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Empirical agent-based model simulation for the port nautical services: A case study for the Port of Rotterdam

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ABSTRACT

Large deep-sea ports are complex environments where different parties work together to handle ships. The ability to model the deep-sea ship handling process is desired with the goal of what-if ex-ante scenario assessment. In this paper, an agent-based model for simulating the port nautical services in the Port of Rotterdam is presented. The model is constructed based on the real-world process descriptions, and is calibrated and validated based on empirical data. We further show that the model can be used as a tool to analyse scenarios, of which two cases are presented in this paper. The bottom-up modelling approach used in this study provides a methodology to grasp the complex, multi-organizational, aspects of the port nautical service chain. The developed model can be seen as a prototype for a decision support tool for the Port of Rotterdam's Port Authority to analyse the impact of measures on this multi stakeholder system without a central control entity. The modelling approach is scalable to other complex large deep-sea ports with necessary adjustments, in terms of spatial elements, agent representations and empirical data.

Introduction

With almost 30 thousand sea-going vessels visiting the port every year, the Port of Rotterdam is one of the busiest seaports in Europe and the world. For ocean cargo it is a gateway into Europe with direct hinterland connections reaching to central Europe. However in the Hamburg-Le Havre range, where the Port of Rotterdam belongs, there are several major sea ports that compete for the business that ocean carriers bring to the ports. To keep a certain market share it is therefore important that a sea port is an attractive transhipment location. Given the alternatives, the reliability and speed of the port handling processes are important criteria for the selection of the port to call. Next to cargo transhipment and bunkering there is a need for smooth essential processes, specifically, the port nautical services, that enable safe and efficient port calls.

The port nautical services are the pilotage, towage and mooring. The Dutch law states that certain sea-going vessels require a certified pilot for fairing into the Port of Rotterdam and other Dutch ports. The large ocean freighters require assistance by tugboats for manoeuvring in the narrow port waters. Mooring services ensure that the vessels are secured to their berth. Operational cooperation of these different services is required to smoothly complete vessel arrival, vessel shifting between the terminal or berth locations in case a number of terminal locations at the port must be visited, and vessel departure from the Port of Rotterdam. The sequence of all these processes is called the port nautical chain.

High hourly asset costs of large cargo vessels imply ocean carriers rely on the quality of service such as trustworthy schedules and

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timely execution of the port nautical chain processes to minimize asset costs. The quality of service in the port nautical chain depends on the service quality delivered by the individual nautical chain service providers. The pilot organization, tugboat organization and mooring service all need to ensure that services are provided without delays and that no service capacity shortages arise, so as to prevent queues. However there are also individual stakes at each organization and there is not one single customer, but a multi-customer environment with various ocean carriers. Moreover, individual organizations incur costs related to the improvement of their service, while the benefits are realized at the level of the port system as a whole. The multi-organizational nature complicates managing the port system as a whole because there is no central control authority. This is a complex environment where the Port Authority, as policy maker, requires new tools for policy analysis.

This research has been partly driven by the need of the Port of Rotterdam to create a better understanding of the port nautical processes and to find a way of conducting ex-ante assessment of the impact of improvement measures. Thus the model discussed in this paper is aimed at gaining more quantitative insights in the decisive factors and elements in the port nautical services and their influence on general port attractiveness. To support this research, an agent based simulation has been developed which can be used to quantify the impact on macro port perspective of changes that occur on stakeholder level. A simulation model is required as experimentation in real world processes is undesirable. Experimentation in a live port environment is difficult to realize and can possibly adversely impact the operations of the port. Moreover, experimentation requires the involvement of all stakeholders, which can be challenging in a deep sea port. A first concept of the model is described by Davydenko and Fransen, 2019 and a further development, application extension and model calibration on real world observations is described in this paper.

The main contribution of this paper is that, by building on the conceptual model described earlier, this paper shows that it is possible to build an empirically validated model for the nautical services at a deep sea port. The paper describes what data are necessary, how these data are used for calibration, and the quality of this calibration, while validating it quantitatively and qualitatively by showing a right model behaviour under varying port workloads. The paper also presents two use cases that are of practical interest to organizations such as the port of Rotterdam: 1) what would the system experience in case of fluctuating (increasing) workload and demand for the services and 2) what would happen if the system is disturbed by external disruptive events such as that of Suez Channel blockade by a ship, inspired by the Evergreen blockade in 2021.

The motivation for this research has been the absence of instruments that help to understand a complex system, such as a large deep sea port. On one hand, port performance is very important to all stakeholders. On the other, the port is a collaborative structure, where the central authority, i.e. the port authority, has very limited powers to optimize or control processes of other organizations that work at or make use of the port. The port authority legislates and supervises the general rules, mainly related to safety and order in operations, and cannot prescribe any normative measures that go beyond its mandate.

The approach devised in this paper reflects on this. The general rules are established in the simulation model through behaviour and interaction of the agents. The effects of the possible improvement measures will be visible at the level of port performance. The model is implemented in a way that it does not provide normative commands from the central authority, but rather allows the agents to react to the measures in a decentralized environment. This is the novelty of the approach - it relates to the concepts of physical internet (Montreuil et al., 2013) and the fast developing domain of self-organization in transport and logistics, such as the recently published ideas on self-organization in other, but related domains (Gerrits, 2020; Quak et al., 2019).

The agent based simulation model focuses on the physical and organizational aspects of the port nautical chain. Organizational aspects include the scheduling of nautical services and communication between stakeholders to accommodate the requesting and scheduling of nautical services. Physical aspects include the sailing and travelling of the agents through the port, meeting of vessels and pilots for pilotage, meeting of vessels and tugboats for towage and berth space occupation by the vessels. Combining both physical and organizational aspects in the same simulation model allows for a scenario-wise impact analysis on the physical process durations and the quality of service. The scenarios can have different natures: starting from capacity of nautical services to different ways of service organization, information exchange and collaboration forms between the stakeholders. The vessel traffic rules and regulations are out of scope of this study and therefore not directly incorporated in the simulation.

The application of agent based modelling to the port nautical services is a relatively novel approach, as to our knowledge, examples of agent-based approach for a real world port using real data are scarcely presented in literature. To gain trust of the future users of the model and to show the empirical quality of the modelling approach to the scientific community, the model has been calibrated using different sources of real world data. Showing a successful calibration of an agent based model is one of the objectives of this paper. The model calibration ensures that the processes that are not explicitly treated by the model, such as vessel traffic rules and nautical regulations, are also implicitly incorporated into the model to ensure empirical validity. The bottom-up approach has been chosen to make a modular simulation model in which behaviour can be changed for scenario analysis. Agent based modelling is used to find macro patterns that emerge from micro system rules in the complex system of the port nautical chain.

Background on agent based model applications has been researched and is described in chapter 2. In chapter 3 the modelled processes and used data are described. Chapters 4 and 5 continue with the calibration and validation of the model. Subsequently in chapters 6 and 7, the model outcomes and two use cases are presented. Chapter 8 contains the conclusions from this research. In addition to this paper, a set of guidelines on applying the developed model can be found in (Fransen et al., 2021).[1]

[1] https://repository.tno.nl/islandora/object/uuid%3Ae6d3783d-e010-4314-bb2e-3738a1d19ba3

Simulation modelling in maritime ports and port logistics

The first concepts of agent based modelling arose in the second half of the 20th century (Schrödinger, 1943; Neumann 1944; Gardner, 1970; Hanappi, 2017). Recent developments in computing power have allowed for much more extensive implementations of these type of models and have led to the first example of implemented simulation models with an agent based approach (Macal and North, 2005; Niazi and Hussain, 2011). For this research literature on agent based approaches and other simulation approaches in deep sea ports have been studied. Applications in logistics case studies and sea port simulation are available, but to the best of our knowledge, no specific literature on agent based modelling in Port Nautical Chain processes is available, besides the earlier work in Davydenko and Fransen, 2019. Literature found on port simulation models focus on different processes in deep sea ports and use different modelling techniques.

Discrete event simulation (DES) is a widely used approach in simulating processes in deep sea ports. Quy et al. (2021) show a possibility to evaluate performance changes for various port investment scenarios. Other applications of discrete event simulation of port processes, such as for container terminal processes can be found in Legato and Mazza, 2001; Budipriyanto et al., 2017; Fajar et al., 2018; Tri Cahyono et al., 2019, while other port processes are covered in Howard et al., 2004; Wang, 2004; Wahed et al., 2017; Legato and Mazza, 2001 present a simulation model to conduct a what-if analysis on the berth planning problem. Budipriyanto et al., 2017 and Tri Cahyono et al., 2019 simulate a container port and optimize berth and quay crane allocation. Budipriyanto et al., 2017 show improvement in ship waiting time and container handling time if container terminals collaborate. Tri Cahyono et al., 2019 show improvement on assignment of resources by their algorithm compared to First-Come First-Serve assignment. Howard et al., 2004 present a DES simulation model to model resource competition to analyse movement of military cargo through seaports. Wang, 2004 provide a simulation study to analyse the waiting time and queue length for ships visiting a deep sea port. Wahed et al., 2017 simulate port performance on the level of cargo throughput. These findings show developments in the simulation of port processes, but the focus is generally on cargo or container handling and the optimization of resource allocation on cargo handling processes.

Some port simulations include tugboats or tugboat scheduling (Wang, 2004; Liu and Wang, 2005; Wang et al., 2010; Wenhui, 2011; Özlem et al., 2011; Chang et al., 2012; Ilati et al., 2014). Liu and Wang, 2005 present a discrete event method of simulating tugboat allocation. The allocation of tugboats is optimized using chaos search, particle swarm optimization, in Wang et al., 2010. These studies show that improved scheduling techniques for tugboats can benefit port processes. Chang et al., 2012 confirm the effectiveness of using particle swarm optimization in tugboat scheduling. Wenhui, 2011 present a heuristic algorithm for optimal tugboat allocation using an evolutionary method that increased adaptability and diversity of the allocation system.

Özlem et al., 2011 developed a simulation that shows the impact of pilot and tugboat resources on traffic performance in the Strait of Istanbul. In their model, pilots and tugboats are only implicitly modelled as a required resource and the specific allocation and scheduling of these services is not included. Subsequently, for the strait of Istanbul, (Ucan and Nas, 2016) developed a discrete event simulation model and provide a solution for the nautical service allocation problem for pilots in this strait. They conclude that optimization of the number of pilots and tugs as well as resource allocation problems, berthing area selections and many more complex and inherently stochastic problems can be reliably solved by simulation experiments. Ilati et al., 2014 use an evolutionary algorithm to find a good global assignment of tugboats, berths and quay cranes. These studies present approaches on simulation of nautical chain processes using a system dynamics approach. In contrast to the above mentioned studies, we present an approach to the port nautical chain that considers it as a complex system, as opposed to from a system dynamics perspective or an optimization perspective. Agent based modelling has been chosen as a modelling approach as it fits well to this purpose. A benefit of agent based modelling compared to discrete event simulation in port terminal simulation is that the communication processes can be explicitly modelled (Fajar et al., 2018) and, if necessary, modified and analysed scenario-wise.

There are some applications of agent based approach in deep sea port related areas. Dragović et al. (2006) present a model developed for evaluation of port performance and port turn-around time. Other applications in sea ports focus on terminal processes (Bin and Xin-qing, 2010; Garro et al., 2015; Muravev et al., 2021), simulation of port expansion plans (Wibowo et al., 2015) or port stakeholder management (Henesey et al., 2003). Jiménez et al., 2021 present a multi-agent approach on information sharing in the Port of Cartagena (Spain) to reduce anchorage time, but apply mixed integer linear programming to quantify a theoretical improvement instead of using simulation. Agent based approaches are also being used in the port simulators used for training ship and tugboat pilots (Longo et al., 2013; Longo and Nicoletti, 2015).

Other port related agent based model applications are developed by Lee et al. (2003), Vidal and Huynh (2010), Démare et al. (2017a) and Gerrits et al. (2017). Vidal and Huynh (2010) describe an agent based model for simulating container crane operations in a seaport container terminal. Lee et al. (2003) uses an agent based model to simulate a supply chain as a complex system to get grip on the multi-objective, interdependent business processes. The different stakeholders in the port nautical chain also have individual business objectives and require cooperation in the service chain, thereby implying an interdependence in their business performance. Gerrits et al. (2017) designed a multi-agent simulation to analyse the performance of automated yard tractors on a container terminal and show validity of using multi agent simulations for a container terminal with a complex system approach.

For the development of the port nautical chain simulation model, a performance measure is required. The port nautical services play a major role in the performance of ship handling in a deep sea port, next to handling by cargo terminals. Studies that look into port attractiveness or research into port services do not focus on details related to the nautical chain service providers and their interaction with overall port performance. A key factor for port performance is vessel turnaround time, as it is considered by ocean carriers as the most influential factor in their competitiveness (Cruz et al., 2013). Clark et al. (2002) state that increasing port efficiency could lead to a shipping cost reduction of 12%, which could a key determinant factor for ocean carriers to be attracted to efficient ports.

Port attractiveness can be related to costs. Tavasszy et al., 2011 have shown that generalized port costs resulting from port operations directly influence port transhipment volumes. The quality of the port nautical service chain is a determinant for the port performance and subsequent generalized port costs. A methodology for evaluating port performance was developed by Talley et al. (2014) and explicitly includes aspects of nautical service collaboration. The individual service performance impacts the overall port performance as congestion at an individual service provider can propagate through the port system (Talley and Ng, 2016). Increasing the reliability of the port nautical service chain could benefit the sea traffic management. Enabling just in time operations with improved sea traffic management could lead to a 15 to 23% reduction in fuel use and greenhouse gas emissions (Arjona et al., 2020).

Observing the port nautical chain as a multi agent system requires an insight into individual actor processes and interactions between the port nautical chain actors. Inter-organizational aspects in port actors are identified by Martino and Morvilo (2008) from a macro perspective. They identified the fundamental role of the Port Authority in identifying critical assets in port actors that create port competitiveness and satisfy port client needs. For a more detailed, micro-level port nautical chain, the essential decision making criteria and organizational interaction are yet to be identified as the modelling of port nautical service providers is not a common practice. One optimization model for the integration of pilot scheduling and vessel traffic management has been developed by Shuai et al. (2019), wherein an integer programming model has been developed which can identify sensitivity of traffic density and number of pilots on the traffic capacity. However, in a multi-stakeholder environment, a real world optimization of processes executed by different and independent organizations is challenging to implement in practice.

The choice for an agent based simulation model is partly attributed to the requirement to incorporate behaviour of individual service actors and to combine individual behaviour with the propagational effects in the port system. Van Hee et al., 1988 describes that the integration of different models, which each describe different decision situations, is a major problem in the development of decision support systems. A multi-agent approach allows the integration of different decision approaches in a simulation model. A challenge, as observed in the literature is that calibrating agent based models is not straightforward (Zhang et al., 2020). There is still a lack of effective parameter calibration methods due to computational restrictions. This paper presents a successful case for the calibration of such a model on real world data. Another challenge to overcome in calibration is the nature of agent based models with respect to matching single target values in real-world observations (Fagiolo et al., 2007). That difficulty is solved by minimizing the difference (i.e. root-mean-square deviation) between modelling outcomes and the observed set of goal parameters. Thus, the calibrated model satisfies the requirement of applicability by showing its practical utility as a decision support system with a sufficient level of realism.

The literature shows various applications of agent based models in deep sea port operations and many simulation approaches for port terminal and nautical processes. However, next to Davydenko and Fransen, 2019, no application of a complex system approach to analyse port nautical chain performance has been found in literature. Therefore to our best knowledge, we present a novel approach to model the port nautical chain process. In this a paper a new application of agent based modelling on the port nautical chain is proposed. Additionally, we apply a calibration method and show empirical validity of the presented agent based model.

The scientific contribution of this paper is in showing the empirical validity of an agent-based approach for a practical case study for the Port of Rotterdam. The simulation models information and physical flows in the port call process. The developed methodology can be applied at other deep sea ports, but port specific organizational aspects and geographical scope would require alterations and subsequently calibration to make the model fit for purpose. Having this model for the Port of Rotterdam provides the Port Authority with the means to analyse interaction between port calls, the port nautical chain and the port infrastructure. It allows to study the impact of policy measures or changes in port resources or infrastructure on the port deep sea ship handling process.

Simulated processes and data used

This study focusses on the deep sea ship handling processes in the port nautical chain at the Port of Rotterdam. In this section we describe the essence of the modelled processes, agents and agent interaction. Details on the model implementation can be found in (Fransen et al., 2021). The key processes in the port nautical chain are the pilotage and tugging as described by Verduijn (2017). These are the main processes integrated in an agent based port nautical chain simulation model by Davydenko and Fransen, 2019, as these processes have the biggest impact on the quality of deep sea vessel handling chain. The agent based model focusses on the following processes: 1) ship arrival process (from the start of the port visit until it is berthed); 2) a so-called shift process (from berth to berth within the port of Rotterdam); and 3) the departure process (from berth to port departure – leaving the geographical area of the port). The processes while berthed, such as loading and unloading or bunkering, are out of scope and the time the ships spend at a certain berth are assumed to be known. The presented model describes the behaviour of port nautical chain actors as agents in the model and the interaction and communication between these agents to simulate the port nautical chain process.

The modelled arrival, shifting and departure processes of a deep sea vessel consist of the physical sailing process with routing, timing and use of the nautical services in parallel with the organizational aspect of information exchange – announcing the port call to the Port Authority, requesting a pilot at the pilot organisation and requesting tugboats at a tugboat organisation.[2] At the Port of Rotterdam a pilot is legally required for most deep sea vessels; tugboats are essential for manoeuvring of deep sea vessels through the narrow passages of the port. The dynamics in the port system and the variety in processes create challenging scheduling problems for the pilot and tugboat organisations. The agent interaction and information flow to accommodate the port nautical chain organization has been studied by Molkenboer (2020) and Nikghadam et al. (2020). In this agent-based model, the agents interact and communicate

[2] There is a single pilot organization and multiple tugboat provider organizations at the port of Rotterdam. The fact that there are multiple tugboat organizations at the port is neglected in the model.

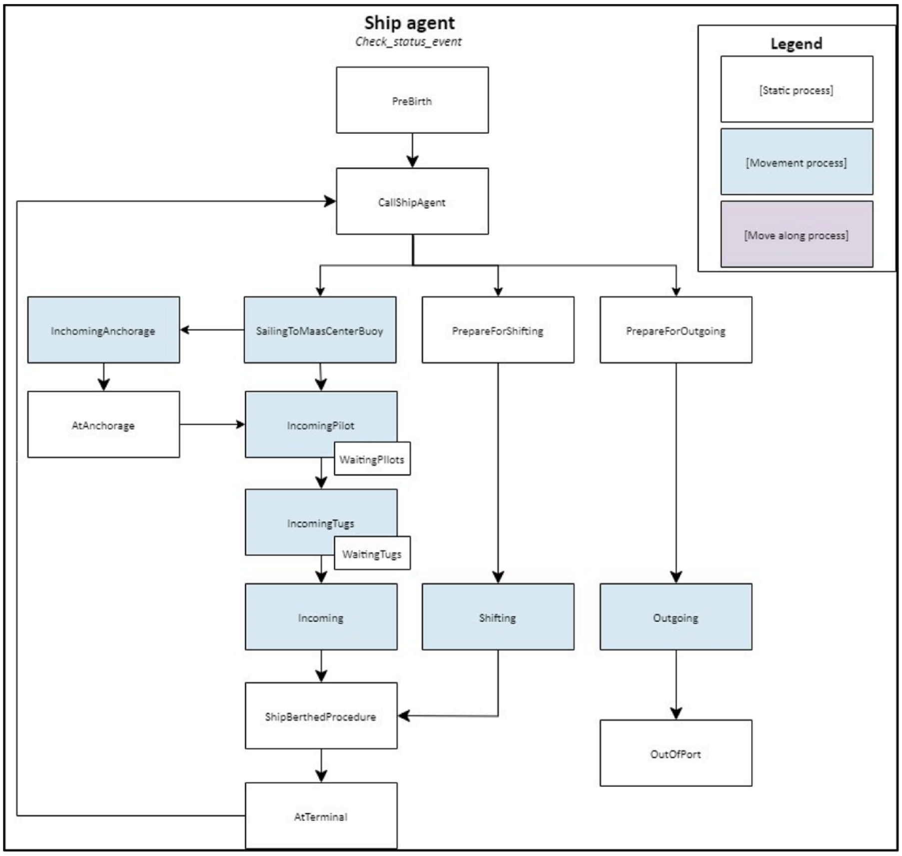

Fig. 1. State flow of ship agent.

via one of two communication platforms or via direct agent-to-agent communication. Note that traffic and safety rules complicate deep sea ship navigation in port waters, but they are treated as out of scope of the developed model. Traffic rules add another dimension to port dynamics,[3] however are considered of relatively minor influence on the turnaround times for the deep sea vessels, which is the primary indicator under investigation by the presented model.

The agents that are implemented in the simulation model are the following:

- Deep Sea Ships
- Pilots
- Pilot Organization
- Tugboats
- Tugboat Organization
- Port Authority

Agent based modelling technique has been used to simulate the system performance based upon individual agent behaviour and to identify emergent system response to change in agent behaviour. The key agents in the port operations can be categorized as physical agents (Deep Sea Ships, Pilots and Tugboats) and organizational agents (Port Authority, Pilot organization and Tugboat organization). Both the physical and the organizational processes that take place in the port nautical chain are included in the model. The integration of physical locations of agents and their movements (physical representation) and job-scheduling (based on information flows) are essential for the representation of the nautical processes at the port. The scheduling of agents presents a nested optimization problem within the simulation. For the pilot and tugboat organization it means that these organizations repetitively schedule their resources to perform their tasks; scheduling problems generally belong to the class of computationally hard problems, which is a challenge for simulation, where scheduling has to be done repetitively.

Examples of physical processes are routing through the port and connecting tugboats to the deep sea ships. These processes are

[3] The Port of Rotterdam has models to analyse the ship traffic and in daily operation. The operational traffic control is deemed to be low level detail of this model thus deemed to better handled by other applications.

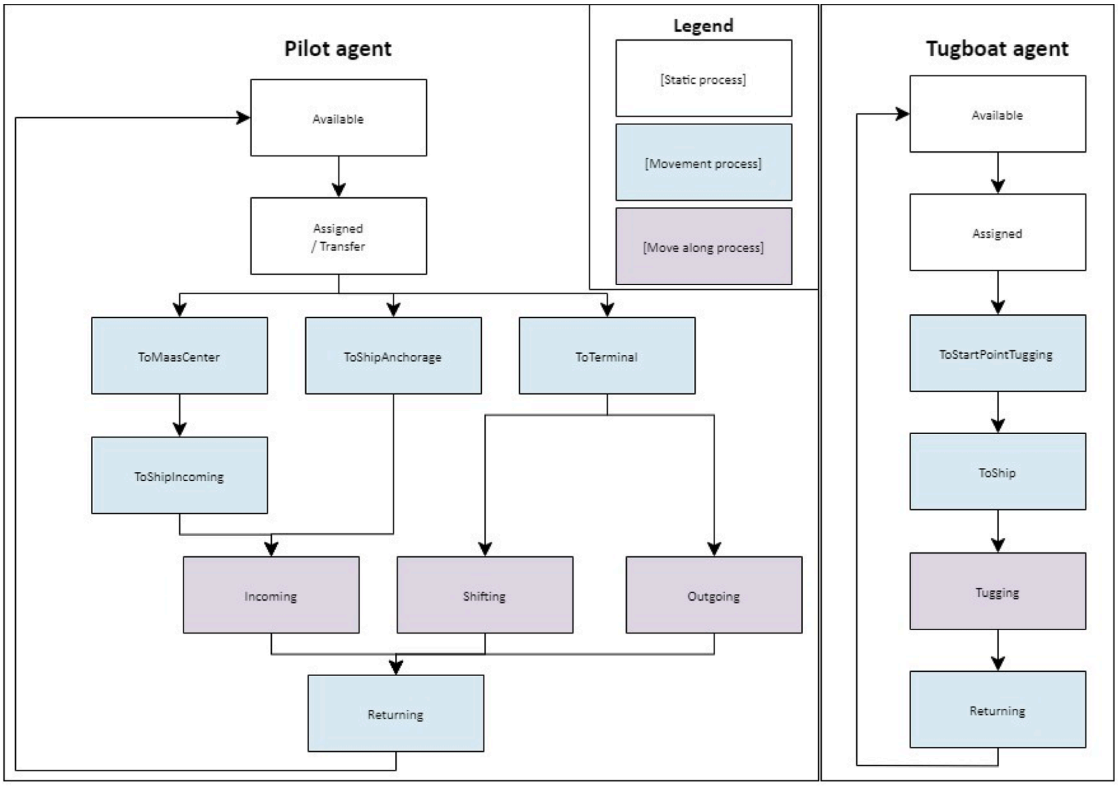

Fig. 2. State flow of pilot and tugboat agents.

known in detail and are implemented in the model such that process times in the simulation match with practice. The agent movement speeds have been calibrated such that the implemented abstraction of the physical process matches real world observations and provides correct movement durations in relation to the port nautical chain process. The three main elements of organization that have been modelled are:

- providing clearance for arrival to ships by the Port Authority,
- scheduling of pilots and
- scheduling of tugboats to the ships by the Pilot and Tugboat Organizations.

To implement these processes in the agent based model, the physical agents have been implemented as a so-called state-machine, where in a state, an agent executes state-logic until the requirements to go a sequential state are met. All the implemented states and the state flows are presented in Fig. 1 and Fig. 2. State transition can depend on the state and position of other agents, provided clearance by Port Authority or on assignments from the Pilot and Tugboat organizations. These organizational agents only have a single state logic of retrieving information on requests and processing these requests, either: 1) by providing clearance to ships by the Port Authority or 2) by assigning service agents to ships as done by the Pilot and Tugboat organizations.

Communication between the agents happens on two different platforms in the simulation. The first platform registers the position of all agents and is used such that agents meet each other and can verify they are close together. This platform is comparable to the Vessel Traffic management System (VTS) of the Port of Rotterdam. The second platform is used to share the information of port call requests, clearance and assignments of service agents. This platform shows similarities to the Rotterdam HArbour Master Information System (HAMIS).

All the agent logic and the simulation logic have been implemented in Python. In this manner all model elements are flexible and can be changed as separate modules in the simulation model, without dependency on third-party software. A downside in this approach is related to the fact that Python is an interpreting language and, therefore, it puts constraints on the model speed. The strategic nature of the model does not require instant solutions and Python, therefore, is considered to fit well for the modelling goals. The results presented further in this paper shows that a Python based implementation can be used as a programming platform for such an agent based model.

To make an empirically valid simulation, all agent parameters such as sailing speeds and meeting locations of ship and tugboats require realistic values. Therefore data on the modelled processes was gathered from real world data observations. Ship, tugboat and pilot transport movements are broadcast by the Automated Identification System (AIS). The port call data (provided by the Port of

Table 1
Reference process durations from AIS data and Port call data from the Port of Rotterdam. (Kaljouw, 2019).

Indicator	Agent type	Reference value
Incoming nautical chain duration	Ship, pilot	93 min
Outgoing nautical chain duration	Ship, pilot	77 min
Duration of tugging incoming ship	Tugboat	44 min
Duration of tugging outgoing ship	Tugboat	25 min

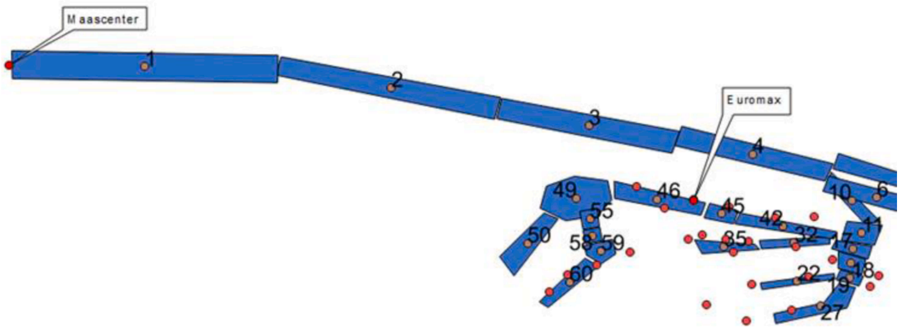

Fig. 3. Overview of water section numbering and berth locations in the Port of Rotterdam Maasvlakte. This figure excludes major port areas such as Botlek, Waalhaven and Europoort.

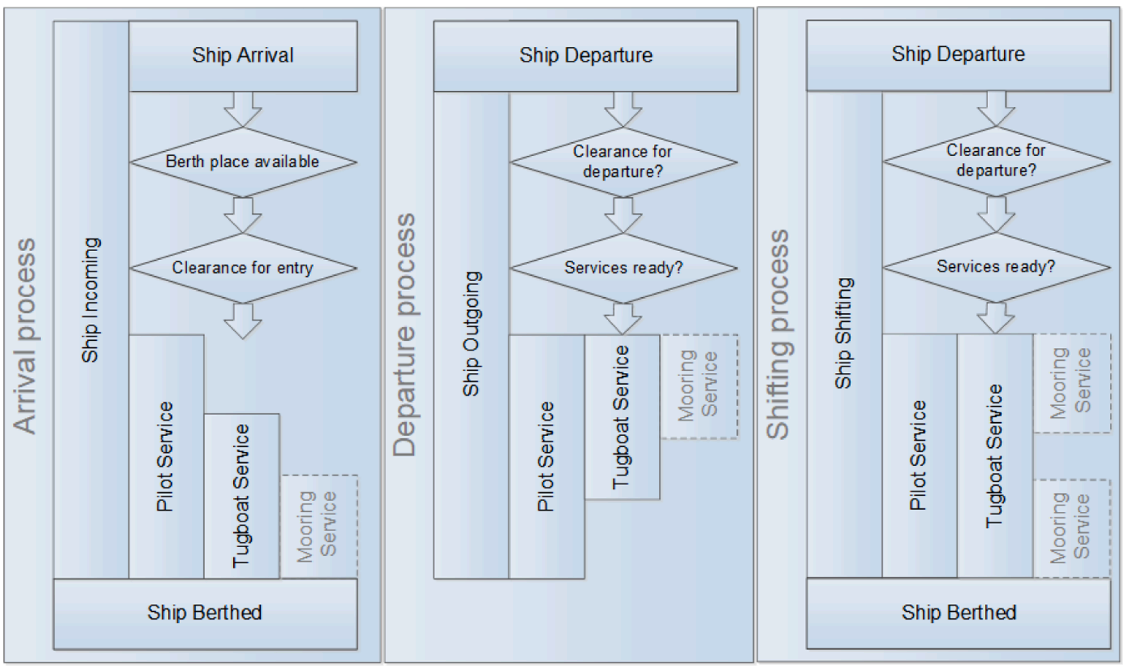

Fig. 4. Abstraction of implemented arrival, departure and shifting processes.

Rotterdam) contains timestamp registrations of ship movements together with movement announcements, start of movement and end of movement including number of used tugboats and pilots. Using AIS data on ship, tugboat and pilot movements and combining the AIS data with ship arrival and departure data from the port call data (Kaljouw, 2019), estimated process durations for the port nautical chain are evaluated. These process durations are considered to define the system performance for the port nautical chain and are shown in Table 1.

Part of developing and implementing the simulation model is calibration of the model, which is needed to ensure that the model represents the real world performance of the port nautical chain process at the Port of Rotterdam. Calibrating the model is a challenge as there is a certain degree of chaos in the modelled complex system, while the quality of calibration is measured by deviation from observed aggregate variables. In other words, the calibration input variables have an unknown non-linear relationship with the quality of calibration. Note that the simulation result is also dependant on the initial seeding of the system: this problem is solved by numerous model runs initiated with different seed values.

The calibration of a bottom-up model of this paper is done on macro performance indicators, where the model parameters are on agent level and parameter changes directly influence individual agent performance. The changes in agent-level parameters result in changes at system level performance and measured by aggregated indicators such as the average turnaround time. Note that quantifying the impact of agent changes on system performance is one of the reasons for developing this simulation model. These observed process durations have been used as a benchmark for the model-estimated equivalented, in other words, these are the model calibration values.

Next to the data on the port nautical chain processes, the data describing the spatial environment of the Port of Rotterdam is also an input to the model. The spatial / physical environment is given by a network of connected waterway sections describing all the waterways and bays in the port together with the geolocations of deep sea ship berths (terminal areas where cargo is loaded and unloaded, as well as bunkering activities take place). The numbered water sections are used to route ships from port entrance to a specific berth, as well as the shift movements between the berths and the port departure movements. Fig. 3 shows a part of the water sections and berth locations in the model.

Fig. 4.

Implementation of multi-agent simulation model for the port nautical service

In Davydenko and Fransen, 2019 a conceptual model has been described for simulating the port nautical service chain. The conceptual model has been extended with real-world data, process details and calibration. The developed agent based simulation model simulates the port nautical chain process of deep sea ships arriving at and departing from the Port of Rotterdam. In these processes the deep sea ships receive service from pilots and tugboats. The first version of the model has proved to provide decent simulation results, specifically adequate behaviour with respect to ship flows and service capacity impacts on the quality of the ship handling processes. However, the model lacked an empirical connection to the actual data of reality, as only a part of the Port of Rotterdam was simulated, the used parameters were not fully realistic and the model had not been calibrated. This study presents a further developed model on the port nautical service chain. The model includes the whole area of the port of Rotterdam, more details on agents and ship arrivals, shifts and departure processes and scheduling of service agents by organizational agents. Moreover, the model has been calibrated on observed data. An abstraction of the simulated arrival process is provided in Fig. 2.

Straightforward scheduling heuristics in the form of a first come – first served have been implemented due to a lack of insight on operational details of pilot and tugboat organizations. For this version of the model the practical approach on scheduling processes of the pilot and tugboat operations present an alleviation of computational requirements, as scheduling has to be done repetitively and in general is computationally hard. However, a production-level decision support system should not neglect inner processes at piloting and tugboat organizations, therefore, this issue is further revisited in the recommendations section of this paper.

Examples of scenario related input of the simulation model are system parameters, such as the number of pilots or tugboats in the system or the operating speeds of the various agents. Next to these parameters, scenario input could also be the changing agent behaviour or business rules. Output of the model is a set of key performance indicators for evaluating the system performance for the simulated scenario – the scenario outcomes can be compared to the reference scenario, which is the default calibrated state of the model. On the system level, the performance of the port nautical chain is observed as the total turnaround time of vessels in the port and total absolute waiting time in nautical chain services. The performance of individual agents can be observed by measuring the occupancy rate of pilot agents and tugboats.

Calibration procedure

To calibrate the model, real-world data on the durations of the nautical chain processes is used, as shown in Table 1. The difference between the real world process durations and the simulated process durations is used as the calibration measure, which should be minimized to calibrate the model. So the measure is defined by the sum of squared errors of time deviations in simulated process durations t_i and observed real world process durations T_i, where i indicates the subprocess and I is the set of all subprocesses which have a real-world observed duration.

$$\min \sum_{i \in I} (T_i - t_i)^2 \tag{1}$$

This calibration measure is defined per agent type, so for each agent we want to minimize the deviations from real world durations. This leads to 3 goal values for the calibration. The parameters which are used to calibrate the model are the speed of the ships outside and inside the port. These parameters have been chosen as they impact all speed durations in the simulated nautical chain process for which benchmark values are available.

Having 2 unknowns and 3 goal values implies there is single best solution to this minimization problem. In general, increasing the speed would have a linear response of decreasing the durations, however due the complexity of the system some non-linear response on durations of subprocesses can occur. For example waiting times at certain points in the nautical chain process could increase.

By using a grid search approach, various combinations of the parameters are explored until a good enough fit of parameters is found. This method is chosen for practicality and leads to a good first result. Result of two steps of the iterative grid search process are

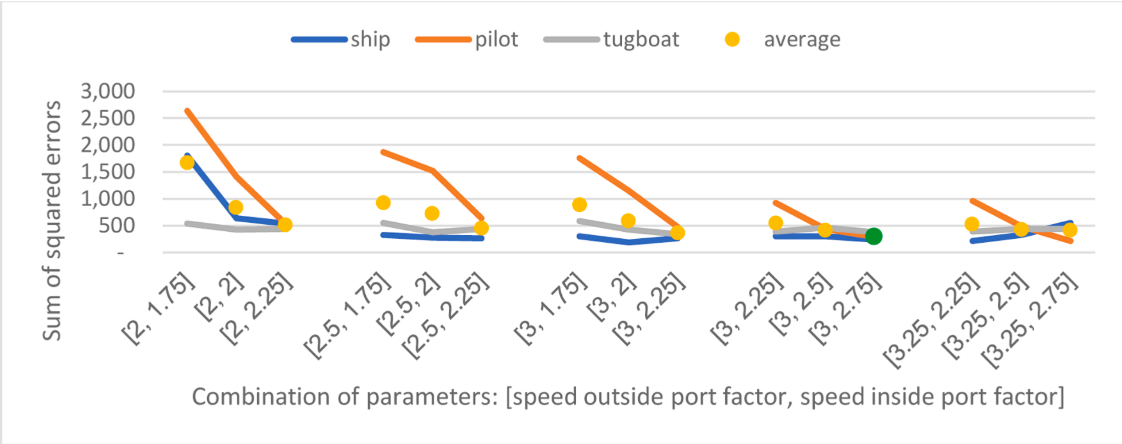

Fig. 5. Sample of grid search results showing reduction in sum of squared errors for varying calibration parameters over two different grids. Green coloured dot is the overall calibration result.

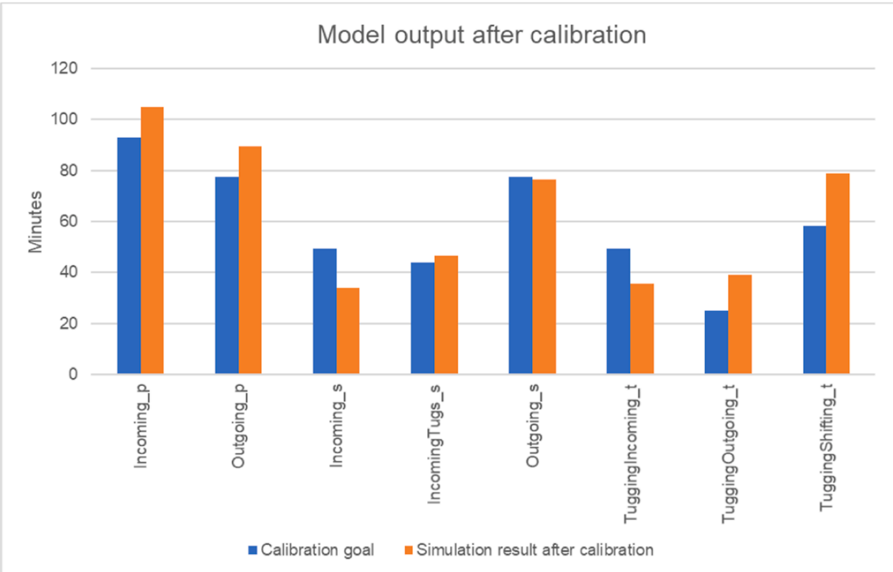

Fig. 6. Model output after calibration with duration of subprocess per agent type compared to real world data observation of subprocess duration.

presented in Fig. 5.

The model output after calibration can be found in Fig. 6. This figure shows the detailed process durations per agent types, of which the sum of deviations per agent type make the goal value for the calibration. The overall pattern of process durations after calibration is in line with the observed values, but there are still some gaps to cross between the real world data observations and the model output. The main reason for these deviations is that there is not a perfect set for the two calibration indicators, due to the nature of the model. Moreover, the quality of calibration can be further improved by a more accurate implementation of the agents' operation logic, which for the time being, is as it is – modelled with some assumptions and simplifications.

From the calibration process, it can be concluded that the model provides a realistic simulation of the nautical chain process and altering the input parameters impact the model output accordingly. Model response and model behaviour is shown more explicitly in the next chapters. First, we present a chapter on model validation, where the scenario analysis has been executed to show the response to alterations in the model input parameters. Subsequently, a chapter with the results of two use cases showing the model applicability is presented.

Validation of the multi-agent decision support system

The agent based model has been validated in both, a qualitative and quantitative manner. The model response to varying input

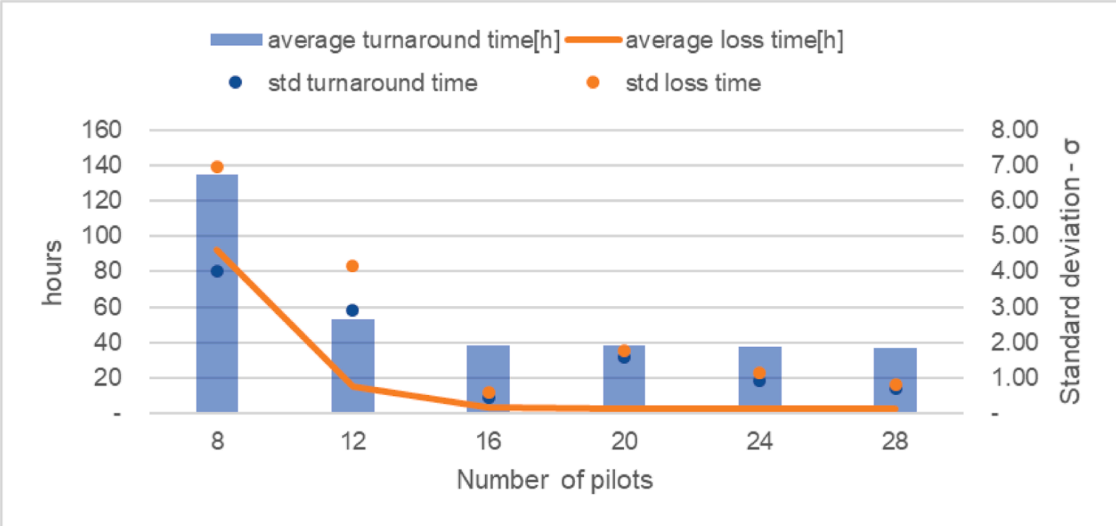

Fig. 7. Model output on average ship turnaround time and loss time for a 90 day simulation with 3 different random seeds.

parameters has been analysed to validate the response on the model output. This has been done by varying the number of service agents, pilots and tugboats and subsequently analysing the impact on the port nautical chain performance in the model output. Qualitative validation has been done by a port nautical chain expert from the Port of Rotterdam.

Stochasticity in the simulation model is implemented by randomly generated ship arrival times. A cascading effect in agent interaction and service agent scheduling in the port nautical chain implies a variation in the performance indicator values for varying simulation runs with the same input parameters, but different random seeds. To minimize the dependency on specific random seeds, it is necessary to simulate a long enough period of days. To reduce the influence of a single random seed, results are additionally achieved through 3 different simulation runs initiated with different random seeds. Subsequently the average value of the performance indicators - turnaround time and lost time of 3 different simulation runs is presented in Fig. 7.

Lost time is the unproductive time spent by ships while waiting for service agents in the simulation. The turnaround time is the total average time a ship spends in the simulated Port of Rotterdam. Each simulation run had a duration of 90 simulated days, which is a sufficiently long period for the stabilization of the system on the one hand, while resulting in reasonable real time durations of software simulation runs on the other. At the end of the 90 day simulation time period, all ships that are still in the port do not contribute to the turnaround time, but do record waiting times and therefore influence the average total waiting time per ship.

Fig. 5 shows a non-linear relation between the number of pilots and the average turnaround time per port call,[4] confirming the expectation that a lack of servers would lead to a fast increase in waiting time. On the other side of the capacity spectrum, it can be seen that from a certain number of pilots in the system, an increase in capacity no longer reduces the overall port turnaround time, thus showing an effect of diminishing returns with respect to extra pilot capacity. This can be explained by the fact that the vessels no longer experience waiting time for pilot services, and the capacity bottleneck shifts to another resource.

Model stability analysis for simulating a smooth operating port nautical chain system resulted in a simulation with 20 pilots. This number has been used to simulate two use cases described in the next chapter. 20 pilots are chosen over 16 pilots to ensure that enough pilot capacity is available and to guarantee a stable system in baseline operations.

Use cases

To show model applicability and to get a better insight in the model outcomes, two use cases are presented in this paper. The deep sea port system can be seen as a number of interlinked production systems, each having a certain service capacity and demand. The simulation model can be used to assess the impact of service capacity on waiting times as well as the impact of increased demand for port nautical service, as may be the case if there is a further growth in international trade, resulting in a larger number of daily deep sea vessel visits to the port. An analysis has been done with a step-wise increased ship arrival rate showing an increase of waiting times for services. A second use case has been inspired by the week long blockade of the Suez canal in 2021 – it analyses the impact of such a disruptive event on the port performance. This blockade caused a sudden dip in ship arrivals at the Port of Rotterdam (as well as other European ports), followed by a peak of ship arrivals after the blockade was lifted. The simulation model has adequately shown how the port system reacts to such a scenario and for how long the result of such a temporary disruption in arrival rate propagates through the system.

[4] Note in case of severe shortage of pilots (e.g. n = 4) and combined with increasing simulation time, the average turnaround time would grow to infinity as the daily port throughput would be smaller than the daily arrival rate of the ships.

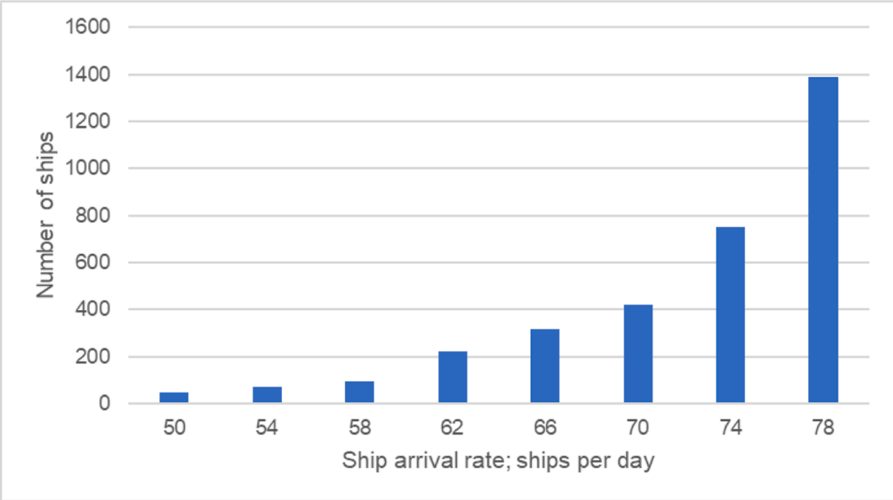

Fig. 8. Total Number of ships that visit the anchor area before port entrance. Only ships that encounter a capacity limit at one of the services or at their berth visit the anchor area.

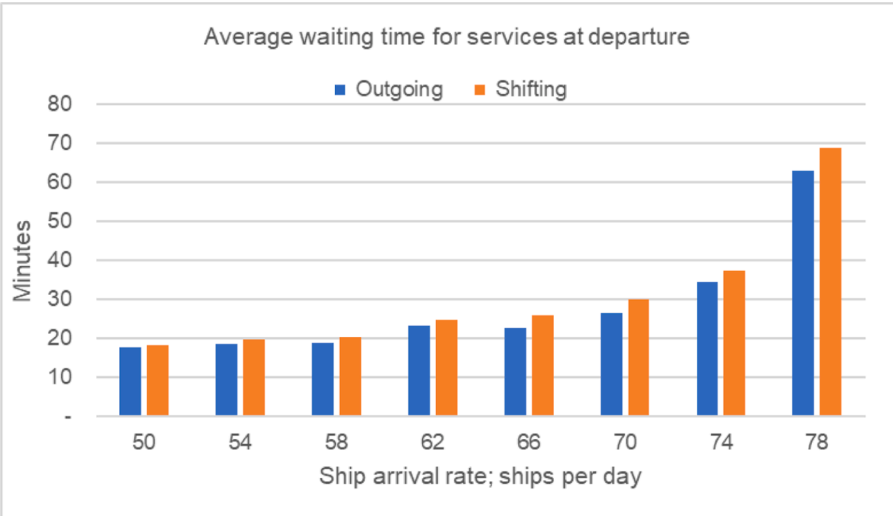

Fig. 9. Average waiting time of a ship for berth departure services – pilot or tugboats.

Use case 1: increasing ship arrival rate

To analyse the impact of a growing ship arrival rate on the port nautical chain system, the ship arrival rate has been increased from the baseline of 50 ships per day to 78 ships per day. The analysis has been done using an increasing step size of 4 ships in daily arrival rates, i.e. 50, 54, 58, … 74, 78 ships per day. For each step the model computed the waiting times for arriving, shifting and departing ships (if no service capacity is available for the arriving ships, then they have to wait in the anchor area; conversely, if there is no service capacity for departing or shifting vessels, they remain moored at the their berthing places). Capacity shortage can either be at pilots, tugboats or at the requested berth place. For the arrival process, the total number of ships that visit the anchor area in the simulated 30 days is shown in Fig. 8. For the departure process, which can either be a ship leaving the port or a so-called shifter that shifts to a next berth, the ships wait at their berth until the pilot and tugboat services arrive. The waiting time for these services start recording if the cargo unloading and loading processes are finished and the next berth spot is available. The change in this waiting time for a growing ship arrival rate in the port system is presented in Fig. 9.

As the port can be seen as a production system, there will be some point at which the demand for service outbalances the service capacity. This implies that at a certain level of demand, the waiting time should grow significantly. Both figures show an exponential increase in the severity of waiting for ships, in the number of ships and in the average waiting time, respectively.

As Figs. 8 and 9 show, the current capacity at the port is capable for dealing with a slight increase in the average daily arrival rate at

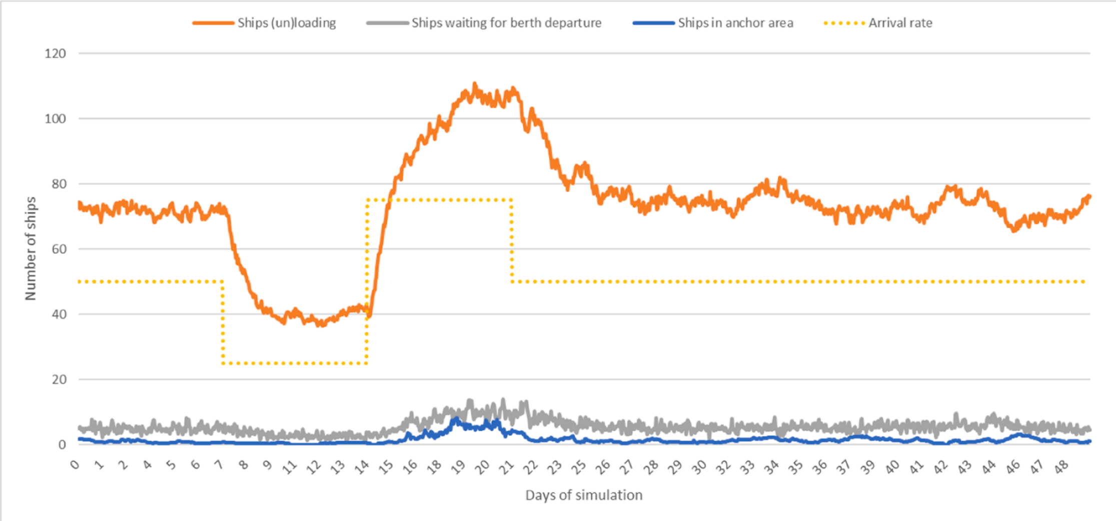

Fig. 10. Average of number of ships in port simulation states for 4 simulations with the Suez blockade scenario arrival rate.

the port. But when the arrival rate crosses a certain threshold, the quality of the nautical services deteriorate rapidly. This implies that if the port intends to grow the volumes that flow via the port, it has to start taking measures well in advance, as for example, the pilot capacity cannot be adjusted on short term due to a long training period for future pilots.

Use case 2: Suez canal blockade

In March 2021 a ship got stuck in the Suez canal, blocking all traffic for almost 6 days. This blockade caused a disturbance in ship arrivals in at European ports. The Port of Rotterdam has not been spared: the incident meant a reduction in ship arrivals at first. When the blockade was lifted, all delayed ships still had to be processed at the port, causing an increased demand for berth places but also for the port nautical services. The impact of such a blockade has been analysed with the developed simulation model.

An approximate scenario for the blockade effect has been simulated with the model, as no exact numbers related to the reduction in ship arrival rate are yet known. In this scenario the arrival rate has been reduced by 50% for 1 week and then increased by 50% the week after, representing all the ships that visit the port with a delay.[5] The simulation results with respect to the number of ships in port system are shown in Fig. 10. This figure shows the stable state of the port in the second week, a more quiet port in the week of the blockade and subsequently a busy week. After the busy week it can be seen that it takes some more days (i.e. from day 28 to day 33) for the system to return to the stable state similar to the one before the blockade. The figure also shows that the port system is sufficiently resilient to accommodate such a disturbance: it resulted in a substantial peak of ships at the port, but the quality of services was not seriously impacted (the waiting did not increase dramatically at both, the berths and at the anchor area). The authors deem the model to be capable for assessing a situation of a longer disruption, for instance, a three week blockade at Suez, but that scenario goes beyond the scope of this paper.

Conclusions

An agent based simulation model has been developed for scenario analysis for the port nautical chain at the Port of Rotterdam and its applicability has been shown. The model describes the basics of key processes of organization and physical agent interaction of the port nautical chain and can herewith simulate the impact of the port nautical chain on port performance. It can therefore be used to analyse impact of nautical chain parameters on macro port performance and identify sensitivity and key relations in the port process.

The calibration of the model shows that the modelling outcomes in base scenario provide an accurate representation of reality. This further means that the model can be used to analyse the impact of scenario changes compared the base scenario. The two use cases show the applicability of the model by presenting the model outcome for two different scenarios. The model has it limits with respect to computational boundaries and an aggregate level of organizational processes and nautical chain agents.

Agent based modelling provides a promising method to simulate the port nautical chain and to catch bottom-up process details and agent communication which impact port the performance from a macro perspective. The method allows the simulation of emergence and system stability of the port nautical service system. This research effort has shown that an agent based simulation model can be calibrated and validated to represent reality sufficiently well for the purpose of scenario-wise assessment of improvement measures.

[5] The scenario assumes that 50% of deep sea vessels coming to Rotterdam were not affected by the Suez blockade, given the fact that port of Rotterdam serves links to other destinations too.

We suggest further research and development efforts related to the enrichment of the modelled processes such as including cargo transfer at terminals and modelled agent behaviour, specifically, modelling of the processes and logic that is used by the nautical services for their main scheduling activities, such as the allocation of pilots to the incoming and departing ships. This enrichment represents an interesting research opportunity as well, since the scheduling problem is an NP-hard problem, which requires repeated solving in the simulation. A follow-up research is, thus, suggested on the ways of efficient process mapping and heuristics for the agent based simulation model.

Although this paper presents a model application case for the port of Rotterdam, we strongly believe it is generalizable for other large deep sea ports that provide similar services to the shipping lines. For the ports that provide pilotage, tugging, linesman and terminal services, the model is conceptually transferable. However, the parameterization of the model in terms of spatial port organization, different agent execution logic and quantitative parameterization, would need to be tailored for different implementations. This contribution shows that it is possible to use this approach to gain empirically validated capability of such a model, such that it is highly likely that a successful calibration at other ports is also possible, thus potentially equipping other ports with a useful tool for performance improvement.

Declaration of Competing Interests

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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