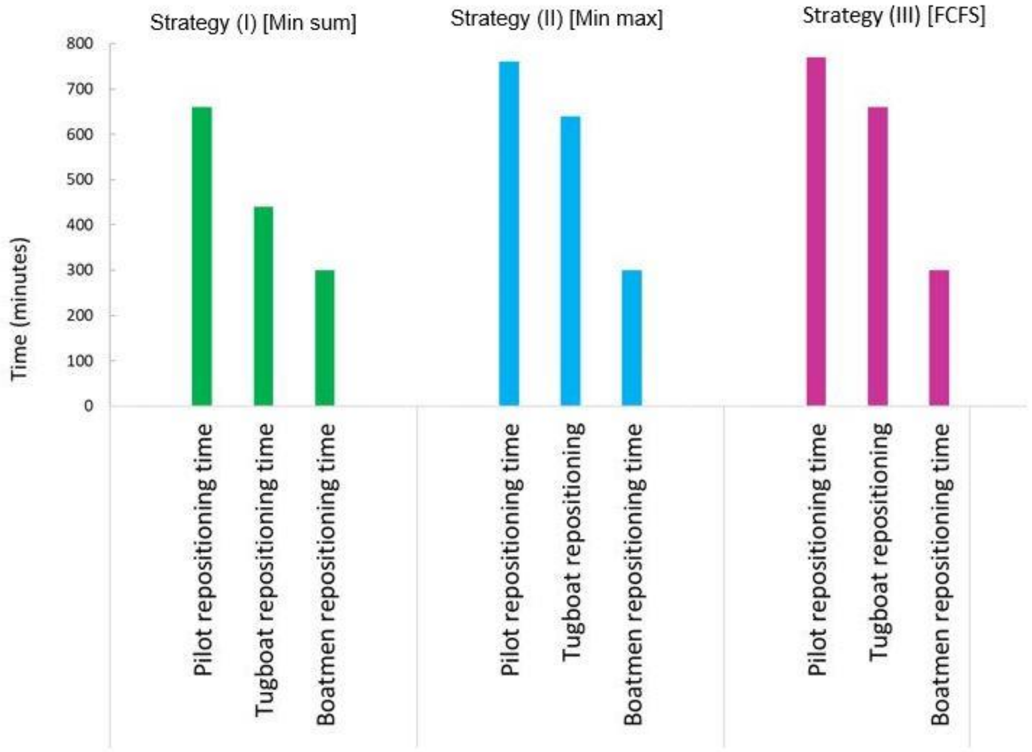


Figure 5.3. The visual comparison of repositioning times for three different strategies

To compare the performance of these three strategies, we summarize the results in terms of deviations from the requested starting times and inter-service waiting times in Table 5.8. The first column under each strategy (referred to as w_{i1}) is the deviation of the vessel i 's scheduled starting time from its requested time. The terms $\sum_{j=2}^{3} w_{ij}$ represent the inter-service waiting time of vessel i, whereas $\sum_{j=1}^{3} w_{ij}$ is the sum of the previous two terms and refers to the total waiting time for resources. Table 5.8 shows that strategies (I) and (II) can determine schedules with the minimum total deviation and the minimum of maximum deviation from the requested times, respectively. Strategy (III) yielded a schedule where deviations from the vessels' requested starting times were minimal. In the first two strategies, inter-service waiting times are 0, while in strategy (III), it is significant. Figure 5.4 compares these three strategies.

Table 5.8. The comparison of schedules for three different strategies (values are in minutes)

Vessel i	Strategy (I) [Min sum]			Strategy (II) [Min max]			Strategy (III) [FCFS]		
	w_{i1}	$\sum_{j=2}^{3} w_{ij}$	$\sum_{j=1}^{3} w_{ij}$	w_{i1}	$\sum_{j=2}^{3} w_{ij}$	$\sum_{j=1}^{3} w_{ij}$	w_{i1}	$\sum_{j=2}^{3} w_{ij}$	$\sum_{j=1}^{3} w_{ij}$
v_1	155	0	155	60	0	60	5	105	110
v_2	5	0	5	55	0	55	5	80	85
v_3	5	0	5	5	0	5	5	0	5
v_4	90	0	90	90	0	90	125	0	125
v_5	0	0	0	0	0	0	0	0	0
v_6	0	0	0	125	0	125	90	135	225
v_7	95	0	95	110	0	110	110	0	110
v_8	0	0	0	0	0	0	0	0	0
v_9	0	0	0	0	0	0	0	0	0
v_{10}	0	0	0	10	0	10	0	0	0
v_{11}	0	0	0	25	0	25	0	0	0
v_{12}	125	0	125	125	0	125	110	0	110
Sum	475	0	**475**	605	0	**605**	450	320	**770**
Max			**155**			**125**			**225**

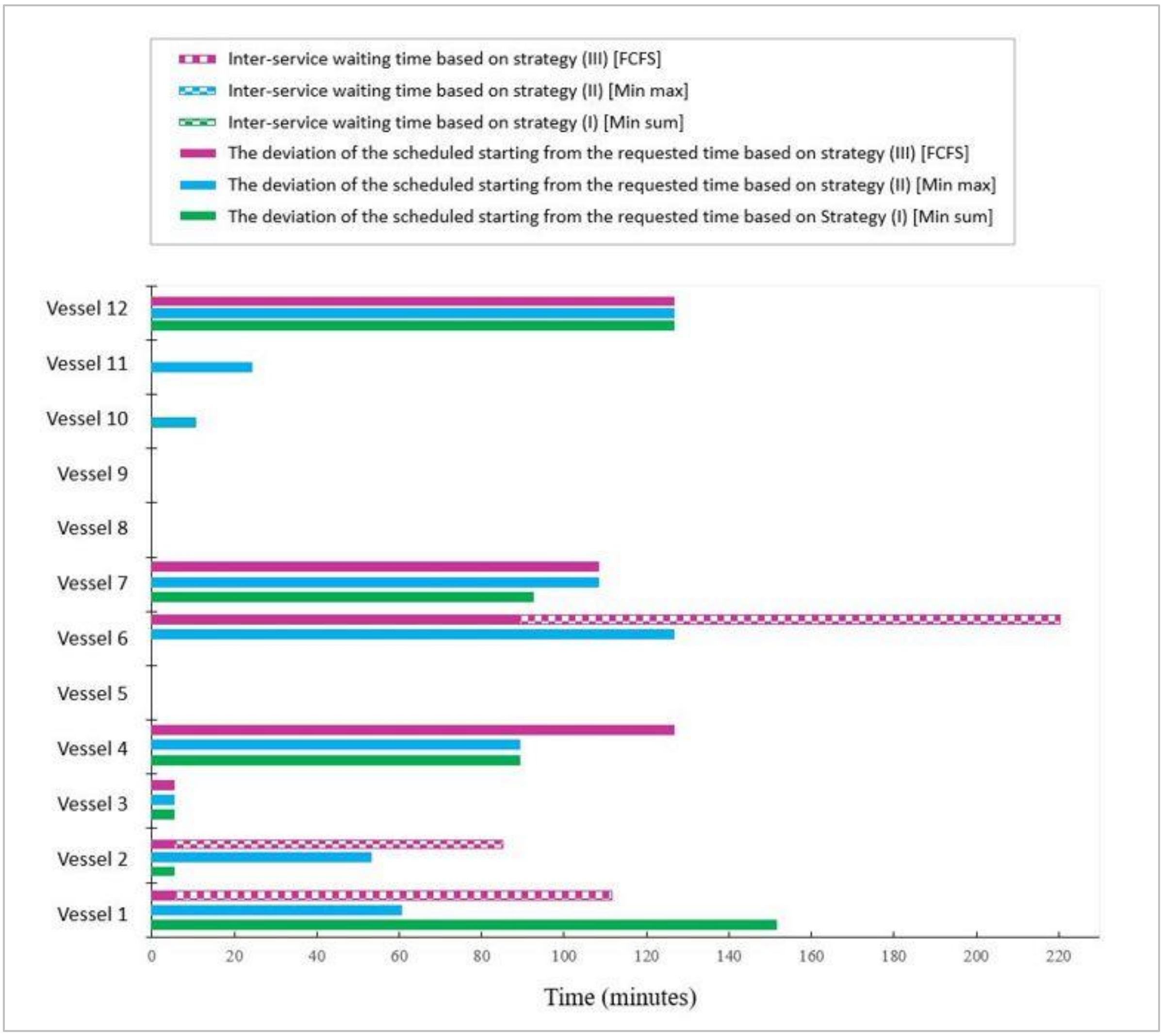


Figure 5.4. The visual comparison of schedules for three different strategies (values are in minutes)

In Figure 5.4, the chequered bar appears only in strategy (III), which shows that, unlike strategy (III), strategy (I) and (II) found schedules where the inter-service waiting times of vessels are 0. Take, for example, vessel 6. When scheduled by strategy (I) and (II), the deviations of scheduled starting times from the requested times are 0 and 125 minutes, respectively. The inter-service waiting times are 0 in both. With strategy (III), this vessel's starting time has a deviation of 90 minutes from its requested time. In addition, it's inter-service waiting time is 135 minutes. The other observation is that the maximum deviation of the scheduled starting time from the requested time for strategy (I) is larger than that of strategy (II). The former equals 155 minutes for vessel 1, while the latter equals 125 minutes for vessel 6. We discuss the results further in the next subsection.

5.5.3 Discussion

This subsection discusses the results of Section 5.5.2

The application of the model for an illustrative case of a large busy port of Rotterdam confirms that the model generates the full service schedule for the vessels and service providers, considering the repositioning and inter-service waiting times. Compared to the currently prevailing first-come-first-serve approach, the results show that significant time savings can be obtained by the joint scheduling of vessels and service providers. Both the vessels and service providers experience these time savings. In peak times, when not all the requested times of vessels can be granted, ports can use the proposed modeling tool to provide vessels with a feedback on their *scheduled times.* Accordingly, vessels can slow down to arrive just-in-time at the port and be served immediately without waiting between services.

The order of the assignments for the resources (as in Table 5.3, Table 5.5 and Table 5.7) shows that the model succeeded to assign the resources successively to incoming and outgoing vessels. This ordering enabled minimizing the repositioning time of resources so that the resources are used more efficiently. The efficient use of resources, in return, helped schedule vessels closer to their requested times.

Ports may use the model by employing different scheduling strategies. Each of these strategies has its strengths and weaknesses. For example, strategy (I) minimized the total sum of deviations from the requested times. By definition, the average deviation from the requested starting time and inter-service waiting time experienced by vessels is the smallest of the three scenarios. However, it may be considered unfair as the deviation from the requested time is larger for some vessels (vessels v_1 and v_{12}) compared to the others. In order to split the deviations among the vessels more evenly, strategy (II) can be employed.

Both strategies (I) and (II) took the inter-service waiting times into account and found schedules with zero inter-service waiting times. This indicates that the model assigns all the resources such that the waiting time for successive resources after servicing has started (by pilot boarding) is avoided for efficient use of resources. However, this important factor is ignored in strategy (III). In this strategy, the model aimed to schedule vessel servicing start times close to their requested times, resulting in longer inter-service waiting times. Existing models in the literature have only considered the starting time of services (Abou Kasm, Diabat and Bierlaire, 2021). Ignoring the inter-service waiting times has a risk of shifting the waiting times to later stages where resources have been occupied. In practice, too, this important aspect of FCFS needs attention. In many ports today, serving vessels based on FCFS is still the most common servicing principal (Yıldırım, Aydın and Gökkuş, 2020), putting extra pressure on service providers' resources by occupying them unnecessarily exacerbating the vessel's waiting times.

The comparison of repositioning times for different strategies showed that strategy (I) outperformed all the other strategies for minimizing repositioning times. This indicates that strategy (I) is the best strategy for the efficient use of resources, particularly in busier and large ports where repositioning time is a factor for the efficient use of service providers' resources. In summary, both strategies (I) and (II) are advantageous from the service provider's point of view. Strategy (I) should be considered to increase their utilization, whereas strategy (II) can be applied to be equally fair to all vessel operators.

Other points of comparison for these strategies relate to the uniqueness of the solution and computation times. Strategy (I) has the advantage of having a unique optimal solution. In the other two scenarios, several solutions may exist for the same problem (Bertazzi *et al.*, 2015), raising the question of which solution to consider. On the other hand, strategy (II) and strategy (III) have the advantage of finding the optimal solution in comparably shorter times. Therefore, for bigger problem instances with larger time horizons and a higher number of vessels, finding the optimal solution in practical time might be difficult, which might make strategy (I) a less attractive strategy.

In this study, we assumed that all vessels are equally important for the port. However, certain vessels may have higher priorities to be served at their requested times (Imai, Nishimura and Papadimitriou, 2001). To investigate such strategies, the Min sum objective function can be further extended by assigning different weight factors for different vessels. This comparison would provide insights into which prioritization strategies are most beneficial. This weighted sum strategy requires an investigation with port managers and shipping companies to assign priorities.

Finally, the proactive involvement of the port authorities in the port call process may require ports to suggest and schedule vessels for times earlier than their requested times. For example, a certain level of earliness can be easily achieved for some vessels in certain circumstances resulting in more efficient port call optimization. Therefore, exploring decision support systems to schedule the vessels earlier than the requested times can be advantageous. However, our model is designed to schedule the vessels for times later than their requested times. We chose this because speeding up to arrive earlier at the port can be costly for vessels due to increased fuel consumption (IMO, 2020). Therefore, the compensation schemes for this request need to be further investigated as the costs would be experienced by the vessels that have to rush, and the benefits are shared among all the parties, both the service providers as well as the vessels. In connection to the above, the benefits of proactive scheduling (while ships are still underway), as modelled here, include fuel savings due to slow steaming and reduced anchorage. Future work could take these benefits into account as well.

5.6 Conclusions

This study addressed one of the main challenges the ports have been facing in the implementation of PCO; determining the time based on which they can guarantee their resource availabilities. It proposed a novel mathematical model which provides a full service schedule created for vessels and service providers. This schedule is decided based on vessels' requested arrivals and departure times and the service providers' resource availability. The model is applicable for larger, busy ports; it is continuous in time and considers inter-service waiting times and sequence-dependent repositioning time of resources, i.e., pilots, tugboats, and boatmen. It can be solved to optimality using exact solution approaches. Three alternative scheduling strategies were formulated via different objective functions. We tested and applied these strategies for a practical case based on data from the port of Rotterdam.

Our application shows that time savings can be obtained by joint scheduling of vessels and service providers, compared to the currently prevailing FCFS servicing principal. Especially in peak demands, when not all requested times of vessels can be granted, ports can use the model to create a full service schedule. Strategy (I) minimizes the total sum of deviations of scheduled from requested times. This strategy is the best strategy for the efficient utilization of the resources. However, the disadvantage of this strategy is that it may lead to higher deviations for some vessels over others. Alternatively, ports that prefer to split the deviations more evenly are suggested to use Strategy (II) which minimizes the maximum of deviations of the scheduled from the requested times. The currently prevailing first-come-first-serve approach studied as strategy (III), resulted in schedules where the scheduled starting times are closest to their requested starting times. However, the vessels had to wait significantly longer. This strategy has a risk of shifting the waiting times to later stages where resources have been occupied.

Future research could include the following. In practice, vessel service requirements may vary with external conditions such as the weather. Future research can extend our model by including stochastic aspects. Another extension could address the assumption of identical service providers, considering various pilotage certificates, and tugboat types. Third, one could include additional port call services, including bunkering, or multiple pilotage services in the case of river navigation. Finally, as the problem studied in this study is NP-hard, the computational time increases strongly when the problem size gets larger. Future work can focus on developing efficient algorithms to solve large-sized problems in shorter times.

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6 Conclusion

This thesis emphasizes the role of vessel service providers in improving port call performance through cooperation. It considers the service providers’ individual contribution to the synchronization and scheduling of services, as well as the impact on their organizations. In Chapter 1, I presented the relevance, aim, contributions, and research questions for this research. In Chapter 2, I systematically studied the information needs of the service providers for improving the port call performance. In Chapter 3, I investigated the service providers' potential to cooperate and share information. In Chapter 4, I developed a simulation model to empirically assess the impact of cooperation on the performance of the port and its service providers. I modelled cooperation between the service providers as information sharing for the joint deployment of their resources. In Chapter 5, I proposed a generic mathematical model that formulates the joint scheduling of vessels and service providers as an advanced form of their cooperation.

This chapter, first, summarizes the key findings of this thesis per chapter and brings them together to address the main RQ. Next, I synthesize the managerial implications of the different studies. Finally, I provide some recommendations for future research directions.

6.1 Key findings

I answered the main research question by answering the four RQs. In the following, I summarize the answer to the RQs per chapter, and finally, I bring them together to answer the main RQ.

RQ 1: Which type of information is needed to be shared with whom to improve port call performance?

In Chapter 2, I proposed a generic approach that systematically studies information sharing between service providers in the port call. I applied the approach to the case of the Port of Rotterdam. I derived a full list of information sharing links during a port call and highlighted the critical ones. The critical information sharing links are those essential for early notice of a delay and informing the relevant parties to avoid delay propagation. To further condense the required strategies, I ordered the critical information sharing links in groups based on specific actors and information content. The ordering led to the following groups:

i. Sharing vessel information between the vessel agent, terminal, the HM, and the service providers regarding the port call details, requested ETA, ETD, and estimated number of tugboats;

ii. Sharing joint scheduling information between the service providers' planning departments and the HM regarding the vessel's requested ETA, ETD, and the service provider's updates for delayed ETA and ETD;

iii. Sharing joint resource deployment information between the service providers regarding their resource availabilities, starting and completion time of their ongoing assignments;

iv. Sharing assignment information i.e. sailing speed and course between the pilot, tugboat captain and boatmen crew during the ongoing assignments;

v. Peer-to-peer information sharing between the pilots of different assignments;

vi. Sharing information of shared resources between the service providers of different assignments.

Among these six groups, I focused on information sharing for joint scheduling (ii) and joint resource deployment (iii) for proposing effective cooperation strategies.

Furthermore, the findings of this Chapter gave rise to the following discussions. Firstly, I found that information sharing links are inter-dependent and inter-organizational. The sender of the information itself receives information from an earlier sender and often requires additional information from multiple senders to make decisions. This interdependency creates complexity in identifying from whom to obtain the information and whom to inform next. The presence of inter-organizational links challenges information sharing even more. Another significant finding was that different operators may operationalize information sharing differently making it difficult to track information. Given all these complexities and challenges, I argue that sharing information in ports is not straightforward. Hence, designing specific guidelines is crucial for the advancement of information sharing in ports. I suggest designing information sharing guidelines for each delay scenario so that the service providers know what to do, who to contact ,and what information to share in each delay scenario. In designing these guidelines, it is essential to pay attention to the dissimilarities in the needs of different service providers. For example, on-time information for one service provider may be inadequate for another, causing delays resulting in performance issues.

Secondly, the results showed the critical position of pilots and the vulnerable position of tugboat companies. Pilots are critical because, in many scenarios, the pilot is the one who notices the delay first and can inform others. Therefore, strengthening information sharing links from other parties to the pilot and vice versa is key for port performance improvements. Tugboats are in a vulnerable position regarding information sharing because they highly depend on the timely submission of information from others for scheduling and deployment, which increases the risk of tugboats being delayed to their assignments. These findings indicated that the information sharing between this pair is highly promising for port call performance improvements. Supported by the organizational interests as addressed in

Chapter 3, cooperation between the pilot organization and the tugboat company is found to be the way forward for more detailed studies in the subsequent chapters.

RQ2: How willing are the port actors to engage in cooperative relationships?

To answer this question, in Chapter 3, I adapted, operationalized, and applied Lambert's (2008) partnership model to the port context. I chose this partnership model for its specificity in systematically evaluating the factors that influence organizational relationships. Although the original model is suggested for supply chains in general, it can be applied by analogy for port studies. Literature provides several studies that argue that the port sector has features of supply chains, including relationships between organizations (Bichou and Gray, 2005; Panayides and Song, 2008). My findings showed that the model can be operationalized well for the ports. Based on the model, I interviewed all relevant actor organizations: the Harbour Master, pilot organization, tugboat company, boatmen organization, and terminal.

The results showed that the potential to cooperate depends on the service providers considered. While some pairs had the potential to reach a strong partnership, the potential of others was very limited. The relationship with the highest potential for a strong relationship was between the pilot and boatmen organizations. The relationship between the pilot organization and the tugboat company showed the second highest potential. These two parties were equally interested to engage in strong relationships. Notably, the mutuality of interests was unique to this pair. Even more interestingly, they both indicated the same drivers. Improved customer service and flexibility were their main two drivers. Overall, the organizational potential was found to be supportive of a Type 2 partnership. Here, information sharing was two-way but unbalanced, predominantly one party being the sender and the other the receiver. Planning might be performed jointly or individually but shared with the partner to eliminate conflicts or performed jointly.

In the subsequent research, I chose to focus on the pilot organization- tugboat company’s pair, given the above-mentioned findings of Chapter 2, namely the vulnerable position of the towage in terms of information sharing and its bigger share in terms of delays, indicating the need to improve information sharing between the pilot organization and tugboat company.

RQ 3: How does cooperation through joint resource deployment impact the performance of port and its individual service providers?

This question was answered in Chapter 4 using a simulation model. Cooperation was modelled as an information exchange between pilotage and towage service providers during towage peak demands. Peak demands were signaled to pilots when fleet availability reaches a pre-specified threshold. When tugboat capacity droped below a certain threshold, the tugboat company signaled the pilot organization, sharing information about the current fleet capacity and location of tugboats. The threshold was defined as the percentage of the tugboat fleet capacity which was free for the next services. The pilot organization was asked to use this information to prioritize vessels with smaller towage requirements to temporarily reduce the peak demand for towage. This prioritization was based on the required number of tugboats for each vessel, the proximity of the tugboats to be served, and the expected towage duration.

The simulation results showed that the port's performance in providing punctual vessel services was constrained by towage. The pilot organization would be able to offer on-time pilotage services with an average resource utilization of around 75%, while this figure was considerably smaller (around 60%) for the tugboat company. The lower average resource utilization for the tugboat company indicated that the excess capacity needed to provide on-time services is larger. As this excess capacity was not cost-efficient from the tugboat company's perspective, longer waiting times for towage were more likely, making the towage service provider more vulnerable. The results also showed that the waiting time for towage also negatively impacts the performance of the pilot organization. Port managers can emphasize this dependency to incentivize the pilot organization's involvement in developing cooperation in ports. Given these results, the cooperation strategy was judged as applicable in practice, and able to acknowledge the service providers' business characteristics, interests, and boundaries.

The model was also applied to the case of the Port of Rotterdam to evaluate the impacts of this measure. The results showed that cooperation is beneficial for the performance of the whole port as well as the individual service providers. The port could achieve time savings of up to 30% in total vessel waiting times. For the pilot organization and tugboat company, the possible time savings were up to 25% and 30%, respectively. The added value of cooperation is bigger when resource capacity is lower. These findings provided the first empirical assessment and confirmation of the expected benefits of cooperation in ports, as voiced earlier in the literature (Talley, Ng and Marsillac, 2014).

RQ 4: How to jointly schedule vessels and service providers?

In Chapter 5, I presented a mathematical model for the joint scheduling of vessels and service providers. Given the needs and potentials as determined in Chapter 2 and Chapter 3 respectively, I model the highest achievable form of cooperation between the pilot organization and tugboat company: joint scheduling of their resources. The model is formulated as mixed-integer linear programming (MILP) problem, continuous in time, considering inter-service waiting times and sequence-dependent repositioning time of service providers. This formulation made the model generic and applicable to larger busy ports, extending the work of Abou Kasm, Diabat and Bierlaire (2021). I tested three alternative strategies with related objective functions.

I. Minimizing the total sum of deviations of scheduled times from the vessels’ requested times;

II. Minimizing the maximum deviation of scheduled times from the requested times;

III. The currently prevailing first-come-first-serve approach.

I found that different strategies yielded different schedules. Therefore ports need to decide based on which strategy they aim to schedule. Each of the alternative strategies has its own advantages. The advantage of strategy (I) is that the scheduled times of vessels are closer to their requested times overall. However, its disadvantage is that the deviations of vessels vary strongly. Ports that prefer to guarantee a certain service level can adopt strategy (II) which distributes the deviations more evenly among vessels. Both strategies (I) and (II) perform well in minimizing the waiting times after the servicing starts. This is an important result because it reduces the overall occupation of service providers’ resources.

In contrast, in strategy (III), vessels are scheduled with significantly long waiting times during the services. Ignoring the inter-service waiting times have a risk of starting the servicing early but shifting the waiting times to later stages where resources have been occupied, which is inefficient from the service providers' point of view. Therefore, strategy (III) is a less attractive scheduling strategy for the port managers and policy makers who would like to take the service providers' interests into account. This application demonstrates the applicability of the model, using the data from the Port of Rotterdam.

Main RQ: How can vessel service providers cooperate to improve their joint services during the port call, considering their individual organizational interests and characteristics?

Altogether, based on the combined answers for the four research questions above, I conclude that cooperation between the service providers through information sharing can substantially improve port call performance. Among all the actors, pilotage and towage service providers’ cooperation is the most beneficial. At the same time, their cooperation is supported, given their organizational interests. Two cooperation strategies are suggested; joint resource deployment and joint scheduling. The first strategy was based on information sharing for the joint deployment of pilots and tugboats during peak towage demand. In practice, when the available tugboat capacity drops below a certain threshold, the tugboat company will signal the pilot organization by sharing information about the current fleet capacity and location of tugboats. The threshold is defined as the percentage of the tugboat fleet capacity which is free for the next services. Then, the pilot organization is asked to use this information to prioritize servicing vessels with smaller towage requirements to temporarily reduce the peak demand for towage. Such a cooperation strategy is expected to mutually improve both the pilot organization and tugboat company’s performance as well as the overall port. The second strategy was based on the joint scheduling of service providers and vessels. With this strategy, the service providers’ servicing, repositioning, and waiting times are optimally scheduled. The proposed mathematical model can be used by ports, particularly the large busy ports. Ports can also decide based on which strategy they prefer to schedule. A notable conclusion of these studies is that the gains are mutual for the cooperating parties. This is important to incentivize their participation and makes it applicable to practice.

6.2 Managerial contributions and implications for practice

The results of this thesis provide insights for port managers and policy makers. Below I discuss the managerial recommendations that follow.

The first and foremost insight for port managers relates to the main reasons behind vessel waiting times during a port call. I found that these waiting times are mainly due to demand fluctuations from vessels and the over-utilization of service providers during peak demand times. The peak demand for pilots depends on the number of vessels requiring a service, whereas for the tugboats, it also depends on vessel size. Providing on-time services during peak demand for some services requires a large capacity to a degree that is not cost-efficient from the service provider's perspective, making long waiting times inevitable. Managing this pressure, ultimately, requires proactive involvement of the ports in the port call process. This involvement means that the Port Authority assesses vessels' requested time, prior to actual arrival or departure and provides them with feedback based on the availability of service providers so that vessels can slow down to arrive just-in-time (JIT) when resource availability is guaranteed. Besides the reported cost saving benefits and environmental sustainability of the slow streaming experienced by the vessels and shipping companies, this proactive role of the Port Authority can also benefit the other actor organizations in the port, including the terminal, as well as the service providers (IMO, 2020) resulting in timely port services, more efficient use of the service providers' resources, and shortening of waiting times of vessels at ports. Given the growing number and size of vessels calling ports, port managers should prioritize strategies that facilitate the proactive role of ports in the port call process. As the current principle of FCFS puts the port and its service providers under a lot of pressure, alternative strategies, such as minimizing the waiting times, need to be considered.

Secondly, drawing conclusions about the responsibility of individual service providers for performance issues is not easy. Therefore, neither the causes of performance issues nor the measures to mitigate them in port must be seen in isolation. The port services form a complex system that needs to be approached systematically. Often the issues attributed to one actor may be mitigated by the intervention of the rest. My findings showed that some actors might be in a more vulnerable position than others. For example, through different investigations from different standpoints, I reached the same conclusion that the tugboat company is in a vulnerable position from three aspects:

(i) the dependency on the timely submission of information from others (Chapter 2);

(ii) their organizational properties in relation to other actors in port (Chapter 3);

(iii) the inherent nature of their services (Chapter 4).

Translated into practice, the above implies that the future port call performance improvement strategies should support the towage services. The pilot organization is the best candidate to help towage performance improvements for three reasons:

a) Being at the central position with regard to information sharing (Chapter 2);

b) Having equally strong interests in cooperating with the tugboat company (Chapter 3);

c) Achieving performance improvements as a result of cooperation (Chapter 4).

This pair was a good example that developing cooperation in port requires tailoring. As one does not fit all, the cooperation strategies between the other actors are most likely to be different. Therefore, port managers should acknowledge the salient characteristics of the actors and tailor their improvement strategies accordingly.

Regarding information sharing among the service providers, much of the managers' and practitioners' focus has been on facilitating the information flow through ICT. However, what has hampered the advancement of information sharing is not the lack of ICT tools (Lind *et al.*, 2020), but the lack of incentives to cooperate from the actor organizations. The comparison of the current information sharing in practice with the information sharing potentials showed a perfect match between the two. This means that the corresponding level of information sharing was practiced where there was potential. Therefore, information sharing across organizations is an attribute of their relationships. To advance information sharing in practice, it is important to promote the relationship between the parties first rather than targeting facilitating information sharing on its own.

6.3 Recommendations for future research

Several detailed suggestions for future research were presented above, connected to the topics of each chapter. I will not repeat those here. Below I provide recommendations for extensions connected to the overall research topic in three broad directions.

As I have investigated a decentrally governed landlord port in this thesis, a logical direction for additional research is on ports with alternative governance models, such as tool ports or service ports (The World Bank, 2007). How do these models impact the cooperation between actors? Which strategies would be more effective for their performance improvements? How do the differences in power balances (Nurhayati, 2021) impact the port actors' potential for information sharing? These questions are interesting directions for future research. In addition, implementing the suggested approaches on other case studies than the Port of Rotterdam, by carrying out comparative studies, can help generalize our findings on preferred strategies of different ports and their governance models.

A second extension of this thesis could involve the cooperation between vessel and cargo service providers. As the scope of this thesis was limited to vessel services, a range of other port services were excluded. As such, for example, cargo services offered by the terminals, bunkering services as well as hinterland transport services offered by train and trucking service providers were out of the scope. Including the service providers in the hinterland side and exploring their cooperation can further complement the contributions of this thesis.

Thirdly, throughout this thesis, I focused on time-related indicators of performance, in particular, vessel waiting times. I made this choice since providing timely services is a major indicator of port call performance. Translating the time savings found in this thesis into cost savings would be necessary for investment decisions and could be an interesting ground for further research. An item that could be included as a benefit is the cost reductions due to additional slow steaming that results from JIT shipping when vessels can arrive later than planned. We note that this may further complicate the problem of cooperation by introducing new organizational aspects of importance, such as unwillingness to invest in infrastructure or unequal distribution of costs and benefits among the parties.

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Summary

Ports are vital for maritime logistics. With the growth of maritime traffic, ports, and their actor organizations have faced rising pressure. Improving port call performance, to accommodate more vessels in shorter times, is now on top of the agenda for many ports. The performance of ports in offering their vessels services can improve by developing cooperative relationships between the vessel service providers. Service providers can engage in cooperative relationships, share information regarding their resources' availability, and adjust their initial plans. Such synchronization can create a seamless sequence of services, shorten the vessel's waiting times and eventually improve the port call performance. Despite the strong aspiration for this improvement, progress is still slow worldwide.

This thesis discusses that a crucial missing piece for the advancement of cooperation in ports is the perspective of service providers. The existing literature, generally, points out the benefits of cooperation for the port as a whole, assuming that the port service providers would cooperate if it benefits the whole port, regardless of the benefits for the cooperating parties. However, in major ports today, port services are offered by self-governed organizations each of which has its own goals. As these organizations run their own business and have their own resources and characteristics, they are likely to avoid actions and decisions that are not in line with their business, even if collective benefits exist. Therefore, considering the service providers' perspectives when designing mutually beneficial cooperation strategies is crucial. To this end, this thesis aims to improve port call performance through cooperation among service providers, considering the perspectives of both vessels and service providers.

Chapter 1 presents this research's relevance, aim, research questions, and contributions. Next, Chapter 2 determines where cooperation of the port actors is most needed and, hence, port call performance improvements can be obtained. It presents an approach which is based on a mapping of information sharing links and their association with the root causes of delays. The proposed approach is applied to the Port of Rotterdam. Quantitative data of 28000 port calls is complemented by qualitative data collected through direct observations and expert interviews with port actors. First, a full list of

information sharing links during a port call is derived, next, the critical information sharing links are highlighted. The critical information sharing links are those that are essential for an early notice of a delay and informing the relevant parties to avoid delay propagation. The critical information sharing links are grouped into distinct information groups based on specific actors and information content to further condense the required strategies. Besides the suggested information sharing groups, the case reveals the critical position of pilots, the vulnerable position of tugboat companies, and the limited contribution of the terminals toward information sharing.

Chapter 3 explores the extent to which service providers are able and willing to take on the challenge to share information. This chapter proposes a conceptual framework to assess the actor’s potential to engage in cooperative relationships in the context of the port call: the Lambert (2008) partnership model. This assessment enables determining their potential for information sharing, consequently. The applicability of the model is tested for the Port of Rotterdam. The results show that the potential for inter-organizational relationships varies substantially between the port actors, which implies an unequal potential for information sharing between them. While some actors show potential for strong relationships, in which two-way frequent exchange of information is supported, others could only support basic, occasional, or unbalanced information sharing. Therefore, it is unrealistic to assume that the information can be exchanged equally between all the actors. This chapter suggests tailored cooperation and information-sharing strategies that fit actors’ business interests and characteristics.

Considering the expected impact and the service provider's cooperation potentials, the findings presented in Chapters 2 and 3 form the basis for the effective cooperation strategies designed in Chapters 4 and 5.

Chapter 4, assesses the impact of a specific cooperation strategy: joint deployment of resources. It presents a quantitative assessment using a port simulation model where the exchange of information has been made explicit. Cooperation is modelled as information exchange between the pilot organization and tugboat company for the joint deployment of pilots and tugboats. Through application to the case of the Port of Rotterdam, the results show that time savings of up to 30% in waiting times can be achieved, while both service providers improve their performance. These findings provide empirical confirmation of the benefits of cooperation for ports as well as the service providers.

Chapter 5, suggests an advanced form of cooperation that involves the proactive and joint scheduling of vessels and service providers’ resources. It proposes a novel mathematical model which provides a full service schedule created for vessels and service providers’ resources. This servicing schedule was decided based on the vessels’ requested arrival and departure times and the service providers’ resource availability. The model is generic, applicable for larger busy ports, and considers inter-service waiting times and sequence-dependent repositioning time of pilots, tugboats, and boatmen. In order to gain insights about alternative joint scheduling strategies, it tests objective functions based on the best overall port capacity utilization, a minimal level of service, and the currently prevailing first-come-first-serve approach. We applied the model to a practical example from the Port of Rotterdam. The results demonstrate that time savings can be achieved for both vessels and service providers.

Finally, Chapter 6 summarizes the key findings of this thesis and brings them together to address the main aim of the research, synthesize the managerial implications, and provide some recommendations for future research.

In conclusion, this thesis offers generic models and insights for improving port call performance through cooperation between service providers, considering the perspectives of both the vessels as well as the service providers. The findings of this thesis provide inputs for the port managers and policy makers to address the major port call management challenges regarding the facilitation of information sharing, currently on top of the agenda of many ports. Adoption of these recommendations is expected to bring significant port performance improvements.

Samenvatting

Havens zijn van vitaal belang voor de maritieme logistiek. Met de groei van het maritieme verkeer staan havens en hun actorenorganisaties onder toenemende druk. Op de agenda van veel havens staat dan ook de vraag hoe er meer schepen in kortere tijd ontvangen kunnen worden. De prestaties van havens bij het aanbieden van hun scheepsdiensten kunnen verbeterd worden door ontwikkeling van samenwerkingsverbanden tussen de scheepsdienstverleners. Hierdoor kunnen ze informatie delen over de beschikbaarheid van hun middelen en hun oorspronkelijke plannen aanpassen en, indien nodig, hun oorspronkelijke plannen aanpassen. Een dergelijke synchronisatie kan een naadloze opeenvolging van diensten creëren, de wachttijden van het schip verkorten en uiteindelijk de prestaties van het aanlopen van de haven verbeteren. Ondanks het sterke streven naar deze verbeteringen gaat de vooruitgang wereldwijd nog steeds traag.

Dit proefschrift toont aan dat een cruciaal ontbrekend stuk voor de bevordering van samenwerking in havens het perspectief van dienstverleners is. De bestaande literatuur wijst over het algemeen op de voordelen van samenwerking voor de haven als geheel, ervan uitgaande dat de havendienstverleners zouden willen samenwerken als het de hele haven ten goede komt, ongeacht de voordelen voor de samenwerkende partijen. In de grote havens van vandaag worden havendiensten echter aangeboden door zelfgestuurde organisaties die elk hun eigen doelstellingen hebben. Aangezien deze organisaties hun eigen bedrijf runnen en hun eigen middelen en kenmerken hebben, zullen ze waarschijnlijk acties en beslissingen vermijden die niet in overeenstemming zijn met hun bedrijf, zelfs als er sprake is van collectieve voordelen. Daarom is het cruciaal om bij het ontwerpen van wederzijdse voordelige samenwerkingsstrategieën rekening te houden met de perspectieven van de dienstverleners. Dit proefschrift laat zien dat samenwerking tussen dienstverleners mogelijk is met behoud van de perspectieven van zowel schepen als dienstverleners.

Hoofdstuk 1 beschrijft de relevantie, het doel, de onderzoeksvragen en de bijdragen van dit onderzoek. Vervolgens wordt in hoofdstuk 2 bepaald waar samenwerking van de havenactoren het meest nodig is en waar dus verbeteringen in de aanloopprestaties kunnen worden aangebracht. In dit hoofdstuk worden links voor het delen van informatie in kaart gebracht alsmede de onderliggende oorzaken van de vertragingen. De voorgestelde aanpak wordt toegepast op de Rotterdamse haven. Kwantitatieve gegevens van 28.000 aangelopen havens worden aangevuld met kwalitatieve gegevens die zijn verzameld via directe observaties en interviews met experts van havenactoren. Tijdens een bezoek wordt er eerst een volledige lijst van de links voor het delen van informatie opgesteld en vervolgens worden de belangrijkste links gemarkeerd. De essentiële links zijn die welke belangrijk zijn voor een vroege kennisgeving van een vertraging en het informeren van de relevante partijen hierover om verspreiding van vertragingen te voorkomen. De belangrijke koppelingen voor het delen van informatie zijn gegroepeerd in afzonderlijke informatiegroepen op basis van specifieke actoren en informatie-inhoud om de vereiste strategieën verder samen te vatten. Naast de voorgestelde informatiedelingsgroepen legt de casus de cruciale positie van loodsen, kwetsbare positie van sleepbootbedrijven en beperkte bijdrage van de terminals aan informatiedeling bloot.

Hoofdstuk 3 onderzoekt in hoeverre dienstverleners in staat zijn én bereid zijn om informatie te delen. Dit hoofdstuk stelt een conceptueel kader voor om het potentieel van de actor om samenwerkingsrelaties aan te gaan te beoordelen gebaseerd op het Lambert (2008) partnerschapsmodel. Deze beoordeling maakt het dus mogelijk om hun potentieel voor het delen van informatie te bepalen. De toepasbaarheid van het model wordt getoetst op de activiteiten van het Havenbedrijf Rotterdam. De resultaten tonen aan dat het potentieel voor samenwerking van de organisaties aanzienlijk varieert tussen de havenactoren, wat een ongelijk potentieel voor informatie-uitwisseling tussen hen impliceert. Terwijl sommige actoren de potentie hebben om nauw met elkaar samen te werken, waarbij de uitwisseling van informatie in twee richtingen wordt ondersteund, zouden anderen alleen elementaire, incidentele of onevenwichtige informatie-uitwisseling willen ondersteunen. Daarom is het onrealistisch om aan te nemen dat de informatie in gelijke mate kan worden uitgewisseld tussen alle actoren. In dit hoofdstuk worden op maat gemaakte strategieën voor samenwerking en informatie-uitwisseling voorgesteld die passen bij de zakelijke belangen en kenmerken van de actoren.

Gezien de verwachte impact en het samenwerkingspotentieel van de dienstverleners vormen de bevindingen zoals die in de hoofdstukken 2 en 3 de worden beschreven, de basis voor de effectieve samenwerkingsstrategieën die zijn ontworpen in de hoofdstukken 4 en 5.

Hoofdstuk 4 beoordeelt de impact van één specifieke samenwerkingsstrategie: de gezamenlijke inzet van middelen. Met behulp van een havensimulatiemodel wordt de uitwisseling van informatie expliciet gemaakt. De samenwerking is gemodelleerd als informatie-uitwisseling tussen loods organisatie en sleepbootbedrijf voor de gezamenlijke inzet van loodsen en sleepboten. Toepassing van dit model laten zien dat er tijdsbesparingen tot 30% in wachttijden kunnen worden gerealiseerd en dat beide dienstverleners hun prestaties verbeteren. Deze bevindingen vormen een empirische bevestiging van de voordelen van samenwerking voor zowel havens als dienstverleners.

In hoofdstuk 5 wordt een geavanceerde vorm van samenwerking voorgesteld dat gebaseerd is op een proactieve en gezamenlijke planning van schepen en dienstverleners. Dit nieuwe wiskundige model biedt een volledig dienstschema aan schepen en dienstverleners. Dit onderhoudsschema wordt bepaald door de gevraagde aankomst- en vertrektijden van de schepen en door de beschikbaarheid van de dienstverleners. Het model is generiek en toepasbaar voor grote drukke havens. Bovendien houdt de rekening met de wachttijden tussen de diensten en met de volgorde-afhankelijke herpositioneringstijden van loodsen, sleepboten en schippers. Om inzicht te krijgen in alternatieve gezamenlijke planningsstrategieën test dit model objectieve functies op basis van optimale benutting van de totale havencapaciteit van een minimaal serviceniveau en van de huidige heersende benadering “wie het eerst komt, het eerst binnen vaart”. We hebben het model toegepast op een praktijkvoorbeeld uit het Havenbedrijf Rotterdam. De resultaten laten zien dat er zowel voor schepen als voor dienstverleners tijdwinst te behalen valt.

Ten slotte vat hoofdstuk 6 de belangrijkste bevindingen van dit proefschrift alsmede de managementimplicaties samen en doet enkele aanbevelingen voor toekomstig onderzoek.

Concluderend biedt dit proefschrift generieke modellen en inzichten voor het verbeteren van de prestaties bij het aanlopen van havens via samenwerkingsverbanden tussen dienstverleners, hierbij rekening houdend met de perspectieven van zowel de schepen als de dienstverleners. De bevindingen van dit proefschrift leveren input voor havenbeheerders en beleidsmakers op om de belangrijkste uitdagingen op het gebied van het beheer van havenoproepen aan te gaan, onder andere door het faciliteren van het delen van informatie, dat momenteel bovenaan de agenda van veel havens staat. Het implementeren van aanbevelingen in dit proefschrift zal naar verwachting aanzienlijke verbeteringen in de prestaties van de havens opleveren.

About the author

Shahrzad Nikghadam was born on the 29th of May 1989, in Tabriz, Iran. She holds a bachelor's degree in Industrial engineering (2011) from the University of Tabriz, Iran, and a master's degree in Mechanical Engineering (2015) from Middle East Technical University, Turkey. During her master's, she was a research assistant for the "Virtual Enterprise" project, funded by the Turkish Ministry of Science, Technology, and Industry. In that role, she developed original supplier selection models for forming a virtual enterprise- a temporary alliance of small and medium-sized enterprises. Parts of this research formed her master's thesis, which was granted the best thesis award of the faculty (2016). She also worked as a project analyst (2012) and system analyst (2016). Examples of her responsibilities in these roles were conducting project planning and control of railway electrification and designing business process management. Later, she pursued doctoral research in the Transport and Logistics at the Delft University of Technology, The Netherlands, which led to this dissertation.

In her Ph.D., Shahrzad investigated effective strategies to improve the port call process by facilitating the cooperation of the port actors. Her Ph.D. was a part of the "SwarmPort project", Self-organization among autonomous agents in nautical processes in modern seaports, funded by the Netherlands Organization for Scientific Research. Alongside her research, she was also a teaching assistant for the course on advanced logistics (2018, 2019). She also supervised three master thesis projects on improving the port's efficiency and resilience (2019, 2021, and 2022). Aiming to bring what she has investigated through research to practice, currently, Shahrzad is a port call analyst at the Port of Rotterdam Authority, The Netherlands.

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Huang, B., *Assessing Reference Dependence in Travel Choice Behaviour,* T2022/6, May 2022, TRAIL Thesis Series, the Netherlands

Reggiani, G., *A Multiscale View on Bikeability of Urban Networks*, T2022/5, May 2022, TRAIL Thesis Series, the Netherlands

Paul, J., *Online Grocery Operations in Omni-channel Retailing: opportunities and challenges,* T2022/4, March 2022, TRAIL Thesis Series, the Netherlands

Liu, M., *Cooperative Urban Driving Strategies at Signalized Intersections*, T2022/3, January 2022, TRAIL Thesis Series, the Netherlands

Feng, Y., *Pedestrian Wayfinding and Evacuation in Virtual Reality*, T2022/2, January 2022, TRAIL Thesis Series, the Netherlands

Scheepmaker, G.M., *Energy-efficient Train Timetabling,* T2022/1, January 2022, TRAIL Thesis Series, the Netherlands