Simulating the port wet infrastructure: review and assessment

Xavier Bellsolà Olba a *, Winnie Daamen a, Tiedo Vellinga b, Serge P. Hoogendoorn a

a Department of Transport & Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft 2628CN, The Netherlands
b Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft 2628CN, The Netherlands

Abstract

Since the continuous growth of maritime transportation due to containerization, ports play an increasingly important role in the freight transportation chain. In ports, high vessel flows and implicit higher densities increase the relevance of the non-terminal related operations. A few simulation models have been developed in the recent decades with different aims and scopes, but none of them has been assessed based on their ability to represent real vessel traffic in ports. In this paper, we identify the main navigational processes and operations related to the port wet infrastructure and review and assess the current port simulation models. The survey of models presented represents an exhaustive overview of the current state of the art of port simulation models. Their assessment focuses mainly on which processes and operations are covered by each model, both wet infrastructure and navigational behaviour, and it also considers where models are complementary and how accurately they are able to represent real navigation. A set of elements is defined and divided in two parts for the assessment: wet infrastructure representation and navigational behaviour. This review shows that the influence of infrastructure design or vessel encounter on vessel navigation behaviour and free path choice have not been implemented in port simulations. Future port simulation models should cover these relevant elements, among others also explained, for a more realistic traffic performance.

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* Corresponding author. Tel.: +31-(0)15-278-4912.
E-mail address: x.bellsolaolba@tudelft.nl
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). Since ports are quite inflexible infrastructures and difficult to expand, the increase in vessel movements has led to more hazardous situations and congestion in some areas. As a result, ports handle a higher traffic demand that implies longer waiting times for vessels and reduces system’s efficiency. Because of this increasing demand, navigational related operations inside the port infrastructure, also called ‘wet infrastructure’, become decisive for port performance. Existing ports need to be optimized or expanded and new ports have to be planned. In both cases, their safety and capacity should be guaranteed and tools to design different scenarios are required.

Maritime transportation simulation models have been proven to be useful tools to represent and predict port operations and processes. Several models have been developed during the last decades with many different purposes. Regarding traffic representation in straits, models consider navigation systems as queueing systems, with first in first out (FIFO) sequences, see for example, Istanbul strait (Köse et al., 2003). Waterway traffic representation in the Osaka Bay was implemented by the Marine Traffic Simulation System (SMARTS) (Hasegawa et al., 2001). This model was also used for marine risk assessment. For a similar purpose, a risk index-based model for vessels was developed, the SAMSON model (Safety Assessment Model for Shipping and Offshore on the North Sea), by MARIN (Maritime Research Institute Netherlands, 2015). Furthermore, a simulation model for vessel traffic based on ship collision probability has been developed (Goerlandt and Kujala, 2011). A more recent vessel traffic simulation tool was implemented to determine the impact of river deepening on navigational issues in the Delaware River (Almaz and Altıok, 2012). Moreover, there are models for detailed port representation and performance analysis, such as Harboursim, a generally applicable model (Groenveld, 1983), or a model developed for the port of Antwerp (Belgium) (Thiers and Gerrit, 1998).

Although a lot of research has been already done in maritime simulation modelling, there is not an existing review of port ‘wet infrastructure’ simulation models. This paper aims to identify the most relevant processes involved in port navigation performance and to review and assess the models already developed on these processes. The differences in their approaches and drawbacks indicate whether gaps of improvement in the port ‘wet infrastructure’ traffic simulation modelling research exists.

The outline of this paper is as follows. Section 2 describes vessels real operations in a port. Section 3 identifies the required elements for port ‘wet infrastructure’ traffic simulation model. Section 4 describes the characteristics of the elements identified. Based on these, the assessment of simulation models will be discussed in two groups, layout and navigational behaviour, in section 5. This paper concludes with a discussion of the comparison results and some remarks for future model development.

2. Port wet infrastructure operations

Ports are complex networks, both from an infrastructure and navigational point of view. This section describes the main operations linked to the wet infrastructure and should lead to a better understanding of them.

Traffic operations in a port start when a vessel arrives and requests access (see Figure 1). The Vessel Traffic Service (VTS) provides information about 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 quay master can enter the port. Otherwise, they wait outside the port in the anchorage until permission is given. Vessels with specific navigational 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 parts has specific requirements in sailing and manoeuvring, 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. 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. Review methodology

Since simulation models require a certain level of detail for a likely representation of the overall performance of the system, existing port simulation models (non-commercial) are compared with respect to their current ability to represent port traffic. The main goal of this study is to compare their capabilities to represent real traffic in ports, considering that each simulation model was developed with a specific purpose. The authors assume that the description of the simulation models presented in the papers agrees with their real implementation.

The assessment is divided into two parts: the first part considers the wet infrastructure representation according to which elements can be modelled, while the second part is related to how navigational characteristics are modelled and how close the simulation resembles a real navigation system. All port infrastructure parts should be included in a model, which are: (1) wet infrastructure, (2) anchoring, (3) berthing and (4) terminal(s) operations, (5) pilot/tug assistance and (6) traffic rules. Moreover, the main elements that affect navigation depending on each type of vessel are: (1) vessel arrival process, (2) fleet considered, (3) influence of infrastructure design or vessel encounter on navigation, (4) path choice possibility, (5) speed variation, (6) external effects and (7) risk assessment. Thus, these elements are used as a basis for the assessment criteria in the next section.

4. Assessment criteria for port wet infrastructure simulation models

A detailed description of all elements identified in the previous section is presented here. Their influence on traffic and port wet infrastructure performance is described and a rating scale is chosen for each element in order to compare the different models.

4.1. Wet infrastructure

The navigational infrastructure in ports is divided into channels (the main waterway for this type of models), inner basins and crossings or manoeuvring areas. Due to the various navigation through each part of the infrastructure, the model capability to simulate the port navigation highly depends on the parts which are considered.

Models will be classified in this part depending on the inclusion of the infrastructure, therefore the following scheme is used:

<table>
<thead>
<tr>
<th>A</th>
<th>Anchorage</th>
<th>W</th>
<th>Waterway</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Channel</td>
<td>M</td>
<td>Manoeuvring areas</td>
</tr>
<tr>
<td>I</td>
<td>Inner basin</td>
<td>B</td>
<td>Berth</td>
</tr>
</tbody>
</table>

4.2. Anchorage

Once the competition between ports reaches the current levels, all processes should be optimized and vessel arrival operations become crucial. However, few research into anchorage capacity, definition or assessment, has
been done. The relevance of this infrastructure increases in busy ports, where manoeuvring activities become more difficult and take more time inside the anchorage. In order to improve the current situation and give the importance that anchoring spots have, Verstichel and Berghe (2009) 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 operation, for a likely port performance, will be discussed in section 6.

- ✔ ✔ Anchorage allocation algorithm, detailed infrastructure and manoeuvring
- ✔ Anchorage with dimensions and vessel sailing and time allocation within the model
- ~ Queueing system without dimensions within the model
- ✗ No anchorage within the model

4.3. Berth

As section 4.2 introduced, the importance of each operation in port performance is crucial for minimizing costs and dwell times. For this reason, vessel berthing has also been an important operation studied in detail by several researchers. Some topics of interest have been berth allocation (Arango et al., 2011; Fararoui, 1989). However, this is a process more related to vessel arrival optimization.

There are different levels of detail for berthing operations, since it can be seen just as a whole process with a dwell time associated or, on the contrary, the different steps of the berthing operation and their manoeuvring can be included. The details for this operation can be relevant when considering busy basins or waterways and a detailed implementation of the process would give a more realistic performance of the system.

The aim of the comparison of the berthing operation 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 operation
- ✔/✗ Berthing operation simplified (no manoeuvring modelled)
- ✗ No berthing

4.4. Terminal operations

There is extensive literature related to terminal operations, optimization and improvement. An extensive research on that topic has been developed for optimizing crane and terminal operations and an extensive review was developed by Stahlbock and Vöß (2007). Related to terminals, researchers have also focused on terminal simulation modelling (Hassan, 1993; Kia et al., 2002). Terminal operations are out of the scope of this paper, but it is important to see how they have been considered in different models. The following scheme is proposed to classify them:

- ✔ Detailed terminal operations
- ✔/✗ Joint terminal operations
- ~ Joint terminal and berth operations
- ✗ No terminal operations

4.5. Tug and pilot assistance

Ports have often 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 can consider an unlimited number of them as a simplification. According to that, models are rated depending on this consideration:

- ✔ Limited number of tugs and pilots
- ~ Unlimited number of tugs and pilots
- ✗ No tug and pilot assistance
4.6. 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 idiosyncrasies. As mentioned before, VTS centres control that vessels follow these rules and that they do not initiate dangerous situations. These rules are directly related to risk and safety levels. 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 |
| C | Crossing priorities |
| ? | Unknown / Not specified |

4.7. Vessel arrival process

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

The arrival process depends 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 the external factors, the most common situation is a random arrival process. A negative exponential distribution (N.E.D.) has been statistically proven to reasonably correspond with this kind of arrival, as a continuous distribution (Fararoui, 1989; Pachakis and Kiremidjian, 2003), or with its discrete derivation as a Poisson distribution (Thiers and Gerrit, 1998).

The correlation between vessel arrivals and approximations to queueing systems were developed for marine bulk cargo ports (Jagerman and Altiok, 2003), and it was proven that there is a negative correlation between arrivals of 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 shipping lines have a regular service, vessel inter-arrival time distribution mainly follows the Erlang-k Distribution (Kuo et al., 2006). In this case, arrivals are not independent.

For simulating real port operations, 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 improve traffic management or scheduling.

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 |

4.8. Fleet generation

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 generation in the models has been rated depending on their ability to simulate different type of vessels.

| ✔ | Different types of vessels |
| ✗ | Unique vessel type |

4.9. Influence on vessel navigation

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

| ✔ | Vessel navigation influence |
| ~ | Vessel navigation influence in encounters |
| ✗ | No vessel navigation influence |

4.10. Path choice

Vessels navigation path choice, or path change, during sailing is a complex element to simulate. This choice depends on several parameters, such as crew behaviour or external conditions. The precision of the models according to real vessel sailing behaviour is related to their manoeuvring behaviour during this process.

The assessment of their ability to choose a random path and to change their course due to human behaviour is rated as follows:

| ✔ | Freedom of movement and path choice |
| ~ | Movement fixed, but path choice generated |
| ✗ | Fixed movement and path |

4.11. Sailing speed

During the navigation process vessels change speeds and their maximum and minimum speeds are different from other types of vessel. 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 sail with a unique speed. According to this speed choice, each model has been classified with the following scheme:

| ✔ | Free speed choice |
| ~ | More than one fixed speed choice |
| ✗ | Unique speed |

4.12. 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 elements. 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 |

4.13. Risk assessment

Risk assessment is one of the common interest and several of the simulation models with other aims include this assessment or evaluation. Although its main goal is different than the rest, one model included in this papers has several similarities with the ones for port performance analysis (Goerlandt and Kujala, 2011).

The way to include risk assessment is out of the scope of this paper and the models have just been rated in accordance of its consideration or not.

| ✔ | Model includes risk assessment |
| ✗ | Model does not include risk assessment |
5. Port simulation models review and assessment

Port operations are difficult to derive analytically. For this reason, simulation models have been developed in maritime transportation. Most of them do not represent the whole infrastructure and/or operations and they can be classified in groups 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 there is not an extensive amount of port simulation models and these ones can be used to compare their navigational approach.

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

Four of the simulation models considered were developed for other scenarios than a port, such as a bay (Hasegawa et al., 2001), a gulf (Goerlandt and Kujala, 2011), a waterway network (Huang et al., 2013) or a waterway approach channel (Rayo, 2013), thus, the infrastructure is not assessed for these models.

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

The bulk port operations model, developed by Park (1987), shows a complete layout structure, with detailed terminal operations 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, hence more simple. As the previous model, the arrival distribution is NED.

Hassan (1993) developed a complete simulation model for ports, including the ‘wet infrastructure’, and all the terminal operations. Although, the infrastructure is not as detailed as in the first model, it has the main parts as well as explicit availability of pilots and tugs, and simplified traffic rules such as minimum headway, encountering priority or speed reduction during encounters. Path choice, vessel influence or weather conditions are not included. Only tide is included as external condition. The vessel arrival distribution is obtained based on historical data. As the previous model, this model has a broad scope, shown by the level of detail of the navigational module.

Another model, developed for the Port of Antwerp (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 exhaustive, with linear paths not influenced by encounters. Vessel arrival follows a Poisson distribution and detailed traffic rules are specified, as can be seen in Table 2.

In addition, the model was improved with pilot observations on whether waiting times occur in a new infrastructure.

Demirci (2003) developed a really simplified macroscopic model in order to cover all operations in the whole port and supply chain, including wet, cargo (loading/unloading), terminal and hinterland operations, which leads to a superficial model that does not reproduce real traffic operations.

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, vessel inter-arrival time is Poisson distributed. Behavioural navigation elements are not considered, just different priorities are given to ships.
Table 1. Wet infrastructure layout assessment.

<table>
<thead>
<tr>
<th>Model</th>
<th>Wet infrastructure</th>
<th>Anchorage</th>
<th>Berth</th>
<th>Terminal operations</th>
<th>Tug and pilot assistance</th>
<th>Traffic rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harboursim (Groenveld, 1983)</td>
<td>A C I M B</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>H E S O C</td>
</tr>
<tr>
<td>(Park and Noh, 1987)</td>
<td>A C I B</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>(Hassan, 1993)</td>
<td>C I B</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>H E S</td>
</tr>
<tr>
<td>(Thiers and Gerrit, 1998)</td>
<td>A C I M B</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>H E S O C</td>
</tr>
<tr>
<td>(Demirci, 2003)</td>
<td>C B</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>(Yeo et al., 2007)</td>
<td>C I M B</td>
<td>~</td>
<td>x</td>
<td>~</td>
<td>X</td>
<td>H C</td>
</tr>
<tr>
<td>(Almaz and Altiok, 2012)</td>
<td>W</td>
<td>✓</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>?</td>
</tr>
<tr>
<td>(Piccoli, 2014)</td>
<td>A C I B</td>
<td>~</td>
<td>x</td>
<td>~</td>
<td>~</td>
<td>H E</td>
</tr>
</tbody>
</table>

Abbreviations: Wet Infrastructure: A=Anchorage, C = Channel, I = Inner basin, M = Manoeuvring areas, B = Berth.
Traffic rules: H = Minimum headway with predecessors, E = Encountering priority rules, S = Speed reduction during encounters, O = Overtaking, C = Crossing priorities.

Table 2. Navigational behaviour assessment.

<table>
<thead>
<tr>
<th>Model</th>
<th>Vessel arrival process</th>
<th>Fleet generation</th>
<th>Influence on vessel navigation</th>
<th>Path choice</th>
<th>Sailing speed choice</th>
<th>External conditions</th>
<th>Risk assessment</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harboursim (Groenveld, 1983)</td>
<td>N</td>
<td>✓</td>
<td>✓</td>
<td>~</td>
<td>V S W T</td>
<td>X</td>
<td>Port planning and expansion.</td>
<td></td>
</tr>
<tr>
<td>(Park and Noh, 1987)</td>
<td>N</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td>Port planning, expansion and economic analysis.</td>
<td></td>
</tr>
<tr>
<td>(Hassan, 1993)</td>
<td>H</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>T</td>
<td>✓</td>
<td>Port planning, expansion and economic analysis.</td>
<td></td>
</tr>
<tr>
<td>(Thiers and Gerrit, 1998)</td>
<td>P</td>
<td>✓</td>
<td>~</td>
<td>x</td>
<td>✓</td>
<td>T</td>
<td>Port planning and expansion.</td>
<td></td>
</tr>
<tr>
<td>(Demirci, 2003)</td>
<td>N</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>Investment planning.</td>
<td></td>
</tr>
<tr>
<td>(Yeo et al., 2007)</td>
<td>P</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>Evaluate port traffic congestion.</td>
<td></td>
</tr>
<tr>
<td>(Almaz and Altiok, 2012)</td>
<td>H</td>
<td>✓</td>
<td>x</td>
<td>~</td>
<td>T</td>
<td>X</td>
<td>Delaware River simulation (waterway)</td>
<td></td>
</tr>
<tr>
<td>(Piccoli, 2014)</td>
<td>E</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>T</td>
<td>X</td>
<td>New port simulation assessment</td>
<td></td>
</tr>
<tr>
<td>(Hasegawa et al., 2001)</td>
<td>H</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>Vessel traffic in a bay</td>
<td></td>
</tr>
<tr>
<td>(Goerlandt and Kujala, 2011)</td>
<td>P</td>
<td>✓</td>
<td>x</td>
<td>~</td>
<td>X</td>
<td>X</td>
<td>Assess risk in vessel navigation</td>
<td></td>
</tr>
<tr>
<td>(Huang et al., 2013)</td>
<td>H</td>
<td>✓</td>
<td>~</td>
<td>x</td>
<td>X</td>
<td>✓</td>
<td>Waterway network simulation</td>
<td></td>
</tr>
<tr>
<td>(Rayo, 2013)</td>
<td>N</td>
<td>✓</td>
<td>X</td>
<td>~</td>
<td>V W T C</td>
<td>X</td>
<td>Approach channel assessment</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Vessel arrival process: N = Negative exponential distribution, P = Poisson distribution, E = Erlang-1 distribution, H = Historical data.
External conditions: V = Visibility, S = Storm, W = Wind, T = Tidal conditions, C = Current.

Almaz and Altiok (2012) developed a model to simulate vessel traffic in Delaware River (U.S.A.). This model represents traffic in the river with several anchorages and berths. Although the infrastructure is not a port, it is close enough to assess it. Berthing operations are not specified; they are assumed to be with the terminal operations. One relevant improvement in this model, compared with the previous ones, is a specific path generated for each vessel based on Automatic Identification System (AIS) data. AIS data helps to develop a more realistic model, though path changes, influenced by the waterway or other vessels, are not possible. Vessel arrival is obtained from historical AIS data, including seasonality. No weather conditions are included due to low influence expected by the authors.

The last port specific model reviewed was developed to assess the port wet infrastructure operations (Piccoli, 2014). The infrastructure is described in a simplified way, considering berth and terminal operations as a joint...
operation. The anchorage is considered as a single queue, without 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. With respect to navigational behaviour, there is no weather conditions or influence between vessels or infrastructure that affects path choice.

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 path 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.

Goerlandt and Kujala (2011) developed a model to determine the vessel collision probability. Based on extensive AIS data, 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 AIS data analysis and model calibration.

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

The last model reviewed was developed for the assessment of port approach channels (Rayo, 2013). Although, this model includes weather conditions and speed variations while vessels navigate, it is not based on real AIS data.

6. Discussion

Some remarks are made about model performance. The discussion is divided in two parts: how existing simulation models include the different port elements and which of them should be considered for a more realistic traffic performance.

6.1. Existing simulation models

Although most of the models include detailed wet infrastructure layout, only two of them consider all the infrastructure parts (Groenveld, 1983; Thiers and Gerrit, 1998). Anchoring operations have not been extensively implemented until now and specific algorithms, introduced in section 4.2, have not been implemented yet. Berthing operations have been considered as dwell times in two ways, independent from terminal operations or as a joint, without modelling the manoeuvring. In the reviewed models, tugs and pilots are included with idle and dwell times, which proves its importance. 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.

In relation to the navigational behaviour assessment, the vessel arrival process has been considered according to several distributions or historical data, which will be discussed in the next section. As shown by the existing models, different fleet generation 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 reviewed (Hasegawa et al., 2001; Huang et al., 2013; Thiers and Gerrit, 1998). This implementation can show the effects of different designs or encountering situations and can help to choose a better port design.

Free path choice has not been implemented in any port simulation, only Hasegawa et al. (2001) developed a model with free and variable path choice, for each time step. Few of the latest models can simulate different fixed path choice, without freedom of movement (Almaz and Altio, 2012; Goerlandt and Kujala, 2011; Huang et al., 2013). While free sailing speed choice has been modelled in two models (Hasegawa et al., 2001; Thiers and Gerrit, 1998) and other consider several fix speeds (Groenveld, 1983; Rayo, 2013), the rest modelled vessel speeds as fixed.

Detailed external conditions have not been extensively implemented. The assessment shows the relevance of tidal windows for port performance. Finally, although this paper does not focus on risk assessment, several of the reviewed models include this element to evaluate the current risk related performance.
6.2. Port model inputs

Since manoeuvring areas 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 wet infrastructure elements is necessary. They can lead to substantial variations in the sailing process of a vessel and thus variations in sailing times. Detailed research in anchoring operations could be implemented to make this operation more realistic. At least anchoring should not be considered as a simple queue process, where anchorage dimensions and vessel distribution do not affect its performance. In the same line, berthing operations are relevant and should be included as an independent parameter. 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 changes to them. A control and traffic verification agent has been shown to be relevant and should be considered. The more detailed these rules are, the more accurate the results will be. 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 discussed and 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, historical data analysis shows to be the best option to adjust a 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 affect the final performance.

In relation to fleet generation, making vessel clustering 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 variable with time, fits better vessel navigation in a port. In addition, the influence on vessel navigation of the infrastructure and encounters between vessels should be included. Free path choice has not been included in port simulation models yet. There is an extensive research on vessel behaviour based on AIS data (Shu et al., 2012) that should be used for new model implementation.

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 operations and performance as an operational time limitation. Weather conditions can be relevant for navigation, depending on the port location. These conditions should be considered as behavioural effects on vessel behaviour and some correlations can be obtained from AIS data analysis with different weather scenarios. Another important parameter that can be crucial for navigation is current. These parameters have been included just in one of the models reviewed (Rayo, 2013).

7. Conclusion

This review and assessment of several port wet infrastructure simulation models leads to a better understanding of the ability of them to represent and perform ports as close as possible to reality. In order to achieve this, the infrastructure implementation should be complete and detailed, as discussed in the section 6.2.

Since current models do not include properly the influence of infrastructure design or encountering situations on vessel navigation, there is a lack of reality in existing models. Moreover, free path choice has not been yet included in any model, which would lead to more realistic results. External conditions are relevant for vessel navigation and have been omitted in most of the models. We recommend to consider modelling current effects in future research.

Future port simulations models should consider detailed infrastructure and explicit tug and pilot assistance, as well as detailed traffic rules. Navigational behaviour should be developed, thanks to extensive AIS data research, which should allow the validation and calibration of detailed models that would fit better the real port performance.
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References


