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Review of maritime traffic models from vessel behavior modeling perspective

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Abstract

The importance of maritime transport keeps increasing with the trade globalization. With the growing demand for waterborne transport, vessel traffic flows are also expected to increase. This paper reviews maritime traffic models from the vessel behavior modeling perspective. The maritime traffic models include the models for vessel traffic both at sea and in confined water area. The aim of this paper is to analyze the underlying modeling paradigms and to assess the extent in which maritime traffic models can represent vessel behavior. Focusing on vessel behavior modeling, this paper provides a broad overview of the current literature on maritime traffic models of the last decades. The commercial models are not included due to the limit of information. To compare the capabilities of models in capturing the vessel behavior characteristics, the considered models are assessed from different aspects of vessel behavior representation, external impact modeling, and model applicability. The assessment shows that none of the existing models describe all dynamic kinetic information in detail for different vessels and consider the impacts from a full range of external factors, which is possibly due to the specific purpose when the models were developed. The models developed for

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specific vessels in specific situations ignore the irrespective behavioral details in other possible scenarios. Models without proper calibration and validation limit the applicability in other cases. It also indicates that few models can accurately simulate the different vessel behavior at a microscopic level. To investigate the possible potential and limitations, the models have been assessed and discussed to indicate the underlying modeling paradigms based on the modeling characteristics. Future developments can focus on the behavior of different vessels in different types of water areas and the corresponding impacts from external conditions (e.g. visibility, wind, current), vessel encounters and traffic rules. Through calibration and validation, future models should be able to fit the vessel behavior in real-life situations.

Keywords:

Vessel behavior; Maritime traffic; Simulation model; Individual behavioral law; Comparison; Assessment

1. Introduction

The importance of maritime transport keeps increasing with the trade globalization. Until 2017, over 80 percent of the global trade by volume and more than 70 percent of its value are carried by waterborne transport and handled by seaports worldwide (United Nations Conference on Trade and Development, 2017). According to the forecast of UNCTAD, the trade volume of seaborne transport will grow at an estimated compound annual growth rate of 3.2 percent between 2017 and 2022. The cargo flows will be expanded across the world with containerized dry bulk commodities. With such a growing demand for waterborne transport, the vessel traffic flow is also expected to increase. The safety of vessels and the capacity of different water areas have therefore drawn more attention from science. Currently, simulation models are widely used to represent the vessel traffic in different areas (at sea, in strait, in port, or in inland waterways). The purposes of developing such traffic models can be various, e.g. scenario research for the future traffic state, assessing the port design alternatives, or investigating the effects of introduction of autonomous vessels. However, the essential issue in common is to improve the capacity of the area while guaranteeing the safety of vessels.

To describe the models for vessel traffic, a lot of terms have been used, e.g. maritime traffic model (Bourdon et al., 2007; Mavrakis and Kontinakis, 2008; Or et al., 2007), marine traffic model (Hasegawa et al., 2001; Huang et al., 2016; Köse et al., 2003; Qi et al., 2017a; Yip, 2013), nautical traffic model (Xiao et al., 2013), ship or vessel traffic model (Groenveld, 2006; Pachakis and Kiremidjian, 2003; Qu and Meng, 2012; Wawruch and Popik, 2011). In this paper, the term 'maritime traffic model' is adopted. Here, maritime traffic models include the models of vessel traffic at sea as well as the models for confined water areas. Thus, a maritime traffic model refers to a system of postulates, data, and inferences presented as a description of the state of vessels moving in a navigable area.

The science of maritime traffic modeling started by Davis et al. (1980) adopting the concept of ship domain by Fujii and Tanaka (1971) and Goodwin (1975). According to the different requirements of application purposes, a broad range of models describing maritime traffic at different levels of vessel behavioral details has been developed. From the viewpoint of collective traffic flows, the maritime traffic flow of a port (Bellsolà Olba et al., 2017; Groenveld, 2006; Pachakis and Kiremidjian, 2003), a canal (Franzese et al., 2004), a strait (Köse et al., 2003) or an area (Yip, 2013) is modeled to present the overall performance. However, in such models, the details of individual vessel behavior are simplified to a large extent. To investigate the traffic state involving different type of vessels, agent-based models are developed for waterway networks (Merrick et al., 2003) or open sea (Vaněk et al., 2013). Different types of vessels are defined as distinctive agents. However, in the model by Vaněk et al. (2013), the sailing behavior of each type of agent (merchant vessel, navy vessel, and pirate vessel) in the models is simplified as an event with origin and destination over a period of time. The behavior of individual vessels can hardly be modeled. Aiming to represent the details of vessel traffic, the detailed behavior of every single vessel in the area is modeled by describing the time-space state (Cheng et al., 2017; Hasegawa et al., 2001; Miyake et al., 2015). To further consider the safe passage of vessels during encounters, the evasive behavior of vessels is included (Qu and Meng, 2012; Watanabe et al., 2008). Qu and Meng (2012) and Qi et al. (2017) introduce the impact of weather and sea state on sailing behavior. Such models considering individual vessel behavior show the interaction between vessel and surroundings (both external environmental factors and other encountering vessels).

Two groups of researchers have reviewed (a subset of the) available models before. Szlapczynski and Szlapczynska (2017) present a systematic review of the models using ship domain for whatever application purposes. However, other models, which are not based on the ship domain but potentially interesting in our application, are not assessed. Bellsolà Olba et al. (2018) review port simulation models adopting different methods and focus on the vessel traffic from a port operations viewpoint. The underlying modeling methodology and the corresponding application limitations are, however, not discussed in detail. The models developed for other areas have not been assessed, either. Therefore, none of the existing reviews analyzes the full range of the maritime traffic models from the viewpoint of vessel behavior modeling. The underlying evolution in methodologies is not discussed, either. However, vessels are the basic elements of maritime traffic. To investigate the models from the vessel behavior perspective allows an overview of how the maritime traffic is described. This way, all involved approaches can also be revealed.

The scope of this review covers all maritime traffic models describing the behavior and interactions of individual vessels, irrespective of the application area. This paper provides a broad, but not exhaustive overview of the current literature on maritime traffic models of the last decades. Commercial models are not included due to the limit of information about the underlying methods. The aim of this paper is to analyze the modeling paradigms and assess the capabilities of maritime traffic models in accurately representing the vessel behavioral details. Within this paper, the performance of the maritime traffic models has been assessed with a series of criteria regarding the capability of modeling vessel behavior in different circumstances. Moreover, the modeling characteristics are also analyzed to indicate the underlying paradigms and implementation issues. The review result will provide suggestions for the future development of a maritime traffic model considering individual vessel behavior.

The rest of the paper is organized as follows. Section 2 explains the research methodology from literature search to model selection and model assessment. Section 3 identifies the criteria to assess the models with detailed explanation. Section 4 categorizes and elaborates upon the model characteristics based on their underlying methodologies. In Section 5, all models are discussed with respect to the criteria described in Section 3. Finally, Section 6 concludes the paper based on the assessment results.

2. Research methodology

The goal of this review is to provide an overview and discussion of all maritime traffic models considering the vessel behavior. Figure 1 illustrates the steps of this review from literature search to model selection and assessment. The detailed methodology is further explained in this section. In section 2.1, the literature search method and process are presented. Section 2.2 introduces the criteria to select models from the search result. Finally, the selected models are assessed according to the criteria explained in section 2.3.

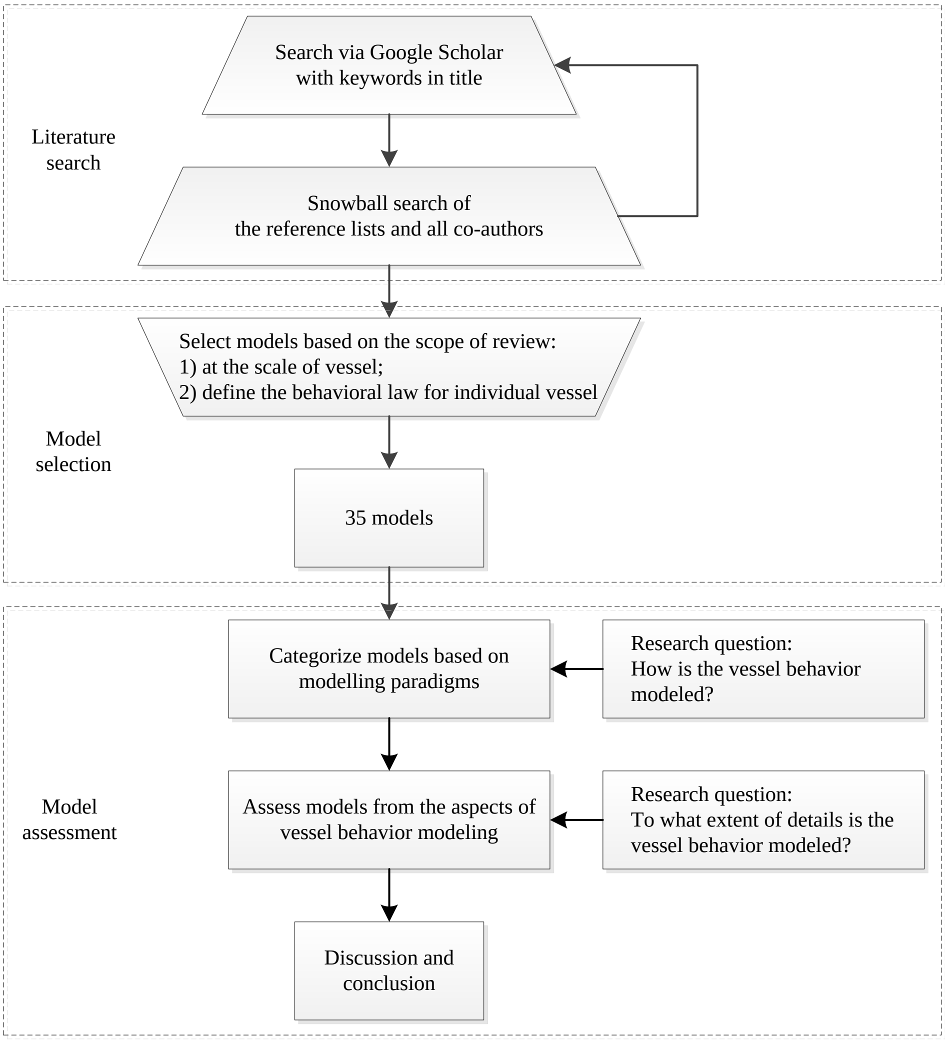

Figure 1. Steps of literature search and model review (The dashed rectangles refer to the steps corresponding to the sub-sections in section 2).

2.1. Literature search

Maritime traffic models have been developed for different purposes of application. The literature search in this paper is firstly performed through Google Scholar to include both peer-reviewed journal articles and conference papers. Included in this paper were articles dated up to December 2018 with the keyword: “traffic model(s)”. This way, all types of models are covered, including conceptual models, analytical models, statistical models, data-driven models, and simulation models. Besides, at least one of the following keywords should also be contained in the title of the article: “marine”, “maritime”, “nautical”, “ship(s)”, “vessel(s)”, “port(s)”, “waterway(s)”, “channel(s)”, “canal(s)”, “strati(s)”, “gulf(s)”, “bay(s)”. All articles in the search results focusing on maritime traffic are deemed as relevant articles for further review. In case of other unexpected keywords, the snowball search is conducted in two ways: (1) searching all of the relevant articles in the references; (2) searching all of relevant articles of all co-authors. Only the articles in English have been assessed. The process and findings of the literature search have been presented in Figure 2. As a result, 66 maritime traffic models in 112 articles are collected for further model selection in section 2.2. The cloud of words in the title and key words of the 112 articles gives an overview of the issues that the studies on maritime traffic models have focused on (see Figure 3). It can be observed that the initially proposed key words for literature search can cover the majority of the relevant papers.

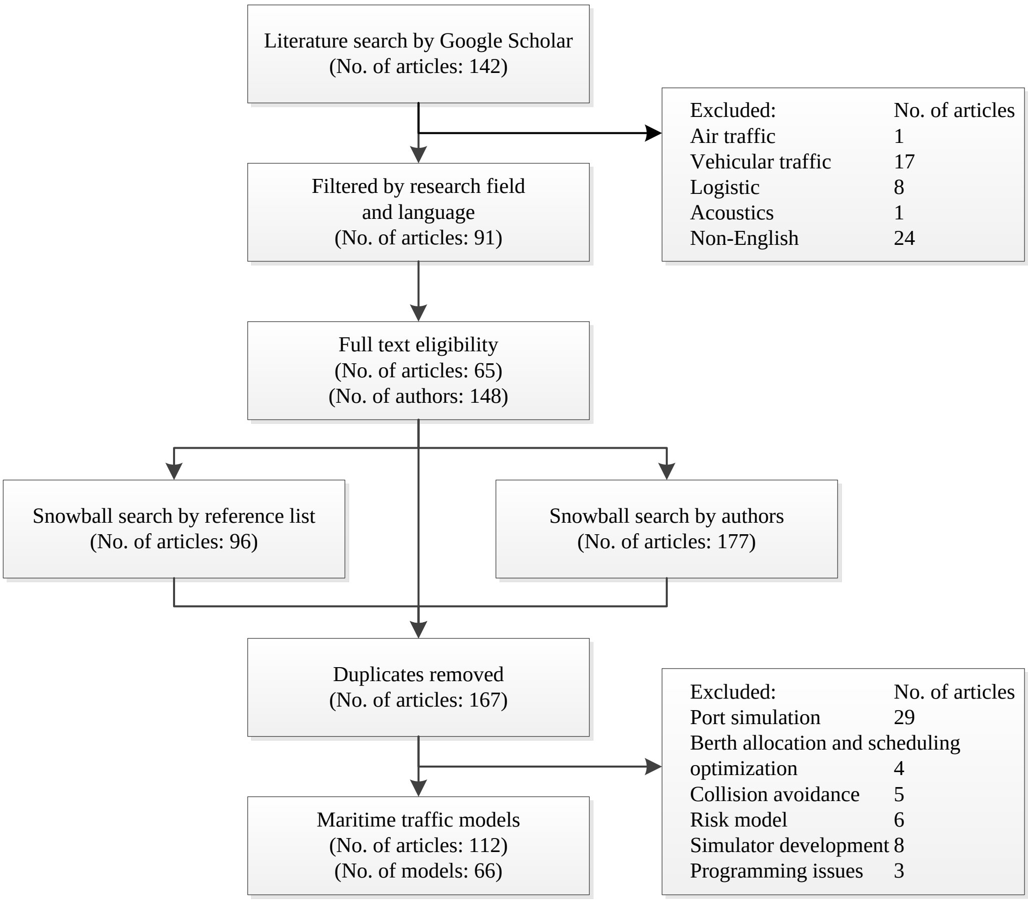

Figure 2. The process and findings of the literature search step.

Figure 3. The cloud of words in the title and key words of the 112 articles on maritime traffic models.

2.2. Model selection

Based on the requirements of the application, the models need to describe different aspects of the maritime traffic flow by considering the dynamic kinetic information of individual vessels or not. The dynamic kinetic information of vessel behavior includes, but is not limited to, position, speed, course, and heading. Starting from this point of view, models are defined to be either microscopic maritime traffic model or macroscopic ones. However, the scale is not explicitly explained. In vehicular traffic analysis, Lesort et al. (2005) also point out that the usual micro/macro classification is not sufficient to identify the characteristics of the models. They proposed a new classification method based on two criteria, being the behavioral law (individual or collective) and the representation scale (vehicle or flow) (Bourrel et al., 2003).

From the vessel behavior modeling perspective, the collective behavioral law at the flow scale only describes the evolution of maritime traffic at an aggregated level. The detailed information of individual vessels and their dynamic behavior is neglected. In order to compare and assess how the vessel behavior is modeled, the criteria to select models for assessment in this review are identified: (1) representing the maritime traffic at the scale of vessels; and (2) defining the behavioral law of individual vessels. According to this definition, 35 models from the search results in the previous step are selected and reviewed in this paper. Among the other models, there are mainly four reasons for the exclusion from the review. Considering the first selection criterion, 10 traffic flow-based models and 3 network-based models are excluded. According to the second criterion, 17 models without a definition of behavioral law for individual vessel are excluded from the review. Besides, one commercial model with brief introduction is excluded, as well.

The statistics of descriptive background information of the selected models is provided in Table 11, with the full list in Appendix. Among the selected publications, it happens that both articles and thesis describe the same model. In this case, the thesis is deemed as the reference which explains the model in a systematic manner. In respect of the collected data sources, AIS data is the most common type to use after its introduction. Regarding the countries of the author's affiliations, European and Asian countries account for the majority.

Table 1. The statistics of descriptive background information of the selected models.

Descriptive information	Categories	No. of articles/models		Descriptive information	Categories	No. of models
Type of publication	Journal articles	24	articles	Country and region	NLD	7
	Conference proceedings	14	articles		CHN	7
	Thesis	6	theses		POL	4
Stated application area	Confined water	28	models		JPN	3
	Open water	7	models		SGP	3
Collected data type	AIS data	14	models		TUR	3
	Traffic data	5	models		BEL	2
	Radar data	3	models		GBR	2
	Ship maneuvering data	3	models		DEU	1
	GPS data	1	model		FIN	1
	Cine film of radar screen	1	model		NOR	1
	Questionnaire	1	model		PRT	1
	No data collected	10	models		USA	1

2.3. Model assessment

The model assessment in this review is performed in two parts, to answer two questions. The first one (section 2.3.1) is to evaluate what kind of vessel behavior related information is included in each model. The comparison results will show to which extent the models describe the vessel behavior and the relevant external impacts. The other one (section 2.3.2) is to discuss how the vessel behavior is modeled, which is to reveal the underlying paradigms in vessel behavior modeling.

2.3.1. Vessel behavior modeling assessment criteria

Maritime traffic models have the requirement to accurately represent the evolution of the maritime traffic state, for every application purposes. Hence, the selected models are compared with respect to their capabilities to represent vessel behavior in maritime traffic. The authors understand that each model is developed with a specific goal and are not expected to capture all details of vessel behavior as is in real-life situations. To fully evaluate the performance of the models, the proposed assessment criteria will cover a wide variety of characteristics of vessel sailing behavior that can be observed in real-life, as shown in Figure 4.

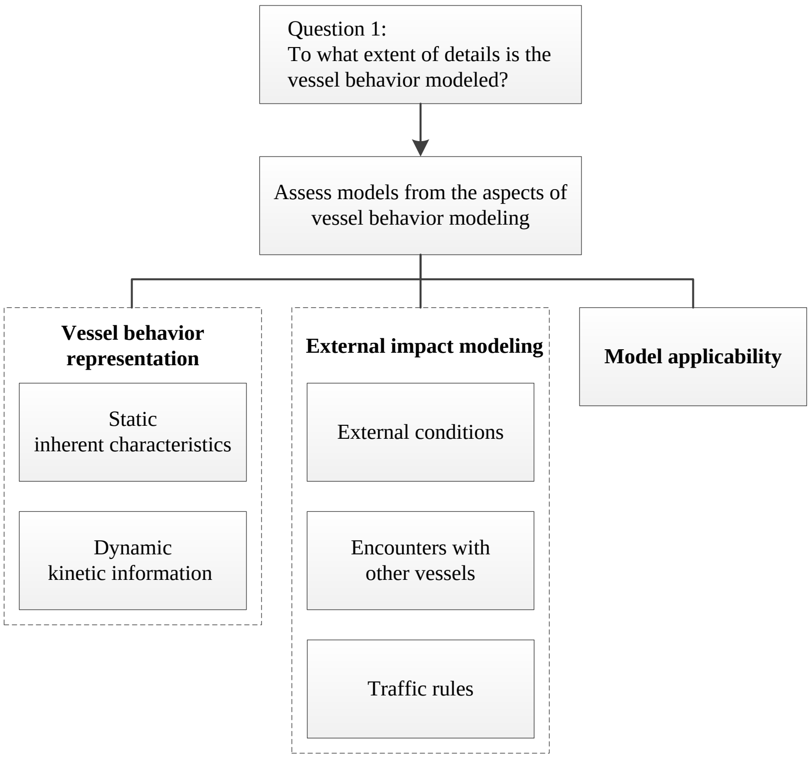

Figure 4. Structure of vessel behavior modeling assessment criteria.

Firstly, the way of representing vessel behavior is assessed in two aspects. The static inherent characteristics indicate how a model distinguish different vessels and whether a model can capture the differences among vessels or at least groups of vessels. To show how the vessel behavior is described in a model, the dynamic kinetic information adopted in a model should be compared.

Since the vessel behavior is highly affected by external conditions as studied by Shu et al. (2017), the way of modeling such external impacts should be evaluated. The external factors include external environmental conditions, encounters with other vessels, and traffic rules as well. The assessment aims to indicate to what extent the details of vessel behavior and the relevant external factors are included in the models. It means there could be some factor that no model has considered yet. Therefore, the existing maritime traffic models are not only compared, the possible limitations of all models could also be revealed.

Additionally, the capability of models to capture different vessel movement base cases is also investigated to show the model applicability. The full range of assessment criteria is explained in section 3.

2.3.2. Modeling paradigm categorization

To elaborate and discuss the possible potential and limitations of the models, the models are categorized based on their underlying modeling paradigms (see Figure 5) and introduced in section 4. The common feature of maritime traffic models is that most of the models represent the vessels as agents. Only a few models considering detailed maneuverability with sub-modules are developed. Thus, agent-based modeling is not a suitable criterion to define the modeling paradigms in maritime traffic models.

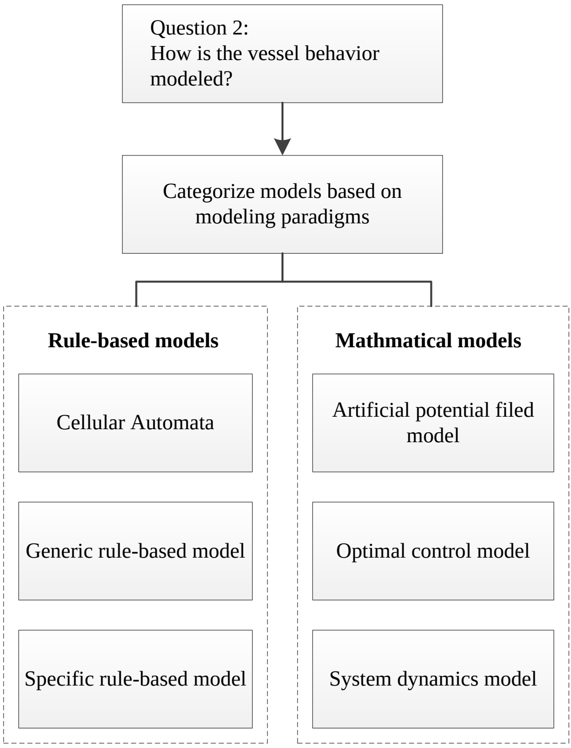

Figure 5. Categorization of modeling paradigms.

Investigating the structure of all maritime traffic models, they can be generically categorized by rule-based models to describe the behavioral law by rule sets and the mathematical models to present the state of vessels in form of differential equations. In the rule-based models, one specific category is cellular automata. The water area is discretized into cells, and the rules are defined to update cell state at time steps. For the other rule-based models, two types of rule sets are distinguished. One type of rules is generically defined for all vessels applying under whatever circumstances, while the other type of rules considers the differences between vessels and the possible interaction between vessels and the circumstances. Based on these differences in rule sets, the rule-based models are further categorized into generic rule-based models and specific rule-based models.

Among the other mathematical models, three typical types are identified. The artificial potential field models calculate the attractive or repulsive potential between the vessels and the circumstances to represent the interacting behavioral laws. The optimal control models describe the system of maritime traffic via a set of differential equations with an optimization criterion as the objective function. Lastly, the system dynamics models describe the vessel behavior by state-space functions. Therefore, the six modeling paradigms identified in this review are cellular automata, generic rule-based model, specific rule-based model, artificial potential field model, optimal control model, and system dynamics model.

The information of all traffic models used in this review is taken from the respective papers proposing or applying the corresponding models. Since the authors cannot implement all models for comparison, we assume that the description of the models presented in the papers agrees with their implementation. Thus, the authors do not implement all models to compare their performance or modeling accuracy. However, even if the model is developed for a specific purpose, the capability of the model to simulate other situations is also assessed with respect to its potential in describing the characteristics and the sailing rules in other types of water area.

3. Assessment criteria – vessel behavior modeling

To compare the capability of vessel behavior modeling, the maritime traffic models are assessed from three aspects, including vessel behavior representation, external impact modeling, and model applicability, as shown in Figure 4. The assessment criteria are described in more detail in this section. Besides an explanation of the criteria, a rating scale is introduced for each criterion to compare the models. For some criteria, the models are only marked as “yes” or “no” to indicate whether such a factor is included or not. For other criteria, the models are rated to the extent that the models can represent the behavior or the impact.

3.1. Vessel behavior representation

The first group of assessment criteria focuses on the representation of vessel behavior, which is the basis of a maritime traffic model. We identify two criteria to assess the representation of vessel static characteristics and dynamic behavior. One criterion investigates how different vessels are defined or classified based on their inherent static characteristics (e.g. vessel type, geometric sizes, or tonnage), and the other criterion assesses how the vessel dynamic kinetic movement is described during modeling.

3.1.1. Static inherent characteristics

The behavior of each individual vessel is unique, even in the same area. The reasons are diverse, including the maneuverability of the vessels, the impacts of external factors, and the decisions and behavior of the bridge team. From the aspect of the vessels, the type, geometric size, or tonnage could influence the maneuverability. Thus, the ability to simulate different vessels in the models has been indicated by the method of vessel classification based on static inherent characteristics, as listed in Table 2. With more characteristics involved, the differences between vessel behavior can be better presented.

Table 2. Explanation of abbreviation to describe static inherent vessel characteristics.

Abbreviation	Description of the static inherent vessel characteristics
T	Vessel types
GT	Gross tonnage, which is a measure of the vessel's internal volume
DWT	Deadweight tonnage, which is a measure of the weight that a vessel can carry without her own weight
L	Length overall, which is the maximum length of a vessel
B	Breadth, which is the greatest breadth of a vessel
S	Specific vessels including all detailed vessel characteristics
(Blank)	No static inherent characteristics, the vessels are equally modeled without classification

3.1.2. Dynamic kinetic information

The vessel motion can be described in six degrees of freedom considering hydrodynamic forces, including surge, sway, heave, roll, pitch, and yaw (Sandurawan et al., 2012). However, from the viewpoint of other vessels or the traffic manager, the detailed motion cannot be observed. For example, the information on the rate of turn can only give a generic impression of fast or slow turning behavior to the other vessel, since the real maneuverability of each individual vessels is unknown. Therefore, only the directly observable dynamic kinetic information is selected as assessment criteria. The behavior of an own vessel can only be observed by position, speed over ground, course over ground and heading. For a detailed assessment, the vessel movement in the models is rated from these four aspects based on the criteria in Table 3.

Table 3. Rating scales for the dynamic kinetic information of vessel movement.

Abbreviation	Rates	Description of the rates
Position (P)	!	Two-dimensional space (both longitudinal and lateral position)
	√	One-dimensional space (only longitudinal position)
Speed (S)	!	Dynamic freedom of speed choice at each time step or continuously
	√	Several fixed speed choices
	×	Fixed speed through the voyage
Course (C)	!	Dynamic freedom of course choice at each time step or continuously
	√	Fixed course to follow the designed routes
	(blank)	Not included
Heading (H)	!	Dynamic freedom of heading choice at each time step or continuously
	√	Same as the course
	(blank)	Not included

3.2. External impact modeling

As mentioned above, vessel behavior is always influenced by external factors in real-life situations. From the viewpoint of each individual vessel, three types of external factors will be assessed in the maritime traffic models, including external conditions, encounters with other vessels, and traffic rules. The criteria will be explained in more detail in this section.

3.2.1. External conditions

The external conditions refer to the meteorological and hydrological factors and the geographical waterway layout which affect vessel navigation. Instead of summing up the external factors already mentioned in the existing models, all external factors relevant to vessel behavior will be included explicitly. Besides the normal conditions, the adverse weather condition is also included as an external factor for vessel behavior, which has been proven to restrict the vessel maneuverability (Bitner-Gregerse et al., 2016). The assessment criteria of external factors are listed in Table 4.

Table 4. Rating scales for the conditions of external factors.

Abbreviation	Rates	Description of the rates
Visibility (V)	!	Included with scales of visibility
	√	Included as good or restricted visibility
	(blank)	Not included
Wind (W)	!	Included with scales of the wind velocity and direction
	√	Included as “yes” or “no”
	(blank)	Not included
Tide (T)	√	Tidal chart included for water level or direction of the main stream
	(blank)	Not included
Current (C)	!	Included with scales of the current velocity and direction
	√	Included as “yes” or “no”
	(blank)	Not included
Adverse weather (A)	!	Included with scales
	√	Specific adverse condition included
	(blank)	Not included
Bank (B)	√	Defined geographical boundaries (bank) with impact on the vessel behavior
	×	Defined geographical boundaries (bank) without impact on the vessel behavior
	-	Not applicable for open water or confined water area with specific routeing scheme

3.2.2. Encounters with other vessels

When two or more vessels encounter each other during navigation, the vessels will possibly take actions to avoid collision and guarantee safe passage. Using a distance of safety in the model is the most generic way to model vessel encounters. However, vessels sailing at sea should comply with the rules in the International Regulations for Preventing Collisions at Sea (COLREGs) (International Maritime Organization, 1972), and vessels sailing in port area should additionally comply with the local rules regarding the responsibility of vessel behavior during encounters. Thus, the inclusion of vessel behavior during typical encounters can be assessed. This is to distinguish the impacts of different encounters on vessel behavior. According to COLREGs, three types of vessel encounter are identified, being head-on situation, crossing situation, and overtaking. Besides the basic types of two-vessel encounter, the multi-vessel encounter (more than two vessels involved) is also considered to indicate the capability of a model dealing with such more complex situations. The detailed rating scales for vessel encounter in the models are explained in Table 5.

Table 5. Rating scales for the description of vessel behavior during encounter with other vessels.

Abbreviation	Rates	Description of the rates
Distance of Safety (DS)	√	Generic or situation-specified distance of safety
	(blank)	No distance of safety
Head-on situation (HO)	!	Both normal (port-to-port) and dangerous (starboard-to-starboard) head-on situations with specified rules
	√	Specified with same rules for both vessels
	(blank)	Not specified
Crossing situation (CS)	!	Specified rules for stand-on vessel and give-way vessel
	√	Specified with rules for only one vessel
	(blank)	Not specified
Overtaking (OT)	!	Specified rules for both overtaking and overtaken vessel
	√	Specified with rules for only one vessel
	(blank)	Not specified
Multi-vessel encounter (MV)	√	Specified rules among vessels
	(blank)	Not included

3.2.3. Traffic rules

As mentioned in the impacts of vessel encounter, the traffic rules, such as COLREGs, may affect the vessel behavior in some circumstances. Besides the regulations issued by IMO, the local authority of government or port can set special rules for the reasons of security, safety or environment protection. In addition to the responsibility of vessels during encounters, these rules may also include speed limit, and waterway usage, etc. The inclusion of traffic rules at different levels of details is assessed based on the classes in Table 6.

Table 6. Rating scales for the inclusion of traffic rules in the model.

Rates	Description of the rates
!	Specified rules by local authority
√	Only COLREGs
(blank)	Not specified

3.3. Model applicability

With specific purpose of model development, not all models can be applied in all types of water area. Thus, the applicability of models is assessed by looking at the application area, listed in Table 7.

Considering the navigable waters for vessel maneuvering, the water area can be distinguished by open water area and confined water area. For confined waters, the boundary can be geographical bank or virtual waterways, e.g. the area with traffic separation scheme. The authors realize that, besides the specific application as stated in the papers, models can be used in more situations considering whether and how the impact of the sailing area boundaries is included. Therefore, the models are not only assessed according to the situation referred to in the papers but also with respect to the application area potential of the models.

Table 7. Explanation of abbreviation to describe the model application area.

Abbreviation	Description of the water area
OW	Open water area
CW_G	Confined water area with geographical boundaries, e.g. inland waterway or coastlines
CW_V	Confined water area with virtual boundaries, e.g. specific routeing scheme
?	Unclear area of application

For vessel behavior in the confined water area, different vessel movement base cases have been identified. The cases have been defined as the predominant sailing situation that might occur in a confined area (e.g. sailing in a straight waterway, turning at an intersection, crossing an intersection, etc.). The movement base cases are expected to cover the whole range of vessel behavior in confined water area with either geographical or virtual boundaries. Thus, the vessel traffic can be a combination of such generic base cases. Figure 6 presents the categories of vessel movement base cases.

Instead of identifying the vessel movement in different waterway layout, the specific traffic flow is considered to indicate the base cases. Firstly, the vessel movement is distinguished by uni-directional and multi-directional flows. The category "uni-directional flow" splits into three separate categories, namely straight flow, bending flow and turning flow. The distinction between straight flow and bending flow is whether the vessel shall take a series of course change actions to follow the route. The distinction between bending flow and turning flow depends on the total course change when passing the area without the course steady in between. If the course change is less than or equal to 90 degrees, the vessel movement is deemed as bending flow. If the course change is larger than 90 degrees, the movement is deemed as turning. The lower figure in Figure 6 (UT_3) under the turning flow indicates the vessel movement in turning basin close to the berth. In the movement cases in turning flows, the ship turning maneuverability usually needs to be concerned. Next to that, the category "multi-directional flow" is further distinguished by bi-directional flows, merging flows, diverging flows and crossing flows. The distinction between crossing flows and the other three categories is the potential route conflict among the flows. Bi-directional flows in a straight waterway (MB_1) or a bending waterway (MB_2) occur due to the local rules, which can be a traffic separating scheme or made by the local port authority. Meanwhile, the merging and diverging flows are mainly due to the layout of such intersection (MM_1 and MD_1). If there is a third vessel from the opposite direction (MM_2 and MD_2), multi-directional flows occur additionally due to the local rules of bi-directional sailing. For crossing flows (MC_1 and MC_2), the waterway layout plays a basic role in the case, while the local traffic rules or the traffic separation scheme also leads to the multi-flows.

The capability of a model to capture such base cases depends on whether the vessel behavior is specified in different situations.

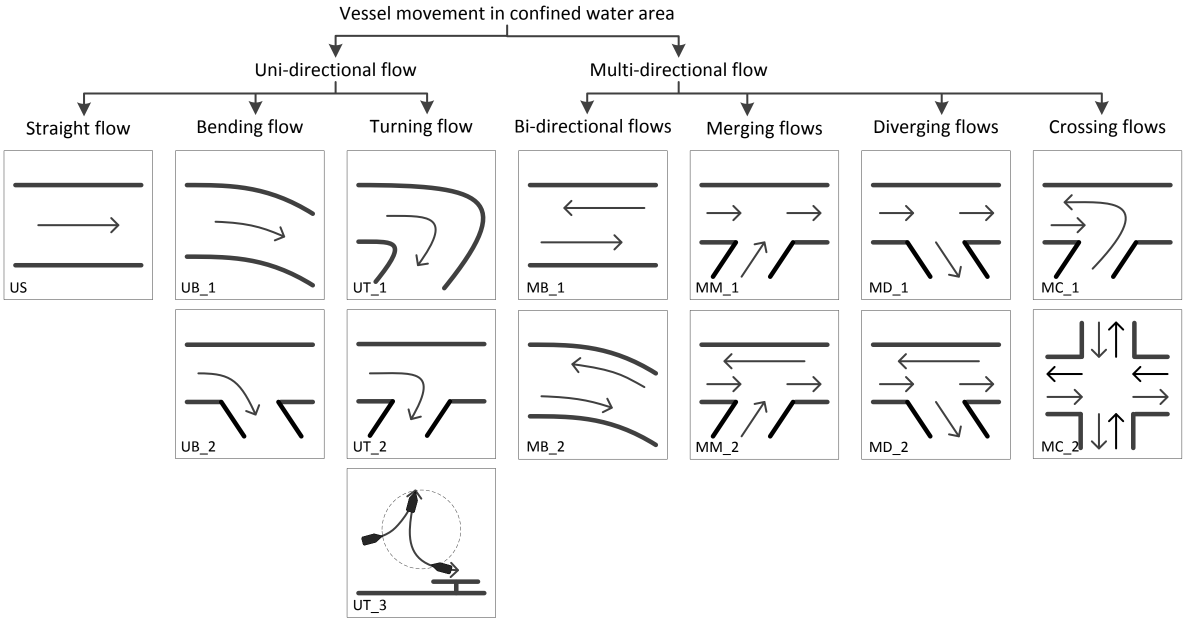

Figure 6. Vessel movement base cases in confined water area.

4. Model categorization – modeling paradigms

All of the maritime traffic models, excluding the commercial ones due to a lack of sufficient information about the methodology, will be categorized based on their modeling paradigms as presented in Figure 5. To illustrate the development of maritime traffic models with their corresponding modeling paradigms, the timeline of the models is presented in Figure 7. It can be observed that the rule-based models (either specific or generic) are adopted throughout the development of maritime traffic models. With the introduction of AIS data and the development of computer science, the trend moves from generic rules to specific rules and from one-dimensional model to two-dimensional ones. The optimal control model and system dynamics model for maritime traffic are first proposed in the 1990s at a conceptual level, due to a lack of data availability. Afterward, both methods are not often adopted, compared to rule-based models. However, in recent years, with the research trend of mathematical models and the various data sources, both modeling paradigms are developed again. Cellular Automata and Artificial Potential Field are adapted to maritime traffic from other fields, namely vehicular traffic flow modeling and robot path planning. Both paradigms have been continuously adopted and developed by different researchers since its first application in maritime traffic models. By categorizing the models into paradigms, the introduction of individual models will also indicate the development within each paradigm.

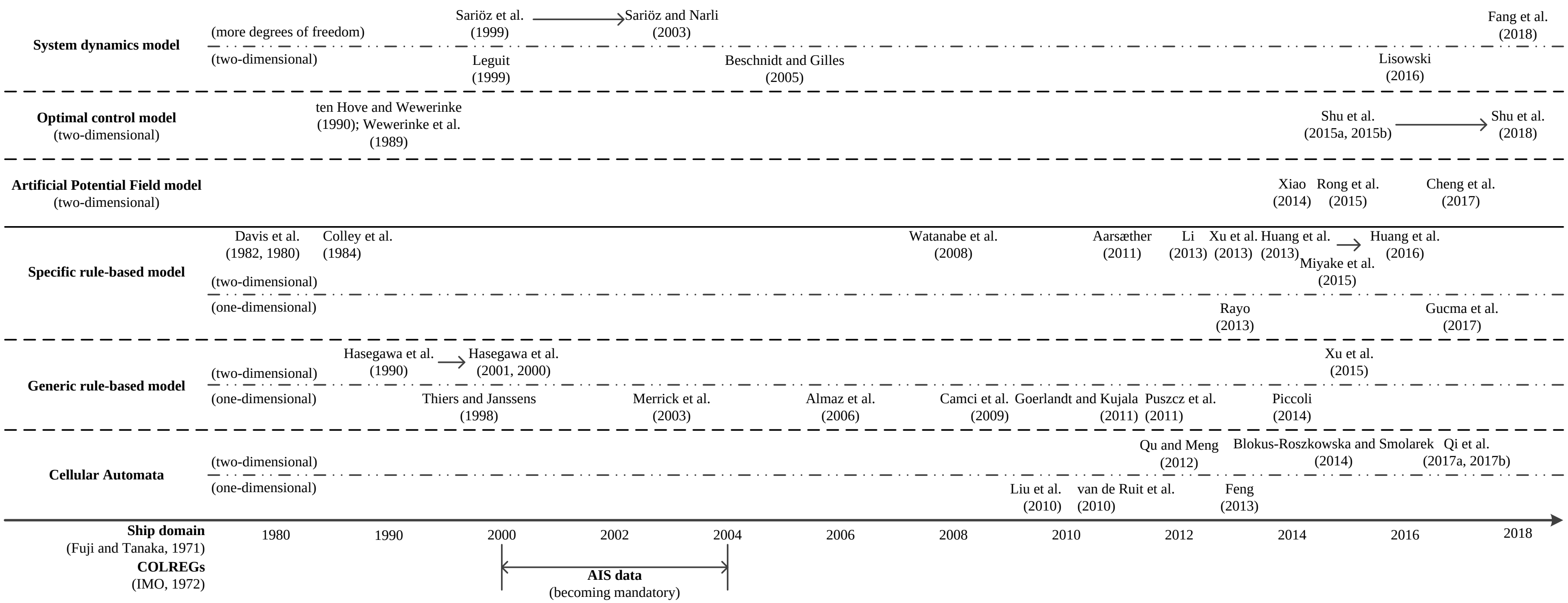

Figure 7. Timeline of the maritime traffic models with corresponding modeling paradigms.

Before the detailed introduction, an overview of the models regarding the characteristics of model development is also presented in Table 8. The model characteristics include the following aspects:

a) *Dimension* indicates how the vessel motion is specified in space.

b) *Scale of time* refers to how is the vessel movement modeled in time, i.e., continuous or discrete. A time-discrete model can be obtained by discretizing the time-continuous model, or directly developed to update vessel movement at time steps.

c) *Scale of space* indicates how is the water area defined in the model (continuous or discrete).

d) *Calibration* refers to the process to find an optimum set of model parameters by minimizing the differences between simulation results and the observed data.

e) *Validation* is the process using an independent data set compared to the one used in calibration, in order to check whether the model replicates reality or not.

f) *Category*: Six modeling paradigms are identified in this paper. The categories are described in the order indicating the potential to capture more details of vessel behavior.

Since all of the reviewed models are stochastic, it is not included as a criterion in the table. In the following sections, Cellular Automata (section 4.1), Generic Rule-Based model (section 4.2), Specific Rule-Based model (section 4.3), Artificial Potential Field model (section 4.4), Optimal Control model (section 4.5), and System Dynamics model (section 4.6) are introduced. Section 4.7 provides an discussion on the overview of the modeling paradigms.

Table 8. Overview of maritime traffic models with respect to the model characteristics.

No.	Model	Dimension	Scale		Calibration	Validation	Category
			Time	Space			
1	Liu et al. (2010)	*1*	*dt*	*d*	×	√	CA
2	Feng (2013)	*1*	*dt*	*d*	×	×	CA
3	van de Ruit et al. (2010)	*1*	*dt*	*d*	×	√	CA
4	Qu and Meng (2012)	*2*	*dt*	*d*	×	√	CA
5	Blokus-Roszkowska and Smolarek (2014)	*2*	*dt*	*d*	×	×	CA
6	Qi et al. (2017a, 2017b)	*2*	*dt*	*d*	×	√	CA
7	Thiers and Janssens (1998)	*1*	*dt*	*d*	×	√	GRB
8	Merrick et al., (2003)	*1*	*dt*	*c*	×	√	GRB
9	Almaz et al. (2006)	*1*	*dt*	*c*	×	√	GRB
10	Camci et al. (2009)	*1*	*dt*	*c*	×	√	GRB
11	Goerlandt and Kujala (2011)	*1*	*dt*	*c*	×	√	GRB
12	Puszcz et al. (2011)	*1*	*dt*	*c*	×	√	GRB
13	Piccoli (2014)	*1*	*dt*	*c*	×	√	GRB
14	Hasegawa (1990); Hasegawa et al. (2001, 2000)	*2*	*dt*	*c*	×	√	GRB
15	Xu et al. (2015)	*2*	*dt*	*c*	×	√	GRB
16	Gucma et al. (2017)	*1*	*dt*	*c*	×	√	SRB
17	Rayo (2013)	*1*	*dc*	*c*	×	×	SRB
18	Davis et al. (1982, 1980)	*2*	*dt*	*c*	×	×	SRB
19	Colley et al. (1984)	*2*	*dt*	*c*	×	√	SRB
20	Watanabe et al. (2008)	*2*	*dt*	*c*	×	×	SRB
21	Li (2013)	*2*	*dt*	*c*	×	×	SRB
22	Xu et al. (2013)	*2*	*dt*	*c*	×	√	SRB
23	Miyake et al. (2015)	*2*	*dt*	*c*	×	√	SRB
24	Huang et al. (2016, 2013)	*2*	*dt*	*c*	√	√	SRB
25	Aarsæther (2011)	*2*	*dc*	*c*	×	√	SRB
26	Xiao (2014)	*2*	*dt*	*c*	√	√	APF
27	Rong et al. (2015)	*2*	*dt*	*c*	×	√	APF
28	Cheng et al. (2017)	*2*	*dt*	*c*	×	√	APF
29	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	*2*	*dc*	*c*	×	×	OC
30	Shu et al. (2018, 2015a, 2015b)	*2*	*dc*	*c*	√	√	OC
31	Leguit (1999)	*2*	*dt*	*c*	×	×	SD
32	Lisowski (2016)	*2*	*dc*	*c*	×	×	SD
33	Beschnidt and Gilles (2005)	*2*	*c*	*c*	×	×	SD
34	Sariöz et al. (1999); Sariöz and Narli (2003)	*>2*	*c*	*c*	√	×	SD
35	Fang et al. (2018)	*>2*	*dc*	*c*	√	×	SD

Dimension: 1=one-dimensional, 2=two-dimensional, >*2*=including more degrees of freedom of vessel motion;

Scale of time: *dt*= discrete-time model, *dc*=discretized from a continuous-time model, *c*=continuous time;

Scale of space: *d*=discrete, *c*=continuous;

Category: CA=Cellular Automata, GRB=generic rule-based, SRB=specific rule-based, APF=artificial potential field, OC=optimal control, SD=system dynamics.

4.1. Cellular Automata

The Cellular Automata (CA) model is a specific type of rule-based model. It is discrete both in time and space to describe the discrete movement of vessels through grids of cells. The waterway or traffic route is discretized into cells with a predefined size. The vessels are assigned a certain number of cells according to the length. The states of cells are assumed to be either available or occupied. For all CA models, the decision of vessel behavior depends on the status of neighboring cells. However, the moving direction and the moving speed differ according to the rules defined in different models.

The position of the vessel is updated at each time step. The vessel speed is modeled generally in two ways. In the simplified method, the speed of the vessels is constant through the voyage, which can be the same for all vessels (Liu et al., 2010) or dependent on vessel type (Blokus-Roszkowska and Smolarek, 2014). Alternatively, the speed of the vessels is decided by rules of following behavior (Feng, 2013; Qi et al., 2017b; Qu and Meng, 2012; van de Ruit et al., 2010).

Regarding the external impacts, Qu and Meng (2012) and Qi et al. (2017a) adopt random variables to represent the impacts of weather and sea state on vessel speed. The interactions with other vessels are considered by defining deceleration rules when another vessel is within a distance of safety (Feng, 2013; Qi et al., 2017a). Blokus-Roszkowska and Smolarek (2014) consider the relative course of the other vessel to determine the reacting behavior, which could be acceleration or course change. Qu and Meng (2012) define crossing rules for vessels about to enter the main traffic route from the branch waterways and rules for overtaking situation.

Since CA models present the dynamics of traffic flow based on vessel speed and position in cells, the detailed behavior of vessels can hardly be simulated. The impacts of external factors are simplified, either.

4.2. Generic rule-based models

In generic rule-based models, it is assumed that the details of the individual vessel behavior (position, speed, course) are simplified as generic movement rules for all agents. In such models, the rules for different vessels are defined as the same under any circumstances.

Most of the generic rule-based models present the maritime traffic in one-dimensional space, i.e. the lateral position of vessels in waterway is not included (Almaz et al., 2006; Camci et al., 2009; Goerlandt and Kujala, 2011; Merrick et al., 2003; Piccoli, 2014; Puszcz et al., 2011; Thiers and Janssens, 1998). The routes are predefined in the models, and with waypoint coordinates if needed. The behavior rule of the agents is to follow the routes and turn instantly at the waypoints. In other models in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data (Hasegawa, 1990; Hasegawa et al., 2001, 2000; Xu et al., 2015). The vessel speed is defined as the same for all vessels (Piccoli, 2014), or dependent on the vessel classification (Almaz et al., 2006; Camci et al., 2009; Goerlandt and Kujala, 2011; Hasegawa, 1990; Hasegawa et al., 2001, 2000; Merrick et al., 2003), or generated from historical distribution (Puszcz et al., 2011; Xu et al., 2015). Thiers and Janssens (1998) determine the vessel speed for each waterway segment, thus the vessels change the speed immediately when entering a new segment.

The conditions of external environmental factors are considered by defining different vessel speed (Almaz et al., 2006; Camci et al., 2009; Merrick et al., 2003; Puszcz et al., 2011), or generating vessels according to tidal window (Piccoli, 2014; Thiers and Janssens, 1998). Qu and Meng (2012) and Xu et al. (2015) define the rules of overtaking by a distance of safety. None of the models define detailed behavior rules for collision avoidance during other encounters. However, Distance of Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) are calculated for risk analysis (Goerlandt and Kujala, 2011; Hasegawa et al., 2001). The traffic rules regarding speed limit or overtaking prohibition are also included for all vessels (Qu and Meng, 2012; Thiers and Janssens, 1998; Xu et al., 2015).

Therefore, the differences in unhindered behavior among different vessels and the external impacts under different circumstances cannot be presented in the generic rule-based models. When applying for macroscopic statistical analysis for a large area as presented in the referenced papers, the models are well applicable.

4.3. Specific rule-based models

Similar to generic rule-based models, the dynamic vessel behavior (position, speed, course, heading) is assumed to be described by a set of rules. However, the specific rule-based models consider the differences between vessels and the possible interaction between vessels and the circumstances. The unhindered behavior of different vessels are usually distinguished. The impacts of the geographical layout can also be included by defining behavior rules. The vessel behavior during an encounter can be determined according to a situation-based calculation.

In respect of the rules for basic behavior, the course of the vessels is designed to follow the route and instantly turn at the waypoints in most of the models, except for Aarsæther (2011). In this model, the course is a proportional feedback of the rate-of-turn when the course of the route is changing. The speed of the vessels are constant through the voyage, which can be dependent on vessel classification (Miyake et al., 2015; Watanabe et al., 2008), or have a specific distribution (Gucma et al., 2017), or a distribution derived from historical data (Colley et al., 1984; Davis et al., 1980; Huang et al., 2016, 2013; Li, 2013; Xu et al., 2013). In other models, the speed of the vessels is determined by the maximum or minimum of the speed limitations (Rayo, 2013). Aarsæther (2011) defines the vessel behavior as a first-order model between the current and desired speed.

Regarding the impacts of external environmental factors, only two models include the corresponding behavior rules. For the impact of bank, Davis et al. (1980) define the domain of bank, while the vessels will change course to sail parallel to the bank and decelerate. Watanabe et al. (2008) assume the waterway bank to be a virtual agent with the same speed parallel to the vessel agent or on the opposite direction.

Nearly all models include the interactions between vessels for collision avoidance, except for Xu et al. (2013). Rayo (2013) and Gucma et al. (2017) only define a distance of safety to determine whether a vessel should decelerate or not, in which course change is not considered in the one-dimensional space. The remaining models adopt different criteria to judge the encounter situation between vessels and calculate DCPA and TCPA to trigger the evasive actions. Aarsæther (2011) only defines a distance of safety as the only criterion. Davis et al. (1980) adopt the ship domain to indicate the timing when the domain is infringed by the other vessel, in which the size is decided by statistical data. Colley et al. (1984) further considers the relative speed of the other vessel and defines the concept of range to domain over range rate (RDRR) in the calculation. This way, the three types of encounter can be distinguished. The behavior rule during dangerous head-on situation (starboard-to-starboard) is also defined. Li (2013) and Miyake et al. (2015) trigger the collision avoidance behavior with an increase of DCPA and TCPA. Watanabe et al. (2008) adopt the concept of CR by Hasegawa et al. (2001) to judge the situation and calculate the timing for the vessel to turn back to the original route. Huang et al. (2016) use DCPA and the Separating Axis Theorem (Eberly, 2001) to detect the collision candidate. All of them assign the responsibility of taking actions among vessels in encounter based on the rules of COLREGs. The resulting evasive behavior is mainly to change course or to change both course and speed. The magnitude of the behavior is decided to best decrease DCPA and TCPA.

In the models by Davis et al. (1982), Colley et al. (1984) and (Miyake et al., 2015), the multi-vessel encounter situation is assumed to be a series of two-vessel encounters. The most dangerous vessel to avoid collision first is chosen with the earliest TCPA. In this case, if the most dangerous vessel is the give-way vessel, and she does not take evasive actions within a certain time, the stand-on vessel at liberty should take action by a round turn. During the collision avoidance, DCPA and TCPA are calculated at each time step to judge the situation.

The specific rule-based models represent the interaction between vessels better than the aforementioned two approaches. However, in most of the pre-defined rules, the safety distance or other parameter value to trigger the evasive maneuver for collision avoidance is subjectively determined by the user for a specific area during model development. It limits the applicability of models in other areas. The impact of environmental external factors is not included yet. To present such impacts on different vessels by specific rules, the detailed maneuvering particulars for specific vessels may be needed.

4.4. Artificial potential field models

An Artificial Potential Field (APF), also known as artificial force field, has been implemented in three maritime traffic models for different types of water area. In these models, vessels are defined as agents. APF provides the course of the vessel subjected to a force which is derived from the sum of the attractive potential and the repulsive forces. All models by APF present the vessel behavior in two-dimensional continuous space. The models are designed to calculate the potential and forces to decide the speed and course at each time step.

The definition of attractive and repulsive potential varies among the models. Xiao (2014) adopts APF to simulate the impacts of banks and encounters (head-on and overtaking situation) on vessel behavior in straight waterways. A similar model is developed by Rong et al. (2015) for traffic in the river, where the boundaries of the traffic lanes are represented by a series of points with the repulsive potential to the vessels. In the model by Cheng et al. (2017), the impacts from fixed obstacles in the multi-bridge area are simulated using APF. The repulsive potential field around fixed obstacles is assumed to be rectangle or circle with three layers, in which the most inside layer is set with the largest repulsive potential. The potential of the three layers is defined separately as a function of distance, speed, and course, while the potential within each layer is the same.

In the models by Rong et al. (2015) and Cheng et al. (2017), the speed of vessels changes only during the encounter with other vessels or obstacles. Otherwise, vessels keep a constant speed determined when generating the vessel in the beginning. Neither of them includes the impact of external conditions, e.g. wind or current. Xiao (2014) developed a sub-model for the behavior of vessels by the Nomoto model (Kawaguchi et al., 2004) based on basic maneuverability. The impact of wind and current is indicated by a variation in course and heading, without influencing the speed of vessels.

APF shows its potential in modeling the course choice under the external impacts from sailing boundaries or other encountering vessels. It can be expected that the method could represent the impacts of external factors as repulsive potential based on the hydrodynamical calculation or sufficient data analysis to calibrate the parameters in the function. However, the method of APF itself hardly simulates the unhindered vessel speed, which is so far derived from historical data or modeled separately.

4.5. Optimal control models

The optimal control models present the vessel behavior in two-dimensional continuous space. The models are designed to continuously describe the behavior, though discretized during implementation.

In different models, the objective function and the constraints are defined differently. The vessel behavior is decided by solving the optimization problem.

Wewerinke et al. (1989) first presented the maritime traffic modeling as a nonlinear control problem. The dynamic vessel behavior of speed and position is to minimize the cost function. The state of the system is defined as a function of speed, rate of turn, heading, position. For any encounter, DCPA and TCPA are calculated. Once the DCPA is less than a certain threshold, the vessels will change their behavior as a state change in the system control. The principle of behavior change is to minimize both DCPA and TCPA. All of the functions are provided as a theoretical study without further calibration or validation.

Another simulation model using optimal control is developed by Shu et al. (2015) to predict the vessel behavior in the port area. The vessel behavior in the model is described at the tactical level to generate vessel route choice and operational level to include the dynamics of the vessel sailing behavior. The impacts of bank and waterway bending on vessel behavior are considered in the route choice model. The optimal vessel course is based on the approach presented by Hoogendoorn et al. (2013), which is the solution to minimize the cost (utility) to the destination for a vessel located at a specific position at the moment of time. But the desired speed of vessels on specific cross-sections are generated from the historical data. But the impacts from other external factors and the interaction with other vessels are not included in the model. The model has been calibrated with Automatic Identification System (AIS) data.

The approach with optimal control provides the possibility to model the real-life sailing environment, by changing the objective function or the constraints. Based on the calibration for optimized parameters, the model can be expected to be applied to any other area.

4.6. System dynamics models

The last modeling paradigm is to describe the vessel movement in state-space representation, which is expected to most capture the details of vessel behavior in maritime traffic. The system dynamics models are designed to present the process of vessel behavior in a system as it is in reality.

Leguit (1999) determines the vessel behavior by a PID controller considering the forces on different modules of vessels (i.e. hull, rudder, and propeller). Other models define the vessel behavior state by differential equations in two-dimensional space (Beschnidt and Gilles, 2005; Lisowski, 2016) or in more degrees of freedom (Fang et al., 2018; Sariöz and Narli, 2003; Sarıöz et al., 2002).

Regarding the external environmental factors, Lisowski (2016) distinguishes the vessel behavior in different visibilities. The impacts of wind and/or current are investigated by including the corresponding forces on the vessel (Beschnidt and Gilles, 2005; Leguit, 1999; Sariöz and Narli, 2003; Sarıöz et al., 2002). Sariöz et al. (1999) and Sariöz and Narli (2003) consider the bank effects by hydrodynamic calculation along the length of the vessel. With respect to the vessel interaction during encounters, a defined distance of safety needs to be maintained by the vessels to avoid collision (Fang et al., 2018; Lisowski, 2016). Fang et al. (2018) further distinguish the responsibilities of the stand-on vessel and give-way vessel according to the encounter situation.

In the current system dynamics models, only the two models presented in more degrees of freedom are calibrated by full-scale maneuvering simulation result or maneuvering data for specific vessels (Fang et al., 2018; Sariöz and Narli, 2003; Sarıöz et al., 2002). It also indicates the limitation in applying such models for an area with a large number of different vessels due to a lack of data for model parameter calibration. The computation load is also expected to be the largest, compared to the aforementioned paradigms.

4.7. Discussion on model characteristics and paradigms

Regarding the dimension of models, most of them simulate the vessel motion in two-dimensional space, which describes the longitudinal and lateral position in the water area. Besides the CA models, only one model discretizes the waterway into segments. All other models simulate vessel movement in continuous space. Meanwhile, only two models are designed to be continuous in time to describe the vessel maneuvering, which are both system dynamics models. Other models update the vessel behavior at time steps or calculate the state-space model discretely. With respect to the calibration and validation processes, more models focus on the validation, while only five models are calibrated to obtain the optimum parameter sets. The model parameters are mostly determined by the users for specific water area or based on historical data.

The overall comparison of the six modeling paradigms based on the proposed assessment criteria is presented in Table 9. Rather than a summary of the existing models' characteristics, the comparison also considers the potential and limitation of the paradigms. It can happen that a modeling paradigm is capable of modeling the vessel behavior under specific external impact, but none of the existing models has implemented it due to the specific application purposes. The applicability of the model is not limited by modeling paradigms, i.e. any paradigm can be applied in open or confined water area. Thus, the model applicability is not compared for the paradigms. To further investigate the details of each model, the selected maritime models are individually assessed in section 5.

Table 9. Overall comparison of the characteristics of the six modeling paradigms.

Modeling paradigms (no. of models)		Vessel behavior representation					External impact modeling											
		Static inherent characteristics	Dynamic kinetic information				External conditions						Encounters with other vessels					Traffic rules
			P	S	C	H	V	W	T	C	A	B	DS	HO	CS	OT	MV	
Rule-based models (25)	CA models (6)	T, GT, DWT, L, B	!	!	!		!	√	√	√			√		!	!		!
	Generic rule-based models (9)	T, GT, DWT, L, B	!	!	!		!	√	√	√			√		!	!		!
	Specific rule-based models (10)	T, GT, DWT, L, B	!	!	!	√	!	√	√	√		√	√	!	!	!	√	!
Mathematical Models (10)	APF models (3)	T, GT, DWT, L, B	!	!	!	√	!	!	√	!	√	√	√	!	!	!	√	!
	Optimal control models (2)	T, GT, DWT, L, B	!	!	!	!	!	!	√	!	√	√	√	!	!	!	√	!
	System dynamics models (5)	S	!	!	!	!	!	!	√	!	!	√	√	!	!	!	√	!

The rating scales are explained in section 3, except for the use of blank cell. All blank cells here indicate the kinetic information or external factor cannot be included due to the limitation of this paradigm.

From Table 9, it can be found most of the maritime traffic models are rule-based, either with generic rules or specific ones. CA models and generic rule-based models can hardly distinguish the vessel heterogeneity and human behavior differences between vessels or represent the external impacts on vessel behavior. However, even with the simplification of the maneuvering processes and the interaction with surrounding environment, the models are well applicable for macroscopic analysis of traffic flow. The specific rule-based models can further describe the evasive maneuvering behavior based on the specific encounter situations. However, the behavior differences between vessels and the impacts of external environmental factors cannot be properly handled, unless the detailed maneuvering particulars for specific vessels can be provided.

The mathematical models (APF models, optimal control models, and system dynamics models) pose their potential in capturing the behavioral differences between vessels and the specific external impacts. The APF models and optimal control models describe the behavior variation between groups of vessels with similar inherent characteristics. The system dynamics models are even capable of simulating the individual vessel behavior in detail considering the whole sailing processes. However, the specific maneuverability of each individual vessel in an area is rarely known. The application purpose of a maritime traffic model is mostly for an area, without strict requirement on individual behavior accuracy. Thus, for the mathematical models, the trade-off between generic application and vessel behavior variation needs to be balanced, and the necessary data for model calibration should be available.

5. Discussion on vessel behavior modeling

In this section, the maritime traffic models described in section 4 will be individually assessed using the criteria introduced in section 3. The comparison results are displayed in Table 10. The performance and potential of models will be discussed from the four aspects, being the vessel behavior representation, the potential to modeling external environmental impacts, the modeling of impacts during encounters, and the model applicability.

Table 10. Assessment of maritime traffic models with respect to the capability of modeling vessel behavior.

No	Model	Vessel representation	Static inherent characteristics	Dynamic kinetic info.				External conditions						Encounter with other vessels					Traffic rules	Area of application	Movement base cases (for confined water area)	Stated application purpose
				P	S	C	H	V	W	T	C	A	B	DS	HO	CS	OT	MV				
1	Liu et al. (2010)	*a*	T, GT	√	×								-	√						CW_V	US	
2	Feng (2013)	*a*		√	!								-							CW_V	US, MM_1, MD_1	
3	van de Ruit et al. (2010)	*a*	T	√	√	√							-	√						CW_V	US, UB_2, UT_2	Flow analysis
4	Qu and Meng (2012)	*a*	T	!	!	!		√	√	√	√		-	√		√	√		!	OW, CW_V	US, MM, MC_2	Traffic volume
5	Blokus-Roszkowska and Smolarek (2014)	*a*	L	!	!	!							-	√		√				CW_V	US, MM, MD, MC_2	
6	Qi et al. (2017a, 2017b)	*a*	L	!	!	√			√	√	√		-	√			√			CW_V	US, MM_1	Flow analysis
7	Thiers and Janssens (1998)	*a*	T, GT	√	!	√				√			×	√		√	!		!	CW_G, CW_V	US, UB_1, UT_1, MB, MM, MD	Flow analysis
8	Merrick et al., (2003)	*a*	T	√	√	√		√					-	√						OW, CW_V	US, MM_1, MD_1	Density analysis
9	Almaz et al. (2006)	*a*	T, L	√	!	√		!			√		-				√		!	OW, CW_V	US, UB_1, MB	Flow analysis
10	Camci et al. (2009)	*a*	T, L	√	!	√		!			√		-						!	OW, CW_V	US, UB_1, MB	Flow analysis
11	Goerlandt and Kujala (2011)	*a*	T, L, B	√	×	√							-							OW, CW_V	US, UB_2, MB, MM, MD	Collision probability
12	Puszcz et al. (2011)	*a*	T, L	√	√	!		√					-							CW_V	US, UB, MB, MM, MD, MC_1	Flow analysis
13	Piccoli (2014)	*a*	T, DWT	√	!	√				√			-	√			√		!	CW_V	US, MB, MM, MD	Flow analysis
14	Hasegawa (1990); Hasegawa et al. (2001, 2000)	*a*	GT, L	!	!	!							-	√					√	OW, CW_V	US, UB_2, MB, MC	Risk assessment
15	Xu et al. (2015)	*a*	T, L, B	!	×	!							-	√			!		!	CW_V	US, MB_1	Flow analysis
16	Gucma et al. (2017)	*a*	L	√	√	√							-	√			√			CW_V	US, MB_1	Flow analysis
17	Rayo (2013)	*a*	S	√	√	√							×	√			√		!	CW_G, CW_V	US, MB_1	Flow analysis
18	Davis et al. (1982, 1980)	*a*		!	!	!	√						√	√	√	!	√	√	√	OW	-	
19	Colley et al. (1984)	*a*	T	!	!	!	√						-	√	!	!	!	√	√	OW	-	
20	Watanabe et al. (2008)	*a*	S	!	!	!	√						√	√	√	√	√		√	OW, CW_G	US, UB_1, UT_2, MB, MM, MD	
21	Li (2013)	*a*		!	!	√							-	√	!	!	!			CW_V	US, UB_1, MB, MM_1, MC_1	Collision analysis
22	Xu et al. (2013)	*a*	L	!	√	√							-							CW_V	US	
23	Miyake et al. (2015)	*a*	GT, L	!	!	!	√						-	√				√	√	OW, CW_V	US, UB_2, MB_1, MC	Collision avoidance
24	Huang et al. (2016, 2013)	*a*	T, L, B	!	×	√	√						-	√	√	√	√		√	OW, CW_V	US, UB_1, MB, MC_2	Flow analysis
25	Aarsæther (2011)	*a*		!	!	!	√						-	√	√	√	√		√	CW_V	US, UB_1, MB, MM, MD	
26	Xiao (2014)	*a*	T, GT, L	!	!	!	√		!		!		√	√	√		!		√	CW_G, CW_V	US, MB_1	
27	Rong et al. (2015)	*a*	T	!	!	!							-	√	√		!			CW_V	US, UB_1, MB	Flow analysis
28	Cheng et al. (2017)	*a*		!	!	!	√						√							CW_G, CW_V	US	
29	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	*a*		!	!	!	!						-	√	√	√	√		√	?		Conceptual model
30	Shu et al. (2018, 2015a, 2015b)	*a*	T, GT	!	!	!							√							CW_G, CW_V	US, UB_1, MB	
31	Leguit, (1999)	*m*	S	!	!	!			!				×							CW_G	US, UB_2, MB_1	Risk assessment
32	Lisowski (2016)	*a*		!	!	!	√	√					-	√	√	!	!			?		Sensitivity analysis
33	Beschnidt and Gilles (2005)	*a*		!	!	!	!		!		!		-							OW, CW_V	US, UB_1	
34	Sariöz et al. (1999); Sariöz and Narli (2003)	*m*	S	!	√	!			!		!		√							CW_G, CW_V	US, UB_1	
35	Fang et al. (2018)	*m*	S	!	!	!	!						-	√	!	!	!			OW	-	Collision avoidance

Abbreviations:
Vessel representation: *a*=agent, *m*=sub-modules based on vessel structure;
Static inherent characteristics: T=type, GT=gross tonnage, DWT=deadweight tonnage, L=length, B=breadth, S=specific vessels;
Dynamic kinetic information: P=position, S=speed over ground, C=course over ground, H=heading;
External conditions: V=visibility, W=wind, T=tide, C=current, A=Adverse weather, B=bank;
Encounter with other vessels: DS=distance of safety, HO=head-on, CS=crossing, OT=overtaking, MV=multi-vessel encounter;
Area of application: OW=open water area, CW_G=confined water area with geographical boundary (bank), CW_V=confined water area with virtual boundary (routeing scheme);
Movement base cases (for confined water area): seeFigure 6.

5.1. Vessel classification method

The assessment on static inherent characteristics shows that most models define some classification criteria to simulate the vessel behavior per class or analyze the statistical data to derive behavioral model parameters for each group of vessels. Among the vessel inherent characteristics, the vessel type is mostly chosen as the criterion or one of the criteria for vessel classification. Regarding the characteristics of geometric size, the length has been more adopted than the breadth. For all of the models using breadth, the length and type are also chosen as the criteria. This way, the horizontal shape of the vessel can be outlined, which best supports the modeling of positional relation between the vessel and the surrounding circumstances. With respect to the characteristics of tonnage, both gross tonnage and deadweight tonnage are adopted as part of the classification criteria to generally categorize the large and small vessels. The inclusion of different classes of vessels presents the diversity of vessels in the area, which has been proven by vessel behavior analysis (de Boer, 2010; Mascaro and Korb, 2010; Silveira et al., 2013; Zhou et al., 2019). Or a specifically developed model can be dependent on the data of vessel particulars based on application purposes.

5.2. Modeling of dynamic kinetic information

All models include position and speed to different extents. Most of the models present the vessel position in two-dimensional space. However, for the models developed for collective traffic flow analysis, the position is simplified into one-dimensional movement. For the vessel speed, besides the way of free speed choices, two other ways of simplification have been implemented in the presented models. One is to determine the vessel speed as a constant variable upon vessel generation based on the historical distribution. The other is to set several choices of fixed speed for maneuvering simulation or theoretical analysis. However, to fully indicate the behavior differences among vessels and the behavior changes under external impacts, the vessel should be able to maintain or change speed under any circumstances through the voyage. For the purpose of emission control, Fagerholt et al. (2015) propose the method of maritime routing and speed optimization. In the studies on waterborne automated guided vehicles, the vessel's path is modeled by a successive linearized prediction by model predictive control (Zheng et al., 2016). In maritime traffic models by optimal control, both methods can be considered by changing the corresponding objective functions to obtain the optimal speed and course, respectively.

Considering the course of the vessel, nearly all of the models include this kinetic information. A simplified way to include the course is that the routes are determined at the beginning, and all of the vessels follow such routes without course changes. In such models, the course is included as a constant. However, under the good seamanship in COLREGs, course change is prior to speed change during encounters considering the vessel maneuverability and the effects of collision avoidance. It has been realized by the other models adopting the principle that vessels normally follow the designed route and change course under external impacts from the encountering vessel or other factors.

As for the heading of the vessels, only a limited number of models consider the heading changes during vessel encounter or route changes. The other models include heading for DCPA and TCPA calculation, but the heading is deemed the same as course. In order to explicitly reflect the vessel behavior changes during encounter and external impacts, heading should be included in a model to indicate the detailed vessel movement.

5.3. Impacts of external environmental conditions

The impacts of external factors on vessel behavior have been proven (Shu et al., 2017), which cannot be ignored in maritime traffic models when considering the individual vessel behavior.

However, external conditions have seldom been considered in the models. Generally speaking, two ways have been adopted to indicate such impacts. The first one is to introduce random variables (Qi et al., 2017a; Qu and Meng, 2012) or generic rules (Almaz et al., 2006; Camci et al., 2009; Merrick et al., 2003). It shows the variation of vessel movement under external impacts. The other way is to consider the vessel maneuverability under specific wind and current conditions to model the corresponding behavior (Beschnidt and Gilles, 2005; Leguit, 1999; Sarıöz et al., 2002; Xiao, 2014). Instead of using specific weather conditions, Kepaptsoglou et al. (2015) introduces the method to consider the weather impacts on container vessel speed as a chance-constrained model, which provides another option. None of the models includes the impact of adverse weather conditions, which implies the models assume the adverse weather condition is excluded in the application. As for the impact of banks, most of the models have included it as a push force from the bank using different methods as introduced in section 4. The method of integrating such impacts on vessel behavior still needs to be investigated.

5.4. Impacts of vessel encounters/interaction between vessels

The impact from encountering vessels on the evasive behavior of the own vessel has been considered in most of the reviewed models. The main method is to define a distance of safety to trigger and calculate the evasive behavior. The distance can be the direct distance between vessels or the size of ship domain. Besides the distance, the relative sailing direction of the other vessels is considered, by calculating DCPA and TCPA, to further distinguish different encounter situations. Specifically, Colley et al. (1984) define behavior rules in the dangerous head-on situation (starboard-to-starboard). All of the models adopt the responsibility of conducts regulated by COLREGs. Regarding the multi-vessel encounters, only Miyake et al. (2015), Davis et al. (1982) and Colley et al. (1984) include the rules to decide the priority of collision avoidance. From the aspect of vessel encounter, the models by Davis et al. (1982) and Colley et al. (1984) can be deemed as the most comprehensive ones. However, the quantification of collision avoidance behavior still needs to be investigated (Fang et al., 2018). Currently, in the field of vessel collision avoidance, the algorithm of generalized velocity obstacle has been developed (Huang et al., 2019), and applied to detect collision candidate (Chen et al., 2018). Instead of the traditional method of calculating DCPA and TCPA, the emerging method can also be applied in maritime traffic models to simulate the vessel behavior during encounters. In a waterway network area with multiple waypoints, Chen et al. (2018) propose the distributed model predictive control for a cooperative multi-vessel situation. Similarly, the method can be adopted to model the vessels' interaction in maritime traffic models.

5.5. Model application area

Currently, most of the maritime traffic models are developed for specific application purposes. However, the capability of the model to simulate other situations (the so-called generalization of the model) is also assessed considering its potential according to the proposed assessment criteria of model applicability. Firstly, the definition of navigable water area in the model implies whether the model can describe the characteristics of other types of water area. Secondly, the corresponding sailing rules of the vessels in such an area indicate the capability of modeling the specific traffic flow. As listed below "area of application" in Table 10, 16 out of 35 models have been considered to be applicable in more areas than stated in the original paper.

From the perspective of the area of application, three types of water area have been identified in section 3.3. The first one with the largest space for vessel maneuvering is open water area. In this type of area, the vessels are sailing with auto-pilot most of the time to follow the designed route. Only during vessel encounters, the vessels should take actions by the bridge team to avoid collisions. All of the encounter types stated in COLREGs should be considered, which have been presented in the models by Davis et al. (1980) and Colley et al. (1984). When the weather or sea state is bad, the behavior is mostly determined by the vessel maneuverability, which is dependent on individual vessels. Therefore, models which are not developed for vessels in open waters can be applied in such a way, provided the behavior during vessel encounters is modeled.

For the confined waters either with routeing scheme or geographical boundaries, the traffic density is usually higher than in open water. The vessel behavior would be expected to be more detailed, including the position in two-dimensional space, speed choices with dynamic freedom, course with free choices, and heading with free choices. This way, the behavioral details between vessels and the external impacts can be presented. Compared to the models for water area with routeing scheme, the impacts of the bank should be considered in the models for physically confined water. However, such impacts are missing in the models designed for port or inland water area (Leguit, 1999; Rayo, 2013; Thiers and Janssens, 1998).

Considering the vessel movement base cases in confined water area (see Figure 6), all of the models are capable to model the vessel behavior in uni-directional straight flow. None of the models describe the turning behavior close to berth, since it is fully dependent on individual vessel maneuverability and maneuvering habit of the bridge team. Compared the applicability of models between modeling paradigms, the generic rule-based models can include more movement base cases. The models based on APF, optimal control or system dynamics require a more specific description of the boundary impacts and the interaction with other vessels in such situations. From this viewpoint, to capture more details of vessel behavior and to be applicable in more situations can be a trade-off according to the application purposes.

6. Conclusions and recommendations

This paper provides a review of the literature on maritime traffic models from the vessel behavior modeling perspective. The maritime traffic models include the models applicable both at sea and in confined water area. The scope of this review is the models representing the maritime traffic at the scale of vessels considering the individual vessel behavioral law. To provide a structured overview of the underlying paradigms, a categorization method is proposed to classify the models into six categories, including Cellular Automata, generic rule-based models, specific rule-based models, artificial potential field models, optimal control models, and system dynamics models. All presented models are assessed and compared based on a set of criteria, namely the vessel behavior representation, external impact modeling, and model applicability.

6.1. Current status of maritime traffic models

All maritime traffic models can describe the traffic state to different levels of details. As indicated by the articles, the models can fulfill the specific application purposes they are designed for. From Figure 7, it can be found that before 2010, a majority of the maritime traffic models are developed only to simulate the generic traffic state in one-dimensional space. The idea of mathematical models is seldom adopted and developed mostly at a level of conceptual model. Afterwards, with the mandatory use of AIS equipment onboard and the improvement of computer science, the models are developed with calibration and/or validation to capture more details of vessel behavior when modeling the maritime traffic. However, two types of limitations are also discovered in the current models.

Firstly, for models with a generic description of maritime traffic state, the behavior variation between vessels and the external impacts are simplified to a large extent. As presented in Table 10, none of the existing models describe all dynamic kinetic information in detail for different vessels and consider the impacts from the full range of external factors. One of the reasons is the current models are developed for a specific purpose. The details of vessel behavior or external impacts have been simplified according to the application area or purpose. For the impact of adverse weather condition, none of the models consider the behavior in such a situation, which implies the models assume that the adverse weather condition is excluded from their application. On the contrary, comparing the model paradigm categorization in Table 8 and the model assessment results in Table 10, the existing models capturing more details of vessel behavior and the external impacts can be applied in less sailing situations. Such models focusing on individual vessel behavior also require the specific vessel maneuvering data for calibration and validation, which also limits the model applicability.

Therefore, a model capable of simulating different vessel behavior in different situations is still missing. Such a model considers the commonality of vessels in classes based on the vessel characteristics. The behavior characteristics in different types of water area or under different external conditions are also analyzed for vessels in classes. For some specific application purposes, the vessel behavior can be simplified. Thus, the balance between generic application and vessel behavior variation can be handled.

6.2. Future research agenda

Based on the results of the review, the possible future research paths are outlined considering the use of different data sources in the era of big data. Future development of maritime traffic models regarding vessel behavior modeling can focus on several directions, which are the main gaps for the current models as mentioned above.

Firstly, the behavior of different vessels should be able to be modeled through the calibration of parameter sets in a generic model. So far, each maritime traffic model is only developed for a specific purpose. The behavior differences between vessels are either ignored or simplified as assumptions of different behavior based on vessel type or size. The general behavior commonality of vessels in classes based on vessel characteristics is still unknown. Thus, a generic model needs to classify the vessels in a systematic way to cover all vessels while identify the vessel behavior differences. When the generic model is applied in different areas or for different purposes, the local AIS data can be used to obtain the optimal parameter sets.

Secondly, the external impacts from external conditions, vessel encounter and traffic rules need to be integrated into the vessel behavior. Since the vessel behavior is highly influenced by the surrounding sailing environment, the external impacts should not be ignored or simply assumed as a given distribution without detailed study. This way, the meteorological and hydrodynamic data corresponding to the period of AIS data can be coupled to explain the behavior under specific circumstances. The emerging algorithms in the waterborne automated guided vehicles and collision avoidance can be adopted to model the vessel interaction during encounters. However, the method of including such external impacts on vessel behavior is needed, especially for the (geographically and virtually) confined water areas.

Finally, the maritime traffic in different water areas and different vessel movement base cases in confined water area should be considered. Based on a systematic description of the vessel behavior characteristics in different areas, a generic model identifies the vessel behavior under different circumstances. Meanwhile, for model users, the model can be specified based on the application purposes.

Such a generic model would meet both requirements of capturing different vessel behavioral details and being applicable for different purposes in different area. The source of AIS data also makes calibration and validation of the models possible.

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Appendix

The full list of descriptive background information for the selected models is provided in Table 11, which is in addition to the statistical information in Table 1.

Table 11. Overview of the descriptive background information of the selected models in this review.

No.	Model	Type of publication	Country and region	Stated application area	Collected data type	Data source
1	Davis et al. (1982, 1980)	J	GBR	OW	Questionnaire	Interview
2	Colley et al. (1984)	J	GBR	OW	Cine film of radar screen	National Maritime Institute
3	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	C	NLD	CW	-	-
4	Thiers and Janssens (1998)	J	BEL	CW	Traffic data	Local observation
5	Leguit (1999)	T	NLD	CW	Traffic data and ship manoeuvring data	Not mentioned
6	Hasegawa et al. (2001, 2000); Hasegawa (1990)	C	JPN	OW	GPS and AIS data	Not mentioned
7	Sariöz and Narli (2003); Sariöz et al. (1999)	J	TUR	CW	Ship maneuvering data	Not mentioned
8	Merrick et al., (2003)	J	USA	CW	Traffic data	San Francisco VTS
9	Beschnidt and Gilles (2005)	J	DEU	CW	Radar and AIS data	Not mentioned
10	Almaz et al. (2006)	J	TUR	CW	Traffic data	Not mentioned
11	Watanabe et al. (2008)	C	JPN, BEL	CW	-	-
12	Camci et al. (2009)	C	TUR	CW	Traffic data	Not mentioned
13	Liu et al. (2010)	C	CHN	CW	-	-
14	van de Ruit et al. (2010)	J	NLD	CW	-	-
15	Aarsæther (2011)	T	NOR	CW	AIS data	Norwegian Coastal Administration
16	Goerlandt and Kujala (2011)	J	FIN	OW	AIS data	Finnish Transport Agency
17	Puszcz et al. (2011)	C	POL	CW	AIS data	HELCOM
18	Qu and Meng (2012)	J	SGP	CW	AIS data	Lloyd MIU ship movement database
19	Feng (2013)	J	CHN	CW	-	-
20	Huang et al. (2016, 2013)	J, C	SGP	CW	Radar data	Not mentioned
21	Li (2013)	T	SGP	CW	-	-
22	Rayo (2013)	T	NLD	CW	-	-
23	Xu et al. (2013)	C	CHN	CW	AIS data	Self-installed receivers
24	Blokus-Roszkowska and Smolarek (2014)	C	POL	CW	-	-
25	Piccoli (2014)	T	NLD	CW	-	-
26	Xiao (2014)	T	NLD	CW	AIS data	MARIN(NLD) & MSA(CHN)
27	Miyake et al. (2015)	J	JPN	OW	AIS data	Not mentioned
28	Rong et al. (2015)	J	PRT	CW	AIS data	Not mentioned
29	Xu et al. (2015)	C	CHN	CW	AIS data	Self-installed receivers
30	Lisowski (2016)	J	POL	OW	-	-
31	Cheng et al. (2017)	C	CHN	CW	Radar data	Self-installed receivers
32	Gucma et al. (2017)	J	POL	CW	AIS data	VTS center in Szczecin Harbour
33	Qi et al. (2017a, 2017b)	J	CHN	CW	AIS data	Not mentioned
34	Shu et al. (2018, 2015a, 2015b)	J	NLD	CW	AIS data	MARIN
35	Fang et al. (2018)	J	TWN (CHN)	OW	Ship maneuvering data	Experiment and sea trial

Type of publication: J=journal article; C=conference proceedings; T=thesis;
Country and region: marked by the affiliation of all authors in abbreviations from country codes of ISO 3166;
Stated application area: OW=open water; CW=confined water;
Collected data type and data source: the models without historical or experimental data input are marked with a dash '-'.

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