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Review Article

State-of-the-art of port simulation models for risk and capacity assessment based on the vessel navigational behaviour through the nautical infrastructure

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HIGHLIGHTS

- State-of-the-art of the current port simulation models for risk and capacity assessment.
- Identification of the main navigational processes related to the port nautical infrastructure.
- Assessment focused on how operations are covered by each model and how they represent realistic vessel navigation.
- Future port simulation models should consider detailed infrastructure, explicit tug and pilot assistance, and traffic rules.
- Existing research should be used for a more realistic port traffic modelling for risk and capacity assessment.

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ABSTRACT

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

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1. Introduction

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

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

As described in the previous paragraph, there is a wide range of maritime simulation models with different purposes. In this paper, we present a state-of-the-art of port models and we assess their applicability to port risk and capacity assessment, as a base for the future development of a port assessment methodology based on a suitable simulation model. This research includes some models recently reviewed (Bellsolà Olba et al., 2015) and models that have been developed since then. It includes, to the best of our knowledge, all the current non commercial port simulation models, which features are described in detail in scientific publications. The commercial models are excluded because their details and features are not available. In previous work, the most relevant processes involved in port navigation were identified a more comprehensive description is presented in Section 2. Moreover, this paper reviews and assesses the models already developed on these processes in a more detailed level. The calibration of the models is an important step to ensure that they properly simulate real traffic. Hence, all the models have been assessed based on if they have been calibrated or not.

The outline of this paper is as follows. Section 2 describes the nautical processes in a port. Section 3 identifies all the required criteria for port traffic simulation. Section 4 describes the characteristics of the criteria identified. Based on these, the assessment of simulation models will be discussed in two parts, layout and navigational behaviour, in Section 5. This paper concludes with a discussion of the results with an overall model assessment in Section 6, and conclusions and remarks for future model development in Section 7.

2. Port nautical processes

Ports are complex networks, both from an infrastructure and navigation point of view. This section describes the main processes linked to the nautical infrastructure necessary to represent the vessel traffic in a port and its evaluation (Fig. 1).

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

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

After the vessel has performed all these steps, the berthing process is performed and loading/unloading operations start.

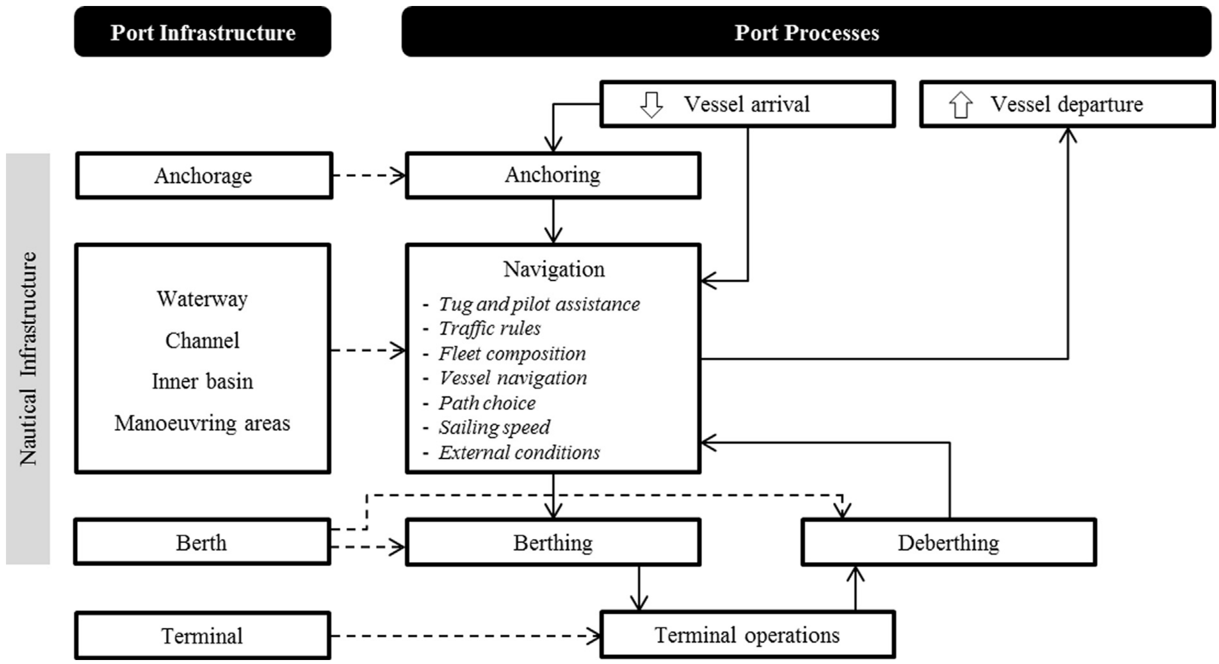

Fig. 1 – Diagram of port nautical infrastructure and processes.

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

3. Assessment methodology

Port simulation models have specific requirements to likely represent the overall vessel navigational behaviour. Hence, existing port simulation models (non commercial) are compared with respect to their current ability to represent the different traffic demands in a port and its associated processes. Fig. 1 shows the representative port infrastructure parts and the main processes. The basis of comparison within this review is to assess each of the characteristics of port processes and vessel navigation that an ideal model should be able to replicate for capacity and risk analysis of a port. This study compares the capabilities of existing models, developed with different purposes, to provide a realistic representation of vessel traffic in ports. In the following paragraphs a description of the relevance of the attributes introduced in Fig. 1 is presented.

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

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

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

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

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

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

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

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

4. Assessment criteria for port nautical simulation models

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

4.1. *Nautical layout assessment*

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

4.1.1. *Nautical infrastructure*

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

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

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

4.1.2. *Anchorage*

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

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

Each model will be classified with a rating system as follows, and which level of detail should be required for this process, for a suitable port risk assessment, will be discussed in Section 5.

√√ Anchorage allocation algorithm, detailed infrastructure and manoeuvring
√ Anchorage with dimensions and vessel sailing
√/× Anchorage with dimensions and vessel time allocation within the model
~ Queueing system without dimensions within the model
× No anchorage within the model

4.1.3. *Berth*

As Section 4.1.2 introduced, the importance of each process in port performance is crucial for minimizing costs and dwell times. For this reason, vessel berthing has been an important process studied in detail by several researchers. A topic of interest has been berth allocation (Alvarez et al., 2010; Arango et al., 2011; Fararoui, 1989). However, this is a process more related to vessel arrival optimization than analysing the vessel berthing process and its dwell time, depending on its characteristics.

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

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

√ Berthing manoeuvring process
√/× Berthing process simplified (no manoeuvring modelled)
× No berthing

4.1.4. *Terminal operations*

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

√ Detailed terminal operations
√/× Joint terminal operations
~ Joint terminal and berth operations
× No terminal operations

4.1.5. *Tug and pilot assistance*

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

√ Limited number of tugs and pilots
~ Unlimited number of tugs and pilots
× No tug and pilot assistance

4.1.6. *Traffic rules*

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

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

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

4.2. *Navigational behaviour assessment*

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

4.2.1. *Vessel arrival process*

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

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

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

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

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

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

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

4.2.2. *Fleet composition*

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

- √ Different types of vessels
- × Unique vessel type

4.2.3. *Vessel navigation*

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

- √ Vessel navigation influence in encounters and due to the nautical infrastructure design
- ~ Vessel navigation influence in encounters
- × No vessel navigation influence

4.2.4. *Course choice*

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

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

- √√ Dynamic freedom of movement, course choice and crew behaviour at each time step
- √ Dynamic freedom of movement and course choice at each time step
- ~ Movement fixed, but path generated at the beginning for each vessel
- × Fixed movement and course with same path for all vessels

4.2.5. *Sailing speed*

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

- √ Free speed choice
- ~ Several fix speed choices
- × Unique speed

4.2.6. *External conditions affecting navigation*

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

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

4.2.7. *Model calibration*

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

√ Model calibration
× No model calibration

5. Port simulation models review and assessment

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

In this section, to the best of our knowledge, the existing port related simulation models (non commercial) are compared in relation to the criteria described in Section 4. A brief assessment of each model is presented below. Table 1 summarizes the ratings of infrastructure related criteria from models developed specially for ports, while the ratings of the navigation related criteria are presented in Table 2. All simulation models are micro-simulation models simulating single vessel units and their microscopic properties such as position or velocity.

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

5.1. *Model 1 – Harboursim (Groenveld, 1983)*

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

5.2. *Model 2 – Park and Noh (1987)*

The bulk port operations model, developed by Park (1987), shows a complete layout structure, with detailed terminal

Table 1 – Nautical infrastructure layout assessment.

No.	Model	Nautical infrastructure	Anchorage	Berth	Terminal operations	Tug and pilot assistance	Traffic rules
1	Harboursim (Groenveld, 1983)	A W I M B	~	√/×	√/×	√	H E S O C
2	(Park and Noh, 1987)	A W I B	√/×	√/×	√	√	?
3	(Hassan, 1993)	W I B	~	√/×	√	√	H E S
4	(Thiers and Gerrit, 1998)	A W I M B	√	×	√	√	H E S O C
5	(Demirci, 2003)	W B	×	√/×	√/×	~	?
6	(Yeo et al., 2007)	W I M B	~	×	~	×	H C
7	(Almaz and Altiok, 2012)*	W	√	×	~	×	?
8	(Piccoli, 2014)	A W I B	~	×	~	~	H E
9	(Ugurlu et al., 2014)	A W B	~	√/×	√/×	√	?
10	(Bellsolà Olba et al., 2017)	W I M B	~	×	~	×	H
11	(Scott et al., 2016)	A W B	~	×	~	×	?

Note: * Waterway model.

Table 2 – Navigational behaviour assessment.

No.	Model	Vessel arrival process	Fleet composition	Vessel navigation	Course choice	Sailing speed choice	External conditions	Calibration	Goal
1	Harboursim (Groenveld, 1983)	N	√	×	×	~	V W T C S	×	Port planning and expansion
2	(Park and Noh, 1987)	N	×	×	×	×	×	×	Port planning, expansion and economic analysis
3	(Hassan, 1993)	H	√	×	×	×	T	×	Port planning, expansion and economic studies
4	(Thiers and Gerrit, 1998)	P	√	~	×	√	T	×	Port planning and expansion
5	(Demirci, 2003)	N	√	×	×	×	×	×	Investment planning
6	(Yeo et al., 2007)	P	×	×	×	×	×	×	Evaluate port traffic congestion
7	(Almaz and Altiok, 2012)	H	√	×	~	×	T	×	Delaware River simulation (waterway)
8	(Piccoli, 2014)	E	√	×	×	×	T	×	New port simulation assessment
9	(Ugurlu et al., 2014)	D	√	×	×	×	S	×	Port handling capacity, efficiency and queues
10	(Scott et al., 2016)	H	√	×	×	×	W T	×	Hidrodynamic impact on port economics
11	(Bellsolà Olba et al., 2017)	D	√	×	×	~	×	×	Port capacity estimation
12	(Hasegawa et al., 2001)	H	√	√	√	√	×	×	Vessel traffic in a bay
13	(Goerlandt and Kujala, 2011)	P	√	×	~	×	×	×	Assess risk in vessel navigation
14	(Huang et al., 2013)	H	√	~	~	×	×	√	Waterway network simulation
15	(Rayo, 2013)	N	√	×	×	~	V W T C	×	Approach channel assessment
16	(Xiao et al., 2013)	×	×	√	√	√	W C	√	Assess risk in vessel navigation
17	(Shu et al., 2015)	×	×	√	√	√	×	√	Realistic vessel sailing behaviour
18	(Xu et al., 2015)	H	√	√	~	~	V W C	×	Multi-bridge waterway assessment

operations but excluding manoeuvring areas. Also the traffic rules are not specified. However, the navigational behaviour is non-existent. Other modules, such as economic analysis, or inland transport mode inside the model, show that the focus of this model is more extensive than the previous one, but the external conditions are not included. As in the previous model, the arrival distribution is NED.

5.3. *Model 3 — Hassan (1993)*

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

5.4. *Model 4 — Thiers and Gerrit (1998)*

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

5.5. *Model 5 — Demirci (2003)*

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

5.6. *Model 6 — Yeo et al. (2007)*

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

5.7. *Model 7 — Almaz and Altiok (2012)*

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

5.8. *Model 8 — Piccoli (2014)*

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

5.9. *Model 9 — Ugurlu et al. (2014)*

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

5.10. *Model 10 — Scott et al. (2016)*

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

5.11. *Model 11 – Bellsolà Olba et al. (2017)*

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

5.12. *Model 12 – Hasegawa et al. (2001)*

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

5.13. *Model 13 – Goerlandt and Kujala (2011)*

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

5.14. *Model 14 – Huang et al. (2013)*

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

5.15. *Model 15 – Rayo (2013)*

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

5.16. *Model 16 – Xiao et al. (2013)*

A traffic simulation model with multi-agent system was developed to simulate dynamic ship manoeuvring to assess maritime safety (Xiao, 2014). This is a new approach for maritime simulation where vessels behave as autonomous agents. The model includes waterway infrastructure and encounter influence, as well as wind and current effects. Although the innovative approach, the model does not consider different fleet compositions and crew behaviour is not sufficiently implemented. The model is also calibrated with AIS data.

5.17. *Model 17 – Shu et al. (2015)*

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

5.18. *Model 18 – Xu et al. (2015)*

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

6. Discussion

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

The assessment of the nautical infrastructure shows that even though most of the models include detailed nautical infrastructure layout (Fig. 1), only two of them consider all the infrastructure parts (Groenveld, 1983; Thiers and Gerrit, 1998).

Anchoring processes have not been extensively implemented until now and specific algorithms, introduced in Section 4.1.2, have not been implemented yet. The models developed by Thiers and Gerrit (1998) and Almaz and Altiok (2012) have an adequate implementation of the anchorage area. The level of detail of these anchorages is sufficient for a port model, but if desired it could still be improved including the anchoring allocation algorithm. Berthing processes have been considered as dwell times in two ways, independent from terminal operations or together, without modelling the manoeuvring. Since the influence of these processes in the overall performance of a port is relevant, they should be properly implemented, considering uncertainty in their modelling. In the reviewed models, tugs and pilots are included with idle times and dwell times, which proves its importance, and should always be considered with this level of detail. Even though some models include several traffic rules, and all models include a control and traffic verification agent that checks rules application, most of them are not complete. This implies that not all the possible traffic situations are covered by these models.

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

Free course choice has not been implemented in any of the port simulation models. Regarding the rest of the models, three of them models developed a model with free and variable course choice, for each time step (Hasegawa et al., 2001; Xiao et al., 2013; Xu et al., 2015). Few of the latest models can simulate different fixed course choice, without freedom of movement (Goerlandt and Kujala, 2011; Hasegawa et al., 2001; Huang et al., 2013). While free sailing speed choice has been modelled in four models (Hasegawa et al., 2001; Shu et al., 2015; Thiers and Gerrit, 1998; Xiao et al., 2013) and others consider several fix speeds (Groenveld, 1983; Rayo, 2013), the rest modelled vessel speeds as fixed.

The external conditions have not been extensively implemented. The assessment shows that some of the external conditions, such as tidal windows, as well as wind and current, have been previously implemented. However, the other conditions have not been considered. Current effects have been included just in the models developed by Rayo (2013) and Xu et al. (2015). Future models should include them in order to compare and assess the effects of them on the navigation and port performance.

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

7. Conclusions

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

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

√ The model can be used for a suitable assessment
~ The model can be used for a partially suitable assessment
× The model should be improved for the assessment

In Table 3, the assessment shows that none of the models previously developed are able to properly represent the vessel navigation in ports to correctly assess the capacity and the corresponding risk. Each of the models reviewed was developed for a specific purpose and their content and output was adequate for each specific purpose, and the focus of this assessment is to check if they could be also used for capacity and risk assessment purposes.

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

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

Future port simulations models should consider detailed infrastructure and explicit tug and pilot assistance, as well as detailed traffic rules. Navigational behaviour should be

Table 3 – Overall model assessment.

No.	Model	Goal	Capacity assessment	Risk assessment
1	Harboursim (Groenveld, 1983)	Port planning and expansion.	√	×
2	(Park and Noh, 1987)	Port planning, expansion and economic analysis.	√	×
3	(Hassan, 1993)	Port planning, expansion and economic studies.	√	×
4	(Thiers and Gerrit, 1998)	Port planning and expansion.	√	×
5	(Demirci, 2003)	Investment planning.	~	×
6	(Yeo et al., 2007)	Evaluate port traffic congestion.	~	×
7	(Almaz and Altiok, 2012)	Delaware River simulation (waterway)	~	~
8	(Piccoli, 2014)	New port simulation assessment	~	×
9	(Ugurlu et al., 2014)	Port handling capacity, efficiency and queues	~	×
10	(Scott et al., 2016)	Hydrodynamic impact on port economics	~	×
11	(Bellsolà Olba et al., 2017)	Port capacity estimation	~	×
12	(Hasegawa et al., 2001)	Vessel traffic in a bay	×	×
13	(Goerlandt and Kujala, 2011)	Assess risk in vessel navigation	×	~
14	(Huang et al., 2013)	Waterway network simulation	√	×
15	(Rayo, 2013)	Approach channel assessment	√	×
16	(Xiao et al., 2013)	Assess risk in vessel navigation	×	~
17	(Shu et al., 2015)	Realistic vessel sailing behaviour	×	~
18	(Xu et al., 2015)	Multi-bridge waterway assessment	√	×

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

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

Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

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