Cooperation between vessel service providers in ports

An impact analysis using simulation for the Port of Rotterdam

Nikghadam, Shahrzad; Vanga, Ratnaji; Rezaei, Jafar; Tavasszy, Lori

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Shahrzad Nikghadam [*], Ratnaji Vanga, Jafar Rezaei, Lori Tavasszy

The faculty of Technology, Policy, and Management, Delft University of Technology, Delft, the Netherlands

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ABSTRACT

Cooperation between vessel service providers can improve the performance of ports. However, the potential impact of such cooperation has not yet been quantitatively addressed in the literature. 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 pilotage and towage service providers for the deployment of pilots and tugboats. A first application of the model is shown for the case of Port of Rotterdam. We find 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 expected benefits of cooperation in ports as voiced in the literature. Furthermore, the results underscore the importance of moving beyond an ad-hoc synchronizations of these services towards systematic cooperation, to the benefit of ports as well as the service providers.

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 et al., 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 et al., 2020) or tugboat scheduling (Wei et al., 2020) are some examples (Wei et al., 2020; Wu et al., 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 et al., 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.

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* Corresponding author.
E-mail address: S.Nikghadam@tudelft.nl (S. Nikghadam).

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 et al., 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 et al., 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 (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 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 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 2. The port vessel and the associated modeling requirements are presented in Section 3. Next, the simulation model is explained in Section 4. In Section 5, we present the experiments and the results. In Section 6, we discuss the findings followed by the conclusion and future research directions.

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 classifies 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 harbor 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 by 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 et al., 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 et al., 2001), (iii) inland transport companies (Song, 2002), and other ports (Woo et al., 2011; Cheon et al., 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 the 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 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 behavior 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 includes sustainable terminal management (Henesey et al., 2003), berth allocation (Yıldırım et al., 2020), terminal investments (Feng et al., 2020) and crane scheduling (Gracia et al., 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 the following the services and the modeling requirements are described in more detail.

3. Vessel services: challenges and modeling requirements

The main indicator to measures port performance around vessel services is 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 stochasticty in service time and requirements. We detail these out 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 in 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 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 are 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
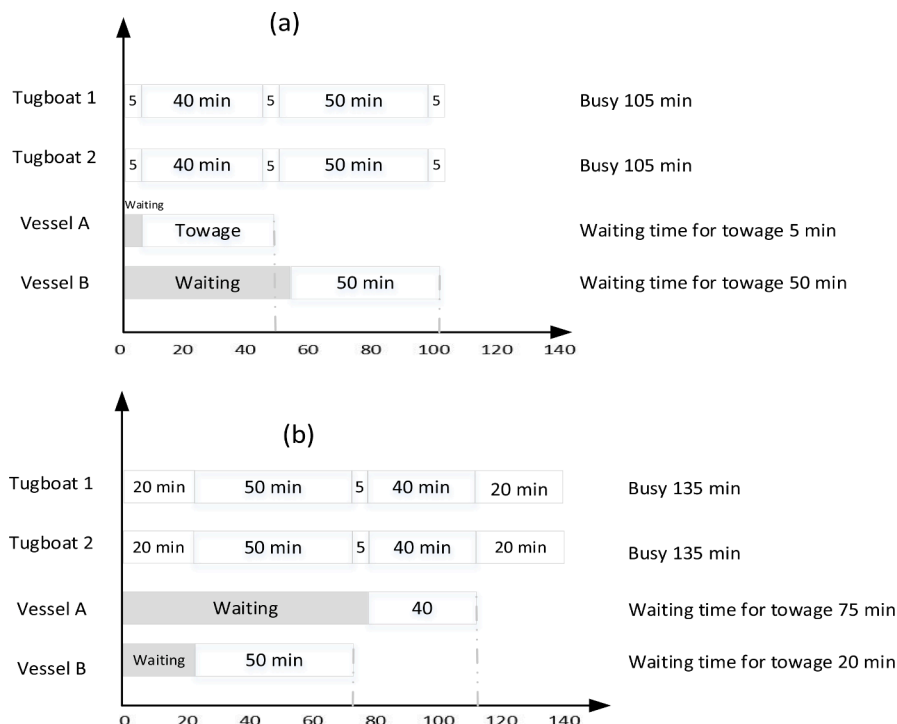

Fig. 1. Effect of servicing order on vessel waiting times: (a) Vessel A served first (b) Vessel B served first.

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.
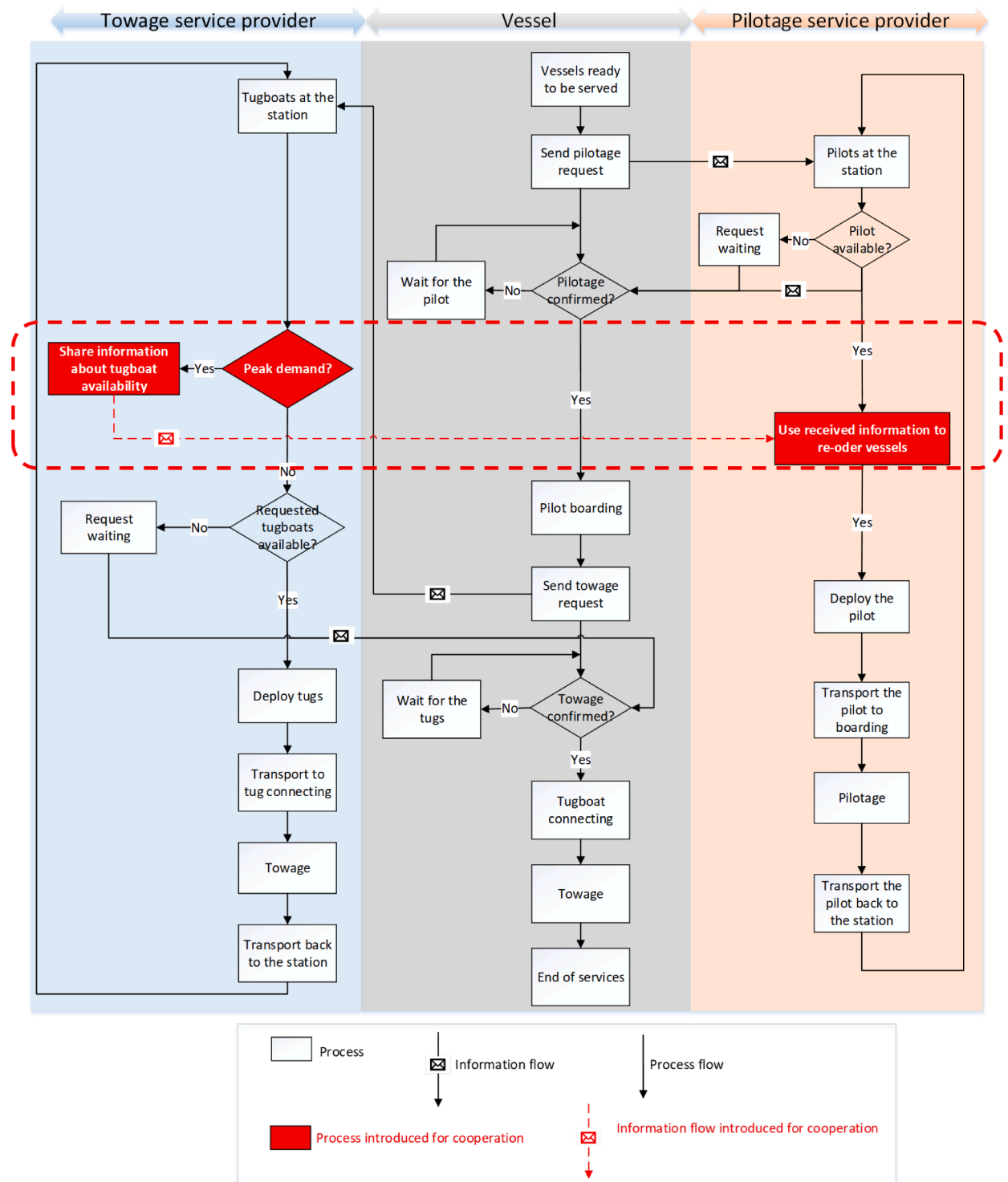

Fig. 2. Schematic diagram of the simulation model.

Vessel A is an incoming vessel with the expected towage duration of 40 min. Vessel B is an outgoing vessel with an expected towage duration of 50 min. The pilotage times for vessels A and B are 100 and 120 min, 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 min, 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 min. By prioritizing vessel A, vessel B must wait 50 min (5 + 40+5) to be served. In this order, vessels A and B's average waiting equals 27.5 min ((50+5)/2). Alternatively, vessel B can be served first, which requires 20 min of transport time for the tugboats to meet the vessel. This order would result in a waiting time of 75 min (20+50+5) for vessel B, resulting in an average waiting time of 47.5 min ((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 min for each tugboat. This simplified example (Fig. 1) shows that the individual service providers' performance and subsequent waiting times are quite different in different servicing orders.

However, if vessel B requests pilot before vessel A, 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).

Another vital characteristic of port operations that effects 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 h 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 order 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. The simulation model

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

Table 1
Model attributes.

Attribute	Description
Input data	Distribution of vessel arrivals per vessel class, mean, min and maximum of 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 in duty), Tugboat company's capacity (fleet in duty)
Scenarios	• Base case • Cooperative case (with information sharing for cooperative deployment of resources)
Simplifying assumptions	• Pilots and tugboats available 24/7 • Single type of pilot. • Single type of tugboat. • 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

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 Fig. 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 shows that, in the new scenario, towage service providers inform pilots as soon as they reach peak demand. We explain the measure further on in the paper in more detail.

The model inputs, outputs, simplifying assumptions are summarized in Table 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 at 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.

4.2. Implementation: case of 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, 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 draft, as shown in Table 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).

The pilotage and towage service times, sailing speed of vessels through the harbor, and the required resources depend on the specific vessel class. Table 3 provides the modelled number of tugboats required in the PoR for each vessel class. The data show that all vessels required one pilot.

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, 2013). 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 validations. 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) 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 2
Port call statistics for 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	
draft (m)			<14.3.3	>14.3	<14.3	14.3–17.4	>17.4	
Number	1750	2062	685	89	154	21	19	4780

Table 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

Table 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%**
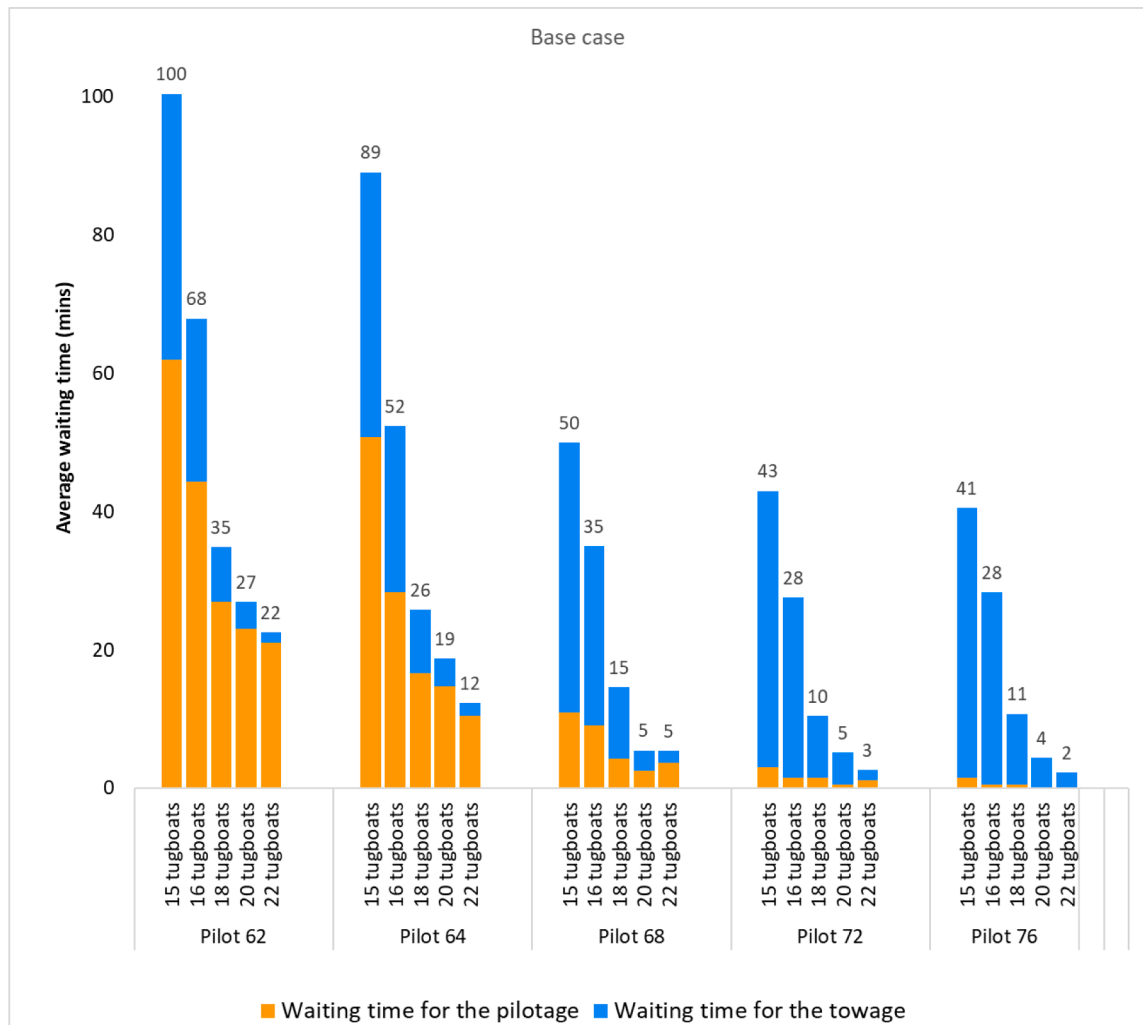
Fig. 3. Average vessel waiting time for services under various capacities; base case.

5. Experiments and results

This section presents the design and results of two sets of experiments: base case and 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 0 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 5.2, we experiment with the cooperative case, compare it with the base case and analyze the performance enhancements.

5.1. Base case – no cooperation

This subsection presents the base case experiments. The data presented in Table 1 and Section 0 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 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. Fig. 3 illustrates the resulting waiting time of vessels from these 25 experiments.

It is clear from Fig. 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 min 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 min 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. Fig. 4(a) concerns the pilot organization, where cross marks indicate their average resource utilization and bars indicate the average waiting time for pilotage. Similarly, Fig. 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.
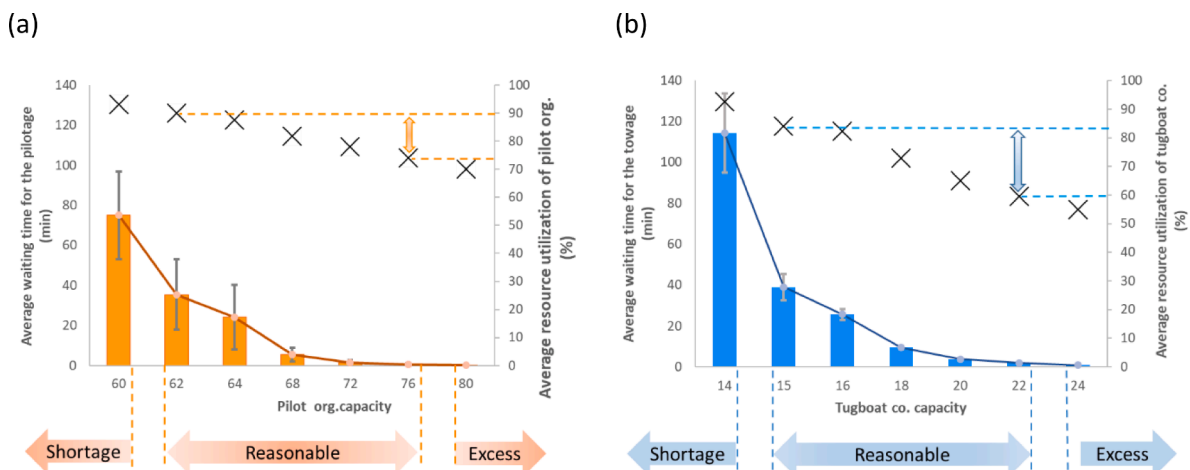
(a)   (b)

Fig. 4. Average resource utilization for the pilot organization (a) and the tugboat company (b); both for the base case.

Fig. 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 rage 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 min for towage but are always less than 100 min 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 the 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. Fig. 5(a) shows the variation in demand for pilots during 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. Fig. 5(b) shows the variation in demand for tugboats throughout in 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. Fig. 6 illustrates the probability distribution function of the demand for the pilots and tugboats over the course of half a year.

Comparison of demand pattern snippets in Fig. 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 arrival of a few big vessels still can create a peak demand for the tugboats.

Fig. 6(a) show 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 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 pilot. This variability explains the earlier results regarding the lower average resource utilization for the tugboat company.

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

5.2. Cooperative case

Based on the insights gained from the base case, presented in section 0, we develop a cooperation strategy in this section and present the results of its assessment. Our aim is to define a solution which addresses the key problem of towage waiting times in peak
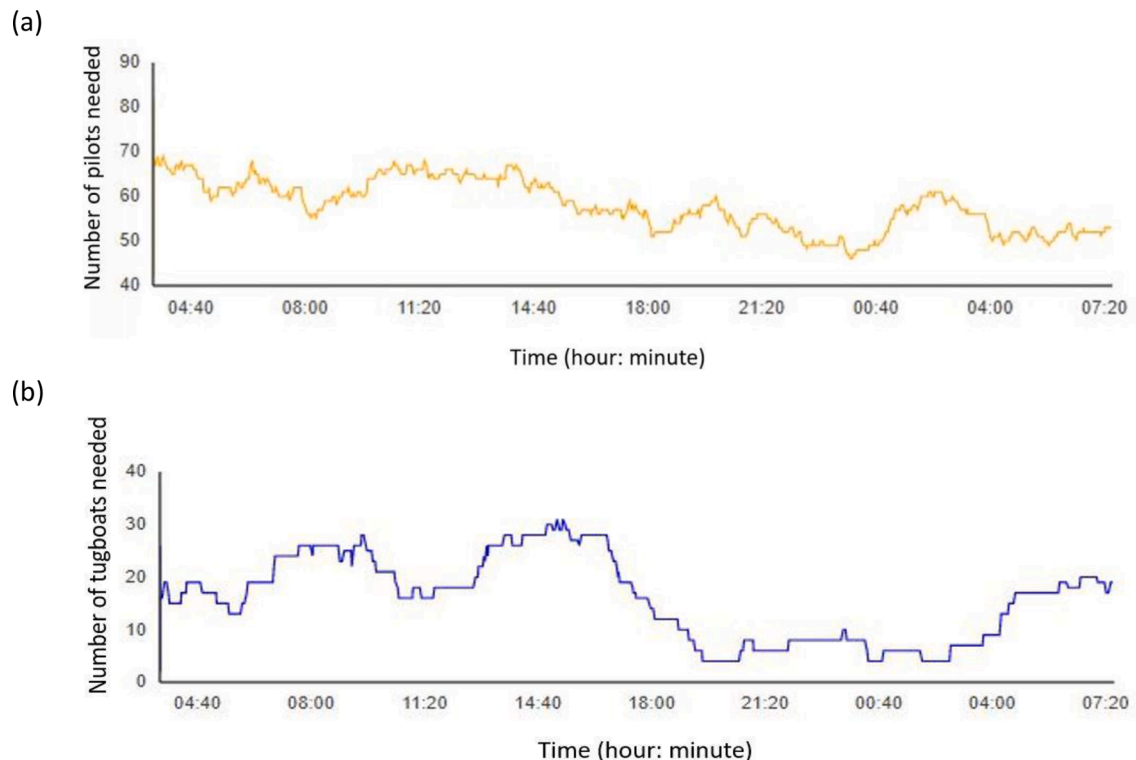

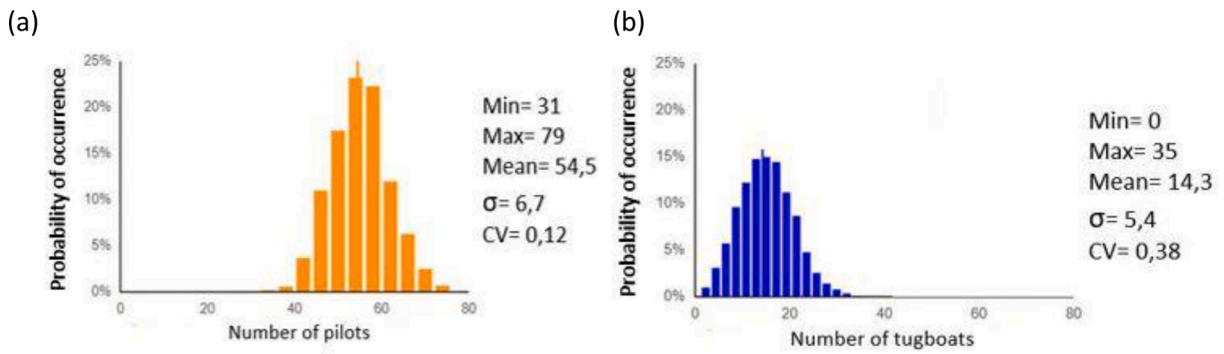Fig. 5. A snapshot of the demand for the pilots (a) and tugboats (b) in a (random) day.

(a)　　　　　　　　　　　　　　　　　　　　　(b)

Fig. 6. Distribution of demand for pilots (a) and tugboats (b).

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 the 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 inputs and outputs of processes* so that 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 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 shortening 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 quantity 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%.

Fig. 7(b) shows the total waiting time of vessels in various capacity combinations for the cooperative case while Fig. 7(a) presents the results in the base case.
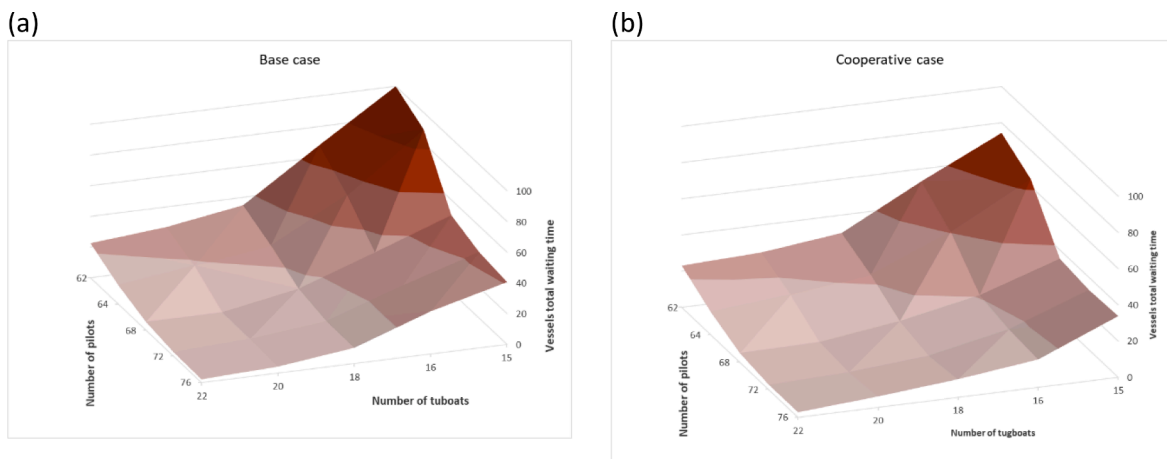
(a)　　　　　　　　　　　　　　　　　　　　　(b)

Fig. 7. Total waiting time of vessels; base case (a) and cooperative case (b).

It is clear from the Figures that the 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 Fig. 8.

The comparison of Figs. 8 and 3 shows that the impact of cooperation depends on the service providers' capacity, reaching a 25% and 30% reduction of 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 min, respectively. These figures were 49 and 25 min in the base case (Fig. 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.

Fig. 9 shows the impact of cooperation for 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.

In order to understand the impact of cooperation on each vessel class, we compared the average waiting time of each vessel class in base case with cooperative case in Fig. 10. The pilotage and towage waiting times are presented in Fig. 10(a) and (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 min for the pilotage and 0–9 min for the towage waiting times). However, these time reductions are bigger for some vessel classes than the others. Note that towage waiting time for vessel classes 1 and 2 in both cases are zero, as these two classes do not require towage assistance.

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
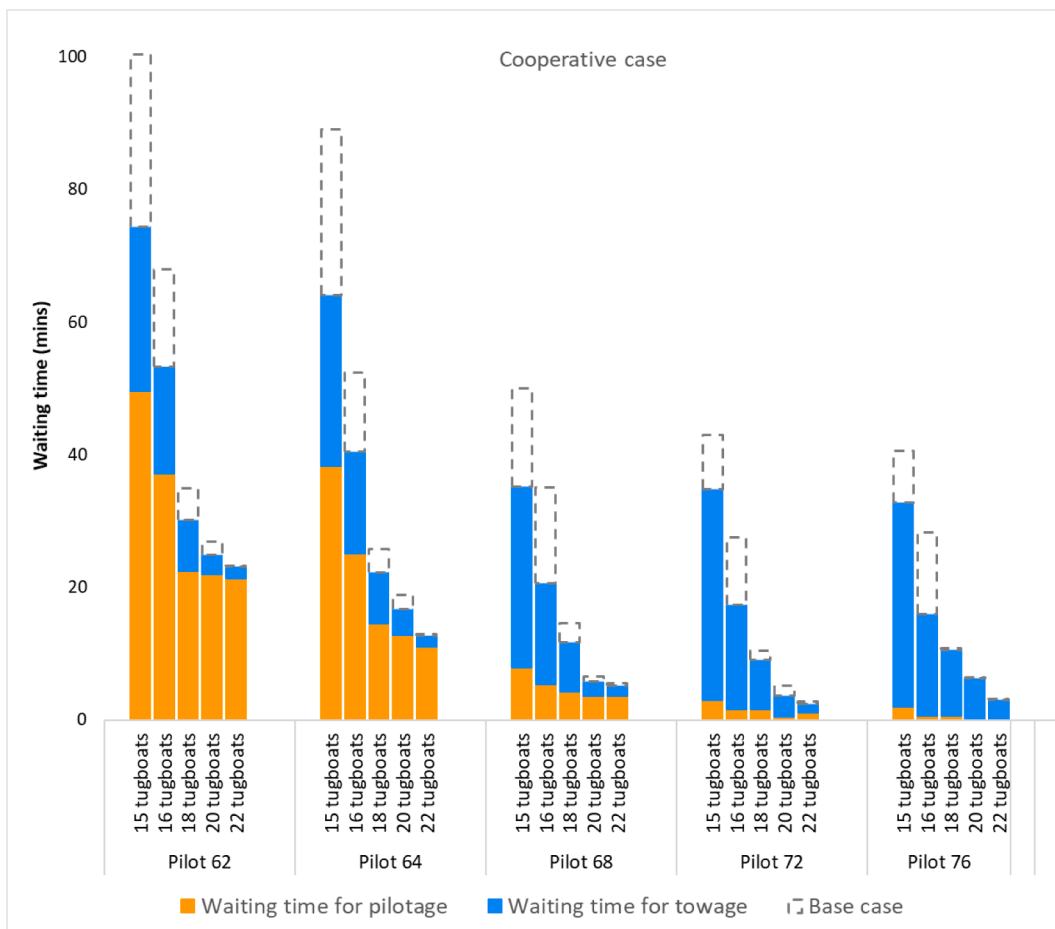

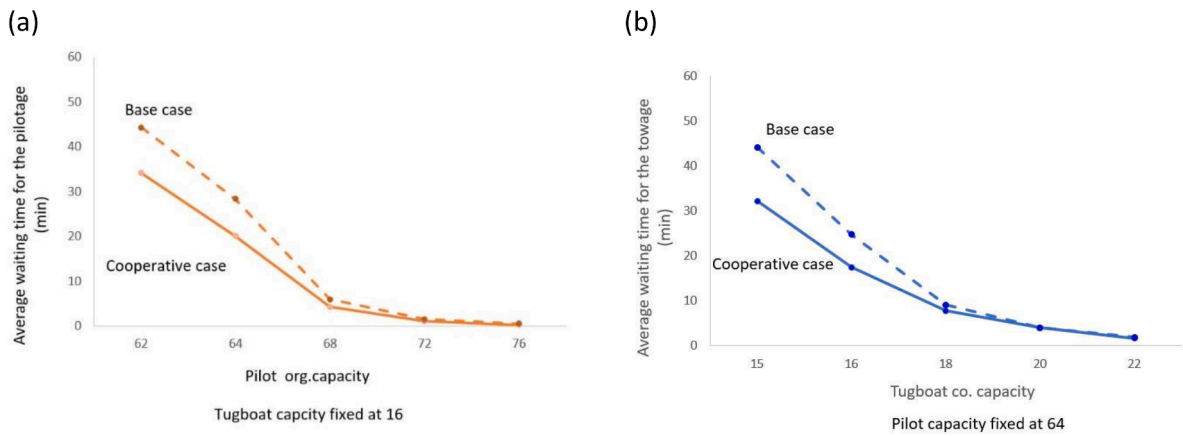**Fig. 8.** Vessels waiting time in various resource capacities; cooperative case.

(a)   (b)

Fig. 9. Average waiting time of vessels for the pilotage (a) and towage (b) in the base and cooperative case.

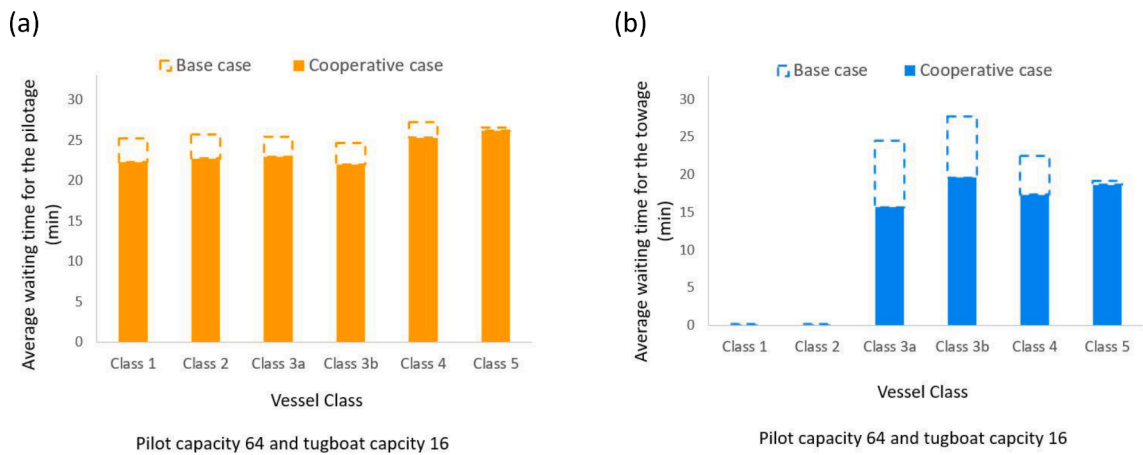(a)   (b)

Fig. 10. Comparison of the average waiting time of different vessel classes for the pilotage (a) and towage (b) in the base and cooperative case.

results i.e. waiting times. For this purpose, we conducted two more sets of experiments with the threshold values of 65% and 100% and compared them with the results of 30% threshold limit. The 65% threshold means that the cooperative deployment of resources starts when the available tugboat capacity reaches it's 65% fleet capacity, while the 100% means the service providers always cooperate. Fig. 11 shows the average waiting time of vessels in various thresholds when pilot organization's capacity is fixed at 64. We chose this pilot capacity as an example. The observations were similar for other pilot capacities.

Fig. 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 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.

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 an 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 min 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
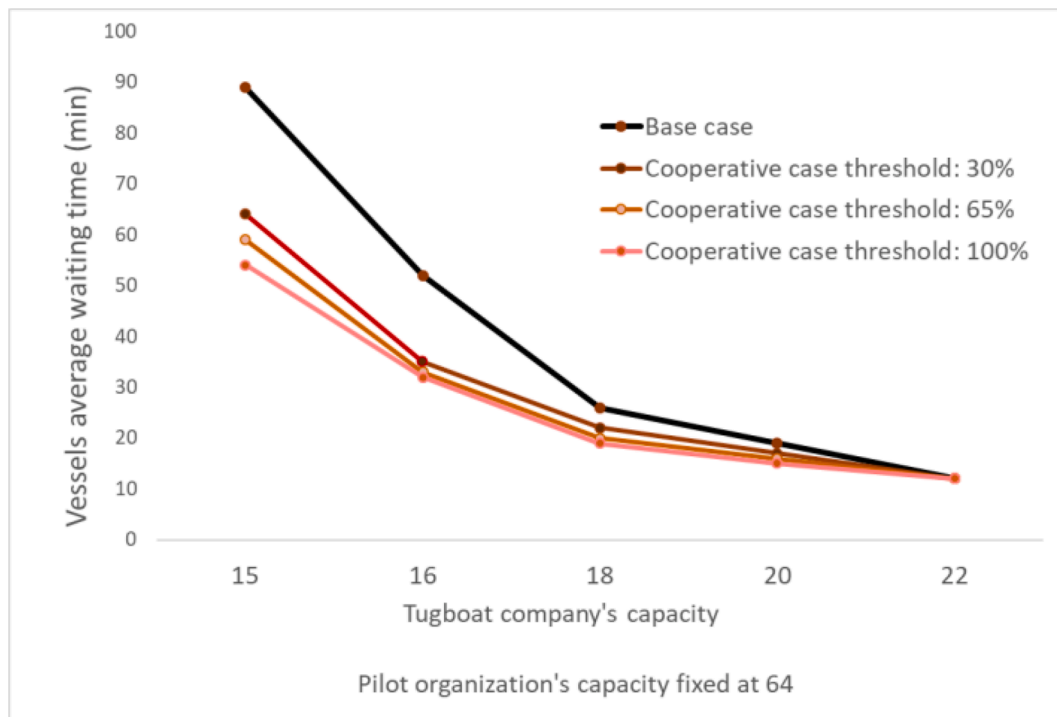
Fig. 11. Sensitivity analysis of the cooperation thresholds.

cost-efficient from the tugboat company's perspective. Therefore, occurrence of longer waiting times for towage is more likely, making the towage service provider the 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 shortening 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 for 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 signaled 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 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 up to 30% in total vessel waiting times. For the pilotage and towage service providers, the possible time saving 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 et al., 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 ground for further research. Finally, we acknowledge that cooperation requires willingness from the parties to share information and adapt their independent practices. Our earlier work (Nikghadam et al., 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 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, are ignored. As the number of tugboats required for serving vessels, in practice, is sensitive to the 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

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.martra.2023.100083.

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