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Review

Probabilistic risk analysis for ship-ship collision: State-of-the-art

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ABSTRACT

Maritime transportation system has made a significant contribution to the development of the world economy. However, with the growth of quantity, scale, and speed of ships, maritime accidents still pose incrementing risk to individuals and societies in terms of multiple aspects, especially collision accidents between ships. Great effort is needed to prevent the occurrence of such accidents and to improve navigational safety and traffic efficiency. In this paper, extensive literature on probabilistic risk analysis on ship-ship collision was collected and reviewed focusing on the stakeholders which may benefit from the research and the methodologies and criteria adopted for collision risk. The paper identifies stakeholders, the modelling aspects (frequency estimation, causation analysis, etc.) in which the stakeholders are interested in. A classification system is presented based on the technical characteristics of the methods, followed by detailed descriptions of representative approaches and discussion. Areas for improvement of such risk analysis approaches are highlighted, i.e. identifying collision candidates, assessing the collision probability of multiple ships encounters, assessing the human and organizational factors. Three findings are concluded from this literature review: (1) Research on collision risk analysis and evaluation of ship encounters from individual ship perspective have facilitated the research in macroscopic perspective, and in turn, results from macroscopic research can also facilitate individual risk analysis by providing regional risk characteristics; (2) Current approaches usually estimate geometric probability by analysing data at certain intervals, which could lead to over/underestimation of the results; and (3) For causation probability induced by human and organisational factors in collision accidents, lack of data and uncertainty is still a problem to obtain accurate and reliable estimations. The paper also includes a discussion with respect to the applicability of the methods and outlines further work for improvement. The results in this paper are presented in a systematic structure and are formulated in a conclusive manner. This work can potentially contribute to developing better risk models and therefore better maritime transportation systems.

1. Introduction

Maritime transportation has made a significant contribution to the world economy. Over 10 billion tons of cargo was transported by sea in 2017 (UNCTAD, 2017). However, with such development, maritime accidents have been posing an unneglectable risk to the individuals and the societies in terms of various aspects, e.g. human and economic loss, and environmental consequences, etc. Ship-ship collision, as a frequent occurred maritime traffic accident (16% of total maritime accident), is one of the major contributors (EMSA, 2017). To prevent the occurrence of such accidents and improve safety in waterways has always been a hot topic of research.

Various definitions of risk can be found in the literature. Kaplan (1997) proposed that risk is a triplet consisting of three critical elements: “Scenario”, “Likelihood”, and “Consequences”. In practices, the understanding of risk often varies when it comes to different stakeholders and implication of risk reduction measures. Goerlandt and Montewka (Goerlandt and Montewka, 2015b) have conducted a comprehensive review on the fundamental issue of risk analysis in the maritime transportation system, where definition, perspective, etc. about risk have been analysed. From the engineering perspective, such as the maritime transportation system, the risk is often considered a product of probability and potential consequence of hazardous event (Kristiansen, 2013). In this paper, we accept such definition while the focus is on the methods to obtain the probability of the occurrence of collision in certain regions, e.g. ports and waterways, etc., and methods

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for providing information for risk identification, quantification, and management for various corresponding stakeholders. Compared with the perspective which focuses on risk analysis for collision avoidance for individual ships, such perspective is defined as the macroscopic perspective of collision risk analysis.

Probability-based risk analysis of ship-ship collision has received growing attention from academia since it provides concise and quantitative results for risk assessment and mitigation in combination with estimation of consequence. The framework proposed by Fujii and Shiobara (1971) and Macduff (1974) has been widely applied, which is:

$$P_{Collision} = N_{Candidate} \times P_{Causation} \tag{1}$$

According to Eq. (1), the probability of ship-ship collision is decomposed into two elements: (1) Number of collision candidates, also known as "geometric collision probability" (Fujii and Shiobara, 1971) and, which describes the probability of ships in encounter that has potential of collision in the assessed region, or the frequency of collision candidate within specific period of time. Such encounter is also known as near miss (e.g. Zhang et al., 2016, etc.) in academia and practices; and (2) Causation probability, which describes the probability of collision due to failures from various aspects, e.g. human reliabilities, human and organisational factors, mechanical failure, etc. According to the literature (Chauvin et al., 2013; Martins and Maturana, 2010; Ren et al., 2008), human and organisational factors are one of the major contributors to the marine accident. These factors, e.g. decision error, violation of the regulation, fatigue, etc. and their causal relationships together contribute to the occurrence of collision. In this manner, both the maritime traffic information and accident causations are taken into consideration in addition to historical accident data and investigation reports.

Several scholars have done reviews on the maritime accident analysis concerning ship-ship collision, which can be classified into two major categories: (1) Review/Overview of research methods and (2) Review on fundamental concepts in maritime risk analysis research. Focusing on the methods introduced into the research, Li et al. (2012) offered a detailed review of maritime traffic risk analysis from the perspective of frequency and consequence estimation, respectively. Lim et al. (2018) provide a general overview on the development of models and algorithms in terms of their methodology, contribution, assumptions, etc., based on a survey of literature concerning maritime risk analysis. Goerlandt and Montewka (2015b) performed a literature review where the definition, perspectives of risk and corresponding applications are well elaborated. Besides, the reliability and validity issues of ship-ship collision risk analysis methods, such as the sensitivity of model results in regard of choice of model parameters are analysed and identified by Goerlandt and Kujala (2014).

In this paper, the focus is on reviewing the methods utilized to obtain the quantitative probability of collision accident from the macroscopic perspective, therefore, the fundamental concepts about risk are not discussed, either the methods for collision avoidance of individual ships. The existing literature reviews have provided a general overview of the risk analysis methods for collision as a handbook. However, these reviews rarely discuss the technical characteristics, e.g. criteria for collision candidate, etc. and their utilities for various stakeholders. Moreover, with the fast development of new technologies such as AIS, artificial intelligence, etc., more new methods and approaches have been proposed recently, which are not included and compared in previous reviews.

To better understand the methodological overview of this topic and their inter-methodological relationships, a comprehensive comparison between different probabilistic risk analysis of ship-ship collision is needed. In this paper, the literature concerning probabilistic risk analysis of ship-ship collision is collected and reviewed from both the area of application and technical methods. A classification structure based on the methodological approaches of risk quantification and criteria utilized in each research methods is established. The aim of this paper is to provide a broad and structured analysis of the current literature on risk analysis of ship-ship collision accident from a macroscopic perspective, to clarify the methodological development of risk analysis on ship-ship collision accident for different stakeholders, and to discuss the technical characteristics and the relationships in terms of methods of them with respects to various risk analysis scenarios. Ultimately, we hope with this paper, a good reference can be provided to the researchers to make further contributions to the industry.

The outline of this paper is as follows: Section 2 indicates how the literature review will be conducted and the research methodology is presented; Section 3 elaborates preference aspects of risk analysis research under different areas of application, as well as the classification of identified technical approaches. In Section 4, various risk analysis methods and models are illustrated and reviewed; In Section 5 a discussion among the models will be given. Concluding remarks will be presented in Section 6.

2. Methodology

To conduct the literature review, extensive literature is collected from the library of the Delft University of Technology through the internet. The scope of this research focuses on probabilistic risk analysis under Eq. (1), which concerns the estimation of collision candidate and causation probability, respectively.

Two steps of literature survey were performed. "maritime accident", "marine accident", "ship collision", "vessel collision", "risk analysis", "risk assessment", "accident analysis", "maritime traffic", "marine traffic", "ship traffic", and "vessel traffic" are chosen as keywords for topics in databases of "Web of Knowledge[1]" and "ScienceDirect[2]" as the first step to collect relevant researches. The literature searching was finished on Feb 1st, 2019. Based on the records extracted from the databases, all the title and abstracts are examined thoroughly to further filter out references which are not closely related to the topic. Fig. 1 indicates the survey procedure. After two rounds of literature surveys and snowballing from the reference within these works, 301 pieces of record are obtained, among which 275 full texts were retrieved including journal papers and conference proceedings. Based on the collected literature, a selection process was conducted according to the following criteria: (1) Does the literature related to probabilistic risk analysis of ship-ship collision accident? (2) Does it include the methods that can be utilized to facilitate research on either one of the components in Eq. (1) or both? (3) From the methodology perspective, is it representative to reflect the new methodology on PRA of ship-ship collision accident, or the application of collision risk analysis in different areas? 112 articles which contain approaches for research under Eq. (1), support the arguments or are representative of the topic are included in this manuscript.

Based on the collected materials, the literature review is conducted with respect to two dimensions: (1) **Stakeholder.** As is well acknowledged, the goal of risk analysis is to support the decision-making process. The maritime transportation system is a complex system where multiple stakeholders (ship, port, etc.) are highly involved. The interests of concern vary significantly among them. Focuses and technical approaches to collision risk analysis are therefore adapted to various needs. In this paper, individual ships and maritime safety administrations, or port authorities are included as representatives of the component and system level of the maritime traffic system, respectively. Therefore, the stakeholders and their corresponding interests of concern will be analysed. (2) **Methodology.** Multiple theories, approaches and models are introduced into the risk analysis on maritime accident

[1] http://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=GeneralSearch&SID=6CfGfBuQT8xP8ugjSBu&preferencesSaved=.

[2] https://www.sciencedirect.com/.

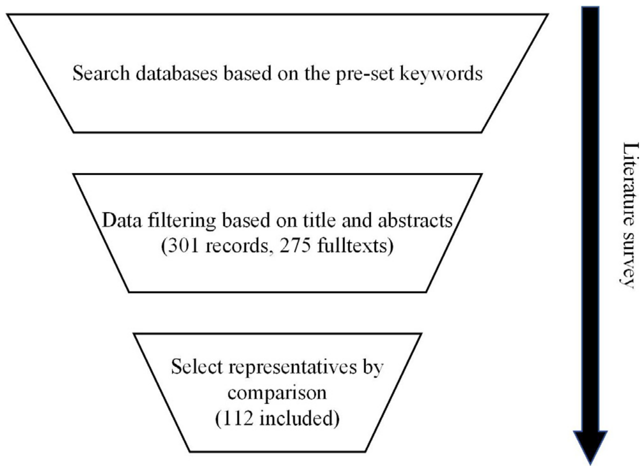

Fig. 1. Procedure of literature survey.

during the late 40 years. These studies are either highly case-dependent or generalized methods that can be implemented in similar situations. To obtain a well-structured overview of the technical development, approaches that are utilized in the literature will be classified into different groups based on their technical characteristics. Their inter-methodological traits, advantages, and disadvantages for application in different scenarios will be analysed and identified.

3. Overview of probabilistic risk analysis for ship-ship collision

3.1. Stakeholder

The maritime transportation system is a complex system where multiple stakeholders are making contributions to the safety and efficiency of the system. Among them, individual ships and maritime safety administrations can be considered as major participants representing the component and system level of the maritime traffic system. The interests of concerns of each part may vary from one to another, hence the methods and focus on collision risk may also be different. Therefore, it is reasonable to have an overview of what are the concerns of each counterpart reflected by the literature.

3.1.1. Maritime safety authority (MSA)

Maritime safety authority or maritime safety administration is the official administration responsible for the embodiment of maritime safety under their authority. Because of the role that maritime safety authority plays in the system, the risk of ship-ship collision is frequently considered from the macroscopic perspective. Risk analysis on ship-ship collision usually serves as a tool to understand the current risk level from the management perspective, and to evaluate the performance of the regional authorities (Mou et al., 2019).

In literature, the interests of concern for risk analysis for maritime safety authority are as follows:

(1) The frequency of accident occurrence and near misses

For maritime authority, the occurrence of maritime traffic accident will directly diminish the safety level within their authority, resulting in potential loss of life, economic loss, and environmental consequences. This, in turn, will reduce their performance impression to the public. Besides, the ship encounters that have potential for collision and undesired consequences, and yet did not lead to the actual collision are also of great interest to the MSA. Such encounter is often defined as near miss, or collision candidate, which have drawn much attention from academia and practices, e.g. van Westrenen and Ellerbroek, 2017; Zhang et al., 2016, etc. Together with other Key Performance Indicators (KPI), these indicators play an important role in maritime safety management (Valdez Banda et al., 2016). To maintain the maritime safety, many scholars have conducted frequency of accident analysis using historical data analysis, statistical regression, stochastic process analysis, etc. to facilitate authorities to identify areas of high risk both in the spatial and temporal dimension, which will provide strong references for the proposal of safety regulations.

(2) Potential consequence

In fact, a collision between ships can result in severe consequences, e.g. the collision accident between Iranian oil tanker "SANCHI" and bulk carrier "CF CRYSTAL" caused "*three crew of SANCHI died and 29 were missing, and resulting pollution occurred*" (Maritime Safety Administration of China, 2018). The environmental consequence is another focus of maritime safety authority which cannot be ignored, among which oil spill after collision and grounding is one of the hot topics in academia and practices, e.g. Yu et al. (2018) and Amir-Heidari and Raie (2018) conducted a probabilistic risk assessment of accidental oil spill in Bohai, Chain and the Persian Gulf, respectively. Goerlandt and Montewka (2014, 2015a) conducted utilized Bayesian Network approach to model risk of the oil spill from product ship and tanker due to collision accident, respectively. Together with research on the occurrence of ship-ship collision accident, research on consequence estimation and response can facilitate maritime authorities to obtain a comprehensive impression of current risk level, to have comprehensive estimation and management on the possible environmental consequence (Helle et al., 2015), and to have a good knowledge on the preparedness of emergency reaction.

(3) Human and organizational factor

As is well known that human and organisational factors are one of the major contributors to the marine accident (Chauvin et al., 2013; Macrae, 2009; Ren et al., 2008), e.g. Decision error, violation of regulations, etc. (Chauvin et al., 2013). Collision between ships also shares this trend. For maritime safety administration, one of their responsibility lies in the examination and certification of the ship crew. Which drew attention from maritime authority to human reliability and human and organizational factors in collision accident.

Table 1 illustrates the sources to have a general overview of the

Table 1
Methods for estimating collision probability from MSA perspective.

Interests of Concern	Sources
The frequency of accident occurrence	van Westrenen and Ellerbroek (2017), Zhang et al. (2017), Zhen et al. (2017) Chai et al. (2017), Cucinotta et al. (2017), Grabowski et al. (2000), Merrick et al. (2002), Silveira et al. (2013), van Dorp et al. (2001), Weng and Xue (2015), Wu et al. (2016), Zhang et al. (2016)
Potential consequences	Goerlandt and Montewka (2014), Goerlandt and Montewka (2015a), Grabowski et al. (2000), Gucma and Bak (2016), Merrick et al. (2002), Montewka et al. (2014), van Dorp et al. (2001)
Human reliability, Human and organizational factors	Sotiralis et al. (2016), Yıldırım et al. (2017), Zhang et al. (2013), Zhang et al. (2018b) Grabowski et al. (2000), Merrick et al. (2002), Uğurlu et al. (2013), van Dorp et al. (2001)

literature focus on interests of concern:

3.1.2. Individual ship

Individual ship plays as the cornerstone of the maritime transportation system. Keeping ship navigating in a safe and good situational awareness throughout the voyage are the paramount objectives for Officers on Watch (OOW). Risk analysis of collision between individual ships focuses on facilitating an individual ship to understand the potential collision and facilitate possible collision avoidance operations and control measures. Based on the literature collected, the interests of concern for individual ships concerning collision risk are as follows:

(1) Risk detection

Obtaining clear consciousness about the risk of collision is of great importance to individual ships. To do that, various methods have been proposed, which takes immediate or projected proximity level in the spatial-temporal domain, etc. as indicators.

(2) Conflict resolution

After the detection of collision risk, the main objective for an individual ship would be conflict resolution, which means the decision making and execution for collision avoidance behaviour. From the literature, we can find that most research on collision risk from an individual perspective has focus on this part, among which ship manoeuvrability and control, knowledge-based decision making, etc. have been introduced.

3.1.3. Ship designer

In recent years, the concept of risk-based ship design has been drawing attention from research in disciplines such as ship design, operation, and regulations (Breinholt et al., 2012). The idea of risk-based design is to integrate risk-based approach, e.g. quantitative risk assessment, etc. into the ship design process to propose an innovative design or improve the current design with respect to safety while considering the efficiency and performance (Papanikolaou, 2009). Based on the literature collected, the interest of concern for ship designers are as follows:

(1) Design

The design is of critical importance to the safety of the ship and the foundation of its whole life operation. For risk-based ship design, structural reliability, damage stability, component and system reliability, etc. are of great significance for the safety of navigation and crashworthiness. To do this, various approaches have been proposed, e.g. impact scenario analysis (Stahlberg et al., 2013), etc. For interested readers, detail reviews and methods can be found in the literature (Deeb et al., 2017; Liu et al., 2018; Pedersen, 2010)

(2) Operation

Risk-based ship operation focuses on improving the performance of OOWs to implement safe navigation and preventing the accident. To do this, ergonomics, innovative bridge and overall ship design, etc. are introduced to improve the performance of OOWs, hence the safety of the ship. e.g. Montewka et al. (2017) quantified the effects of noise, whole body vibration, and ship motion on OOWs' performance, which can be incorporated into risk-based ship design. Sotiralis et al. (2016) established a Bayesian network-based model for ship collision accident, where human operation and performance under different working situations are well integrated.

(3) Regulation

As proposed in (Papanikolaou, 2009), instead of prescriptive regulation after the occurrence of the accident, the tendency of goal-based standard and risk-based regulation have become clearer. The goal of such regulations is to provide a regulatory framework, e.g. risk evaluation criteria, etc. to facilitate the risk-based design. One of the representatives of such framework is Formal Safety Assessment (FSA) (IMO, 2018), which is proposed by IMO as guidelines to systematically assess new or existing regulations for maritime safety and environmental protection.

3.1.4. Other stakeholders

As aforementioned, the maritime traffic system is a complex system where multiple stakeholders participate in. Besides the three representative stakeholders mentioned in the previous sections, various more also contribute to the safety of maritime transport from different aspects, e.g. shipping companies, insurance companies, Search And Rescue (SAR) departments, etc. However, since this paper is to collect and review probabilistic risk analysis and management on the occurrence of ship-ship collision accident, details about these stakeholders will not be further discussed.

3.2. Methodology for probabilistic risk analysis of ship-ship collision

Research on risk analysis of ship-ship collision for different stakeholder usually concerns three elements: the probability of an accident, potential consequences, and human and organisational factors of ship collision. Probability is one of the most common indices to reflect the risk of ship-ship collision. Among the literature, the probability of ship-ship collision is estimated via two technical approaches: (1) statistical estimation approach and (2) synthetic estimation approach.

For statistical estimation, historical accident and traffic information within certain waterways are collected as data sources, and techniques such as statistical analysis, regression, artificial intelligence (neural network, support vector machine, etc.), etc. are introduced to estimate the probability of accident. For the synthetic approaches, the probability of collision is estimated according to the framework proposed by Fujii and Shiobara (1971) and Macduff (1974), which has won the popularity for a long period. In this way, both the maritime traffic information, e.g. dynamic information of ship movements and accident causation factors, e.g. human and organization factors, external factors are taken into considerations.

Combine the two major categories, we have identified methods that are frequently used in estimating the probability of ship-ship collision from the macroscopic perspective, to the best knowledge of us. Table 2 illustrates the results and a detailed description of the approaches will be given in Section 4.

To estimate probability by statistical analysis of historical data, techniques such as regression (Yip, 2008), synthetic aggregation (Christian and Kang, 2017), etc. were introduced.

For geometric probability, various methods have been proposed in the literature. From the perspective of criteria for collision candidate detection, this group of research can be classified into the following groups: (1) CPA-based approach; (2) indicator-based criteria; (3) safety boundary-based criteria, and (5) velocity-based criteria; the details of each criterion will be illustrated in Section 4.

Causation probability is another critical element for probabilistic risk analysis. It describes the probability that a ship will collide due to factors such as human errors, mechanical failure, external elements (rough sea, high wind, etc.), etc. As aforementioned, human factors are one of the major contributors to the occurrence of collision accident (Chauvin et al., 2013; Martins and Maturana, 2010; Ren et al., 2008). Research on the human reliability (Groth and Swiler, 2013) has provided effective and efficient tools to facilitate causation probability research from multiple aspects, e.g. human factors determination and classifications, causation relationships determinations, etc. To obtain the causation probability, the following techniques were introduced,

Table 2
Methods for estimating collision probability from the macroscopic perspective.

Method	Description	Sources
Statistical analysis	Perform statistical analysis on historical accident data, methods such as regression, artificial intelligence are introduced.	Grabowski et al. (2000), Kristiansen (2013), Kujala et al. (2009), Merrick et al. (2002), van Dorp et al. (2001)
Geometric collision probability analysis	Design a mathematical model to identify potential collision candidate base on traffic statistics	COWI (2008), Lušić and Čorić (2015), Pedersen (1995)
	Ship domain-based collision candidate identification	Chai et al. (2017), Szlapczynski and Szlapczynska (2016), Weng and Xue (2015)
	Indicator-based collision candidate identification (e.g. relative speed, bearing, etc.)	Qu et al. (2011), Zhang et al. (2017)
Causation collision probability analysis	Statistical analysis of historical accident data	Kujala et al. (2009), Mou et al. (2019)
	Fault Tree analysis to obtain the causation probability	Martins and Maturana (2010), Pedersen (1995)
	Bayesian Network to incorporate multiple sources of information, e.g. historical data, expert knowledge, etc.	Harrald et al. (1998), Martins and Maturana (2013), Montewka et al. (2014), Montewka et al. (2017), Trucco et al. (2008)
	Human reliability analysis and Human and organizational factors analysis	Harrald et al. (1998), Martins and Maturana (2013), Montewka et al. (2017), Sotiralis et al. (2016), Ung (2015), Valdez Banda et al. (2015), Xi et al. (2017)

which will be illustrated in Section 4 in detail: (1) statistical analysis of historical accident data, e.g. Kujala et al., 2009; (2) Fault Tree Analysis and Event Tree, e.g. Martins and Maturana, 2010; (3) Bayesian network, e.g. Goerlandt and Montewka, 2015a; Sotiralis et al., 2016.

4. State of the art methods

In Section 3, we have illustrated the major categories of research in literature according to the criteria to determine geometric probability and approach to obtain causation probability. For better understanding, this section will elaborate on the details of methods utilized in the categories aforementioned.

4.1. Geometric probability

Geometric probability, also known as the number of collision candidate, is the first step for probabilistic risk analysis on ship-ship collision using Eq. (1). It describes the number of ships encounters which have the potential for collision and undesired consequences. Such an encounter is also defined as near miss in many research and practices. In this section, the majorities of approaches for the geometric probability of ship-ship collision are collected and elaborated.

4.1.1. Synthetic indicator approach

For synthetic indicator approach, variables that can reflect spatial-temporal relationships between ships are often selected to construct criteria for the task. Closest Point of Approach (CPA) and its parameters: Distance to CPA (DCPA), which means the closest distance between two ships and Time to CPA (TCPA), which is the time left to the CPA point (see Fig. 2), are important parameters for OOW to

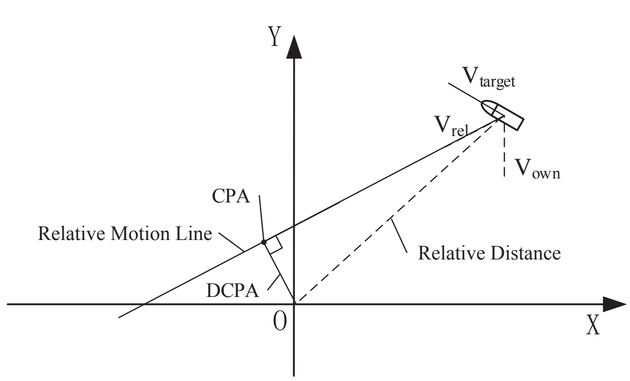

Fig. 2. CPA and its parameters.

determine whether the risk of collision exists and the urgent level of the situation. It indicates the linear projected spatial and temporal proximity between ships under the **assumption** that own ship and target ships maintain their kinematic status (speed, course, etc.) during the encounter situation.

For individual ships and maritime safety operators, if the measured value of CPA by facilities such as AIS, ARPA Radar etc. is smaller than a pre-set threshold, a warning will be given to the OOWs and possible collision avoidance suggestion could also be proposed. Such parameters are usually utilized in two manners: (1) criteria for collision candidate detection, which is the same as individual risk analysis and (2) synthetic proximity measurement with a combination of D/TCPA in the form of $f(\mathrm{TCPA}, \mathrm{DCPA}, \ldots,)$. A numeric value will be obtained according to the function, which will be utilized as an indicator of risk. Thanks to the simplicity, such method has won popularity in the practices of risk analysis and avoidance of ship collision, e.g. Wang et al., 2017, especially with help of Automatic Radar Plotting Aid (ARPA) (Bole et al., 2014).

Directly analysing indicators that can reflect their spatiotemporal relationship is another approach. Distance, absolute/relative speed, course, heading, etc. are usually utilized as indicators to measure proximity level between ships. Series of functions are established upon these indicators, e.g. inverse proportional function (Zhang et al., 2015b), etc. By incorporating these indicators as risk function, a numerical value can be obtained which reflects the risk level of the current situation. However, as this approach takes multiple factors into consideration, the meaning of the results is not as explicit as that from CPA-based approaches. When determining the risk of collision among ships, such results usually serve as comparable values to determine which encounter is more dangerous than others.

Many pieces of literature can be identified that utilized these approaches to detect collision candidate with various sources of information. Table 3 gives an overview of the literature identified, followed by the detailed introduction of each work:

As for the application of CPA in collision risk analysis, many examples can be found in literature: Bukhari et al. (2013) introduced fuzzy logic as an instrument to process DCPA and TCPA values to determine collision danger from the perspective of Vessel Traffic Service Operator (VTSO). Zhen et al. (2017) developed a real-time collision risk measurement model for maritime traffic surveillance. Encounters with high potential for collision can be identified by risk function which utilizes TCPA and DCPA as variables. Among these works, the collision candidate is determined based on the threshold of CPA parameter or its combination.

Following another approach, Mou et al. (2010) proposed a dynamic collision risk model for waterways on the basis of Safety Assessment

Table 3
Sources of literature for synthetic indicators.

Parameters utilized	Sources
T/DCPA	Bukhari et al. (2013), Debnath and Chin (2010, 2016), Debnath et al. (2011), Mou et al. (2010), Zhang et al. (2015a), Zhen et al. (2017)
Distance, absolute/relative speed, course, heading, etc.	Li et al. (2015), Zhang et al. (2016), Zhang et al. (2015b), Zhang et al. (2017)

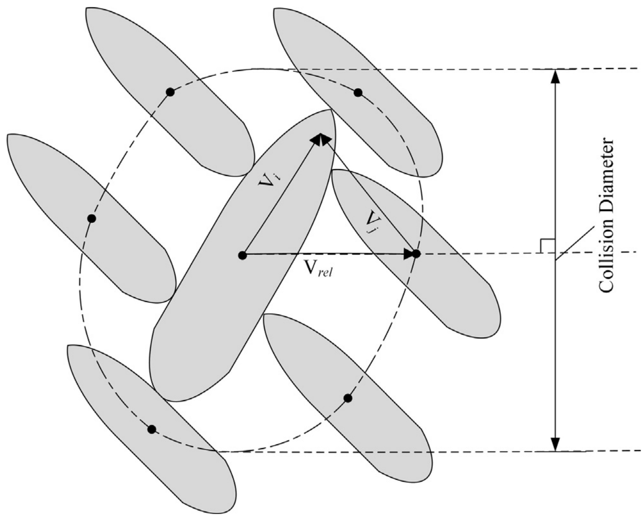

Fig. 3. Collision diameter (Fujii and Shiobara, 1971).

Model for Shipping and Offshore on the North Sea (SAMSON) model by incorporating exponential function of DCPA and TCPA of ships, where CPA values of encounters are introduced to incorporate with static probability of collision to assess encounters. Debnath and Chin (2010, 2016, 2011) developed Navigational Traffic Conflict Technique (NTCT) by estimating risk of in fairways where a truncated gamma distribution of maximum value of DCPA and TCPA between ships is estimated as one of the critical elements of the risk formula.

For research directly utilizing distance and other variables to assess encounter situation, works by Zhang et al. (2016, 2015b, 2017) are one of the representing researches. The distance between ships, relative speeds, course difference, etc. are incorporated as a function, which is defined as Vessel Conflict Risk Operator (VCRO). The distance between ships and domain contour are added afterwards as the improvement that considers ship domain. One of the functions utilized in these works is shown in Eq. (2):

$$VCRO \sim ((\mathrm{x} - \mathrm{l}_{\alpha})^{-1}, \mathrm{y}, \mathrm{g(z)}) \tag{2}$$

where x is the distance between two ships; l_α is the distance between target ship to the safe boundary of own ship; y is the relative speed, and z is the phase which indicates the relative angle between two ships.

Besides, Li et al. (2015) developed navigational traffic conflict technique to identify ships in a conflict encounter situation, where relative distance, bearing, relative speed, course, DCPA, and TCPA are considered indicators to construct the classification model. A Support Vector Machine (SVM) was trained to identify collision candidate with new data. Hilgert and Baldauf (1997) utilized CPA parameters and actual distance as indices to determine the risk of collision by comparison with limit values.

For individual ships, synthetic indicator approach is often utilized as a decision-support tool to analyse the encounter situation and support collision avoidance. Zhang et al. (2015a) developed a distributed collision avoidance supporting system with the integration of ship manoeuvrability model and COLREGs, taking CPA and its parameters as indices of collision risk. Goerlandt et al. (2015) integrated CPA parameters and expert knowledge to propose a framework of risk-informed collision alerting system. Ożoga and Montewka (2018) proposed a multiple encounter collision risk analysis and visualisation method for individual ships by integrating CPA parameters, ARPA system with multiple sources of information, to support collision avoidance in heavy traffic basins.

Among the literature, one can find strong similarities between collision risk analysis for individual ships and macroscopic research, e.g. risk analysis for ports and waterways. However, since the status of ships during the encounter is continuously changing, the assumption that their kinematic status remains unchanged could result in detection errors.

4.1.2. Safe boundary approach

Besides synthetic indicator approach to detect collision candidate and estimate the risk of such event, approaches that introduce spatial boundary to reflect spatial relationships between ships are also introduced, among which collision diameter and ship domain are two important concepts frequently introduced in research. In this section, the details and applications of the two concepts are discussed.

(1) Collision diameter

To estimate the number of ship-ship collision in Japanese waters, Fujii and Shiobara (1971) first proposed the concept of Collision Diameter (CD). According to the definition, CD is a safety boundary utilized to analyse collision candidate and risk of collision, which is shown in Fig. 3. It describes the minimum area around the ship to avoid collision. If the distance between ships is smaller than this criterion, collision is then likely to happen.

Fujii and Shiobara (1971) indicated that CD is proportional to the lengths of ships, however, the explicit mathematical method to obtain such parameter is not provided. This work is fulfilled by Pedersen (1995), as shown in Eq. (3):

$$D_{\mathrm{ij}} = \frac{(L_i V_j + L_j V_i)}{V_{ij}} \sin\theta + B_j \left\{1 - \left(\sin\theta \frac{V_i}{V_{ij}}\right)^2\right\}^{\frac{1}{2}} + B_i \left\{1 - \left(\sin\theta \frac{V_j}{V_{ij}}\right)^2\right\}^{\frac{1}{2}} \tag{3}$$

where

L_i, L_j – Length of ship i and j;
B_i, B_j – The width of ship i and j;
V_i, V_j – The speed of ship i and j;
V_{ij} – Relative speed;
θ – Course difference.

Based on this criterion, a series of methods have been developed. One major group is to establish stochastic process models to estimate geometric collision probability. The idea is to build probability function of collision candidate based on CD, by taking traffic flow information (average dimensions, speed, course for a certain category of ship, etc.) into consideration, to estimate the probability of two ships which violate such threshold. The most representative model for this approach is Pedersen model (Pedersen, 1995), which is shown in Fig. 4.

Suppose two waterways intersect as Fig. 4 indicates, the traffic flows within them follow certain normal distributions. The geometric collision probability within the risk area can be obtained according to Eq.

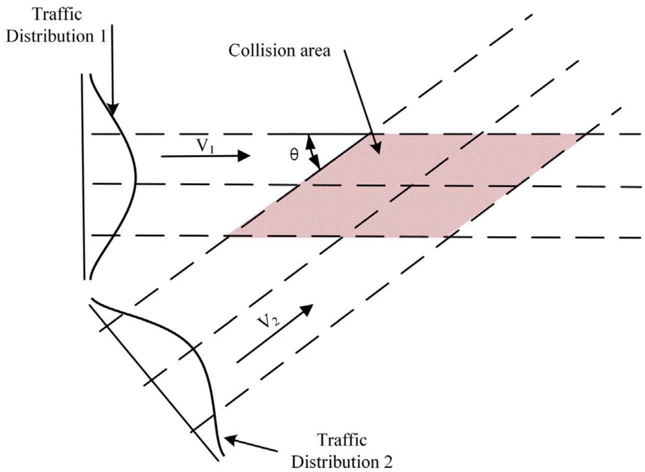

Fig. 4. Illustration of Pedersen's model (Pedersen, 1995).

(4):

$$N_a = \sum_i \sum_j \iint_{\Omega(z_i z_j)} \frac{Q_{1i} Q_{2j}}{V_i^1 V_j^2} f_i^{(1)}(z_i) f_j^{(2)}(z_j) V_{ij} D_{ij}\, dA \Delta t \tag{4}$$

where

Q_{1i} Q_{2j} are traffic volume of ship category i and j in waterway 1 and 2, respectively;
V is the average speed of each category of ship;
$f_i^{(1)}(z_i)$ is the traffic distribution of each category of ship;
V_{ij} is relative speed;
D_{ij} is collision diameter.

Similar works can also be found in COWI (2008), etc. Utilizing this criterion, various application have been conducted: Kujala et al. (2009) conducted research on maritime traffic safety in the Gulf of Finland, within which Pedersen model was introduced to obtain geometric collision probability. Silveira et al. (2014, 2013) analysed traffic patterns in the coast of Portugal using AIS data, on the basis of which probability of collision within these waterways is obtained in the same manner. A similar approach was also adopted by Christian and Kang (2017) to estimate the probability of collision of the ship which transports spent nuclear fuel and Cucinotta et al. (2017) to obtain the frequency of ship-ship collision in Messina Strait. Dong and Frangopol (2015) utilized a similar method to estimate the probability of ship-ship collision as part of collision risk analysis considering multiple risk attitudes.

Compared with synthetic indicator approach to obtain the geometric collision probability, researches utilizing collision diameter focus more on the current status of traffic flow rather than analysing the linear projected status between ships. By doing this, the potential error of detection due to the linear assumption could be avoided. Another advantage of such an approach is the conciseness and simplicity of application, where most of the work focuses on establishing the stochastic process models. One can find this approach has already been implemented into risk analysis software such as Grounding And Collision Analysis Toolbox GRACAT (Friis-Hansen and Simonsen, 2002) and International Association of Lighthouse Authorities Waterways Risk Assessment Program (IWRAP) (IALA, 2009), etc. However, as collision diameter is established upon the assumption that two ships have almost physical contact, some scholars also argue that it could lead to potential underestimation of the results (Montewka et al., 2010).

(2) Ship domain

Ship domain, which was proposed by Fujii and Tanaka (1971) is another important concept utilized in risk analysis of ship-ship collision accident. According to the definition, the ship domain indicates a space around the ship that would like to be kept clear from others. The intrusion or overlap of such area between ships can indicate the potential for collision. The graphical illustration of ship domain is shown in Fig. 5. For details about ship domain, interested readers can refer to the literature review by Szlapczynski and Szlapczynska (2017b) for more information.

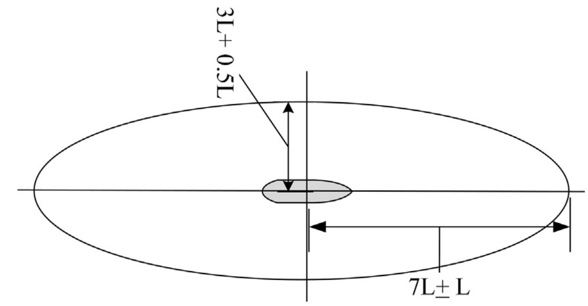

Fig. 5. Illustration of ship domain according to (Fujii and Tanaka, 1971).

The principle for collision risk analysis using ship domain is that if the domain was violated by other ships or overlapped by other domains, collision accident is then likely to happen due to potential misconduct of ship behaviour or influence of external factors (wind, current, etc.), etc. It provides another angle to measure spatial proximity between ships. However, it also focuses on the current spatio-temporal relationships between ships.

Under such logic, various approaches have been proposed in literature from individual ships and macroscopic perspective, respectively, among which model-based data analysis and computer simulation are two major technical approaches. For model-based data analysis, ship domain is utilized as the criteria for collision candidate detection where historical traffic data, such as AIS data, etc. are introduced to obtain the probability or frequency of domain violation/overlap. Such logic is also implemented in a computer simulation, while the difference is that historical traffic data are analysed to obtain traffic characteristics as simulation input rather than being directly utilized as data sources. Literature which applied ship domain as criteria is illustrated in Table 4, followed by detail descriptions:

Wang (2010) and Wang et al. (2009) provided a concise mathematical expression to describe different shapes of ship domain which is named as quaternion ship domain and it can be adapted in various application scenarios and various navigational rules, e.g. COLREGs. Their quaternion ship domain facilitates the utility of ship domain in many aspects, especially in collision risk assessment. For instance, Qu et al. (2011) conducted a risk assessment for collision accident in Singapore strait where overlapping of fuzzy quaternion ship domain (FQSD) is implemented as one of the indicators to reflect risk level. Different from Wang's work, Montewka et al. (2012, 2010) proposed a new form of ship domain by considering ship manoeuvrability and applied such model into collision probability estimation. Baldauf et al. (2015) proposed manoeuvring areas, which is an area around the ship, and was originated from research in aviation, into risk analysis and collision avoidance research by considering ship manoeuvrability.

As for the application of ship domain in collision candidate detection, Weng and Xue (2015) estimated collision frequency in Singapore fairways using the violation of circularly shaped ship domain as criteria, which was further developed and introduced in Chai et al.'s research (Chai et al., 2017). Besides this, Goerlandt and Kujala (2011) and Goerlandt et al. (2012) established maritime traffic simulation models to estimate the probability of collision where ship domain is utilized as the criterion for dangerous encounters. Instead of utilizing intrusion of ship domain as criteria of dangerous encounter, Szlapczynski and Szlapczynska (2016) proposed a new model to analyse

Table 4
Sources of literature for ship domain approaches.

Technical approach	Sources
Model-based data analysis	Chai et al. (2017), Montewka et al. (2012), Montewka et al. (2010), Qu et al. (2011), Wang (2010), Weng and Xue (2015)
Computer simulation	Goerlandt and Kujala (2011), Goerlandt et al. (2012), Rong et al. (2015)

the risk of collision by introducing two indices: the degree to domain violation (DDV) and time to domain violation (TDV) to replace DCPA and TCPA by using ship domain.

Compared with collision diameter, ship domain also assesses the potential of collision via violation/overlapping based on the analysing maritime traffic information, e.g. AIS data or by computer simulation, etc. However, in practices, there are several issues that have influences on the models' reliability: (1) Choice of ship domain. As indicated, various forms and shapes of ship domain are proposed in the literature, taking different factors, e.g. ship manoeuvrability, local traffic characteristics, etc. into account. And (2) potential over/underestimation. For geometric probability estimation based on ship domain, many works are conducted by analysing data with a certain time interval. Such approaches could lead to a situation where the dangerous encounter between the interval is not detected.

4.1.3. Velocity-based approach

For traditional research, geometric collision probability is determined and measured utilizing spatiotemporal relationships between ships. However, the aforementioned methods consider spatiotemporal relationships separately by introducing various elements, e.g. TCPA, DCPA, TDV, DDV, etc. Under such situation, conflicting indications may arise, e.g. for certain encounter situation, the DCPA can be very small while TCPA could be very large.

The velocity-based approach provides another perspective for collision risk analysis. The idea was addressed in the work by Degré and Lefèvre (1981), as shown in Fig. 6, where the distance, velocities between ship A and B are presented in velocity space of ship A (own ship) and the shadow area are the possible velocities for ship A that the collision is likely to happen if it takes them. Lenart (1983, 2015) formulated this idea as Collision Threat Parameter Area (CTPA) by assuming the ships keep their speed and headings constant during navigation. A CTPA is illustrated in Fig. 7. Later on, many researchers follow this idea and expand it in maritime practice.

This idea is also well-studied in the robotics domain, where this method is called the velocity obstacle (VO) algorithm. Researchers loosened the linear motion assumption from linear to nonlinear and from deterministic to probabilistic. These developments are also noticed by maritime researchers. Huang and van Gelder (2017) and Huang et al. (2018) proved that CTPA is identical to linear VO and they are another form of T/DCPA in velocity space. Additionally, the author also demonstrates the non-linear VO, Probabilistic VO, and Generalized VO algorithms in the maritime environment. The non-linear Velocity obstacle is shown in Fig. 8. For interested readers about the application of velocity obstacle algorithm and its improvements in collision avoidance research, please refer to Huang et al. (2019), Huang and van Gelder (2017) and Huang et al. (2018).

For the velocity-based approach in collision probability research, few works have been conducted since it is a relatively new idea in the maritime domain. Many focused on identifying collision risk from the individual perspective, e.g. Huang and Gelder (2019) utilized VO set to measure the collision risk which is formulated as the proportion of reachable velocity leading to collision; Zhao et al. (2016) developed a collision avoidance algorithm for the unmanned surface vehicle where VO was utilized as a criterion of collision risk. Szlapczynski and Krata (2018) and Szlapczynski and Szlapczynska (2017a) conducted series of research to further develop CTPA with the combination of ship domain as the replacement of minimum safe boundary in the algorithm.

Several scholars have conducted work on macroscopic risk analysis with the velocity-based approach: Van Westrenen and Ellerbroek (2017) analysed near miss on the North Sea where the variation of CTPA is utilized as the criterion of near miss (collision candidate). Based on the non-linear VO, the authors (Chen et al., 2018) also developed a collision candidate detection method as an approach for probabilistic risk analysis and compare the method with 8 collision candidate detection methods which utilize ship domain and CPA as the

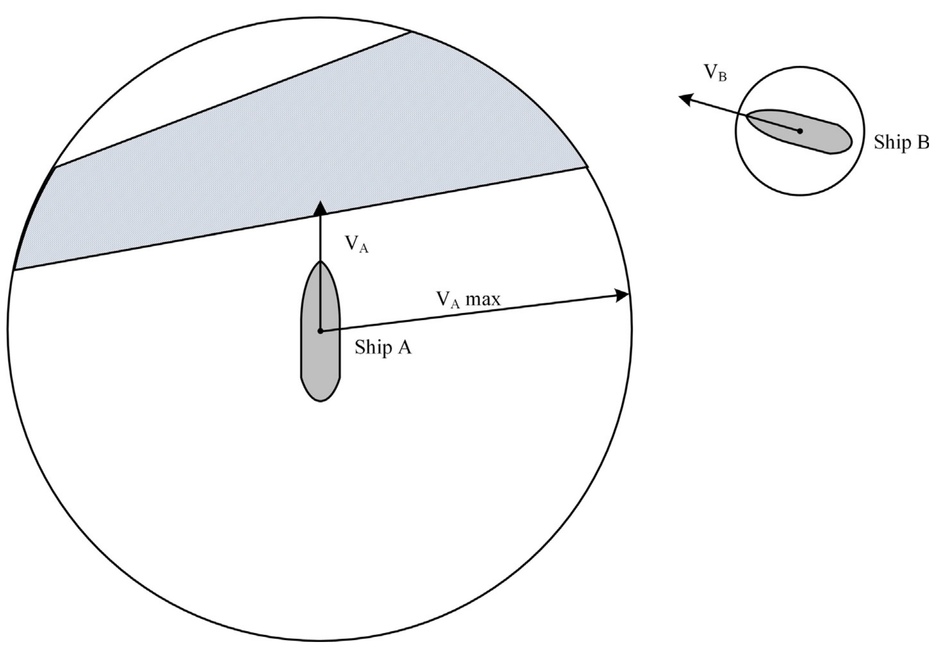

Fig. 6. Illustration of room to maneuver.

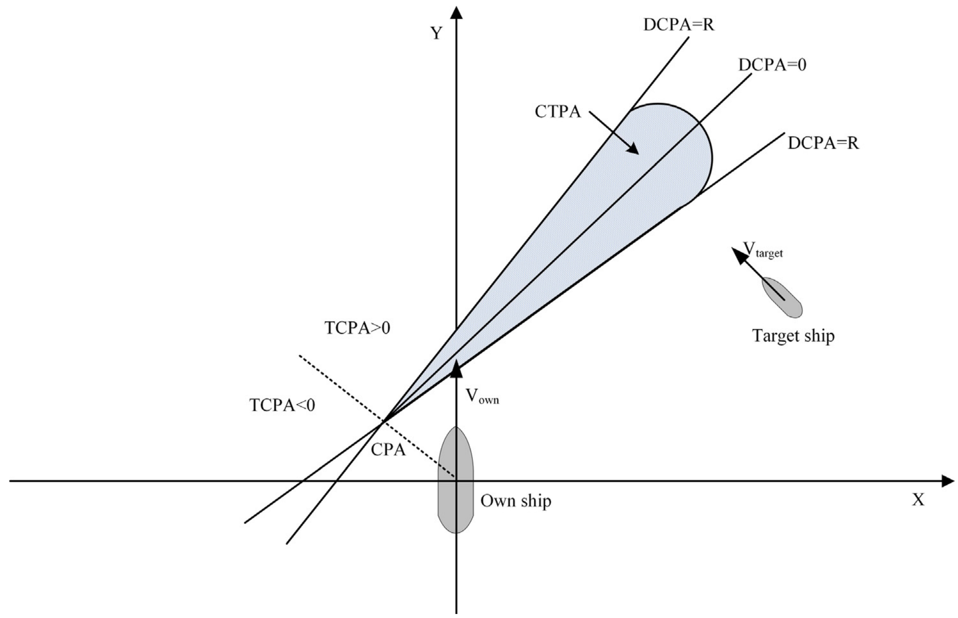

Fig. 7. Illustration of CTPA.

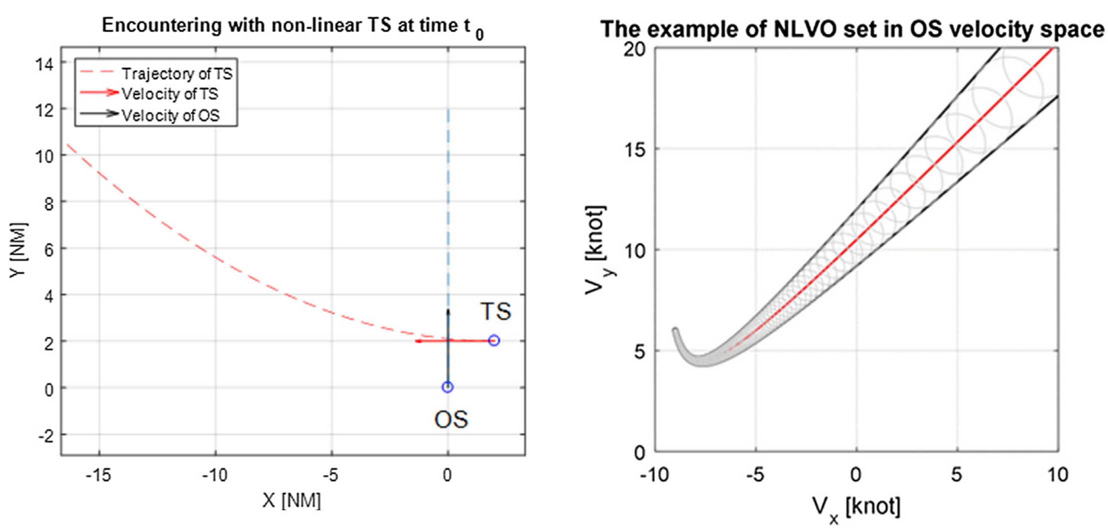

Fig. 8. Non-linear velocity obstacle (Huang and van Gelder, 2017).

criteria. The results indicate with non-linear VO, the reliability of collision candidate detection is improved to some extent.

Compared with synthetic indicator and safety boundary approaches, one of the major advantages of Velocity-based approach is that it considers spatiotemporal proximity between ships in velocity space, a space that can consider these two dimensions at the same time. It also provides the opportunity to consider the whole procedure of encounter as the basis to detect collision candidate instead of analysing time-sliced data. In this manner, the potential error of the results can be reduced, which in turn, could improve the reliability of results in terms of parameter choices of the models.

4.2. Causation probability

As a variable that describes the possibility that ships in encounter situation result in actual collision accident due to factors such as mechanical failures, human factors, etc., the causation probability is an indispensable element for probabilistic risk analysis of ship-ship collision under Eq. (1). In this section, the major approaches for obtaining such probability are collected and elaborated.

4.2.1. Statistical analysis approach

Analysis based on the historical accident data is one of the fundamental methods to obtain insights into the influence of human and other factors on the probability of ship-ship collision. Information such as accident investigation reports, accident databases, e.g. Marine Casualties and Incidents information from Global Integrated Shipping Information System (GISIS) established by International Maritime Organisation (IMO) are often referred as the data source. To conduct such analysis, statistical analysis methods such as regression, frequency analysis, etc. are introduced. Fujii and Shiobara (1971) utilized historical accident data in Japanese waters to estimate the causation probability. Similar work has also been done by Pedersen (1995) and Hänninen and Kujala (2009), respectively.

With its simplicity and straightforwardness, such analysis has been widely applied in local risk assessment, the results of which have also been applied in many succeeding works, e.g. Friis-Hansen and Simonsen, 2002; Kujala et al., 2009; Montewka et al., 2014, etc. However, as the ship-ship collision is a category of the accident with the rare occurrence, the amount of accident investigation reports may not be sufficient to conduct the analysis, meanwhile, the quality of the data

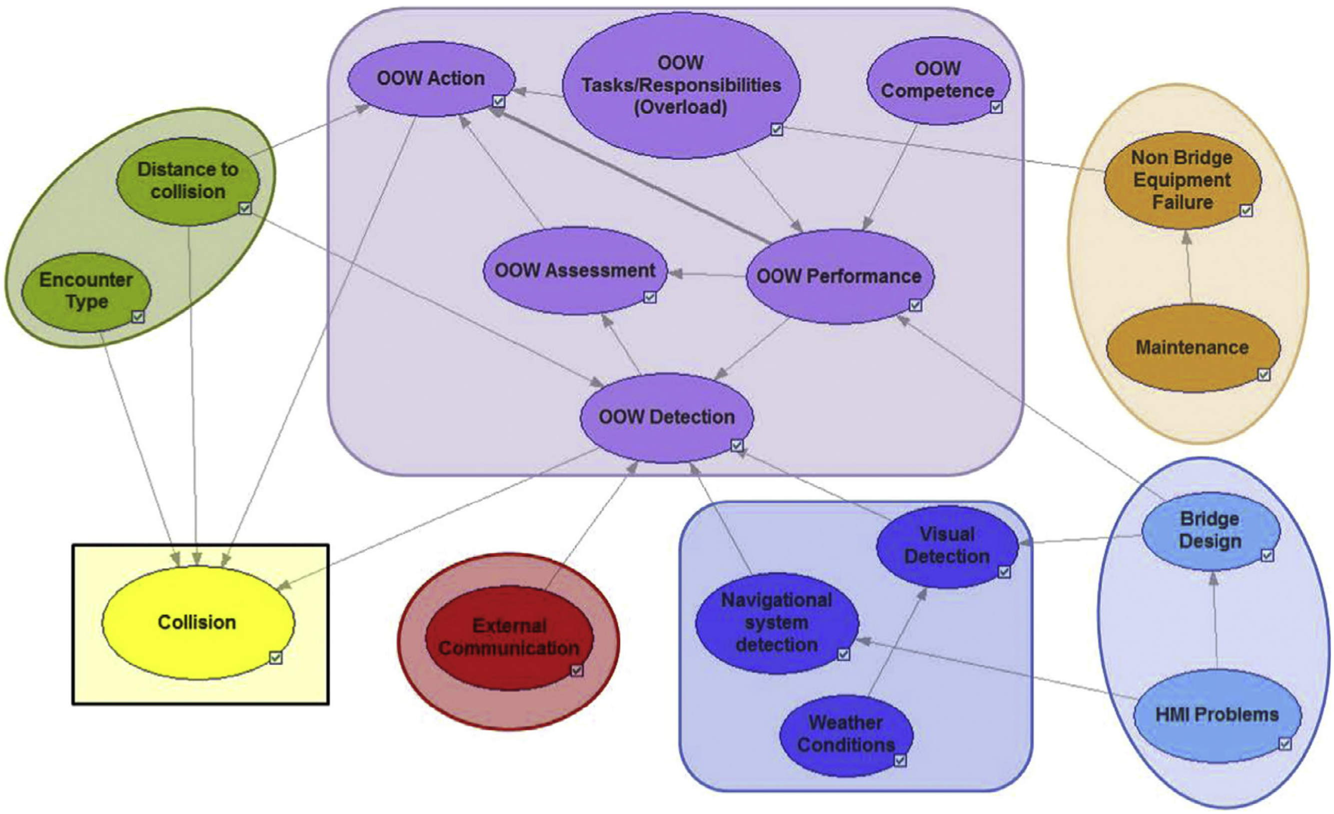

Fig. 9. Generic Bayesian Network of collision risk modelling (Sotiralis et al., 2016).

(e.g. incomplete information) also diminishes the efficacy of the results. Therefore, new methods that could integrate extra information, e.g. expert knowledge are introduced.

4.2.2. Fault tree approach

As aforementioned, a large proportion of collision accidents are caused by human and organisational factors and their inter-relationships (Ren et al., 2008). To obtain the probability of collision caused by these factors, analytical methods are necessary to be implemented. Fault Tree Analysis (FTA), which is developed to perform deductive analysis of system failure based on Boolean logic, is one of the classic approaches for this task.

FTA is generally conducted based on causation analysis of either accident investigation reports, or knowledge from experts in the field, based on the relevant literature. Accident contributing factors, e.g. negligence of watch keeping, fatigue, engine failure, etc. are identified as "Event" in the model, together with their causation relationships. Research on Human reliability analysis have facilitated such process from various aspects, e.g. determine, classify the contributing factors, and their causal relationships, etc. (e.g. Harrald et al., 1998; Martins and Maturana, 2013; Xi et al., 2017). These "Events" are grouped into various parts based on the causation relationships identified in the form of Boolean gates, e.g. "AND", "OR", etc. and finally synthesized into the tree-shaped structure to graphically illustrates the effects of components to the top event (ship-ship collision). The occurrence probability of each component was obtained based on statistically analysis, interview, questionnaire, etc. and the probability of ship-ship collision accident (top event) can be calculated using Boolean algebra.

In practices, FTA is usually utilized to obtain the causation probability of ship-ship collision and analyse the corresponding causes. Such an approach is also advised by the International Maritime Organisation (IMO) as one of the suggested approaches to perform Formal Safety Assessment (FSA) for the maritime accident (IMO, 2018). When Pedersen (1995) proposed the mathematical model for collision candidate estimation, causation probability in his model was also calculated by a concise FTA. Following the guideline of FSA, Martins and Maturana (2010) analysed the contribution of human errors to ship-ship collision accident and built a comprehensive Fault Tree to estimate causation collision probability. Similar research was also conducted by Uğurlu et al. (2013) where the probability of collision accident was estimated considering multiple factors.

Compared with the statistical analysis approach to obtain the causation probability of ship collision, FTA integrates causal analysis, which identifies the accident causations and their inter-relationships, and historical accident data. During the procedure, knowledge from field experts can be introduced to determine the structure of the factors. According to the literature, FTA has obtained popularity in causation probability analysis since its concise structure and simplicity to implement, however, due to the nature of the binary state of variables in the model, it could be difficult to define some factors which contain multiple possible states.

4.2.3. Bayesian approach

Although FTA has been introduced into risk analysis of ship-ship collision accident, some characteristics of itself have constrained its applicability in this field. One of them is its exponentially growing structure, which was already identified by Li et al. (2012). The structure of Fault tree will become complicated to a large extent when multiple factors are considered. Another characteristic is that due to the nature of FTA is based on Boolean logic, the state of each component is binary, which is not suitable for factors with multiple states. To improve such deficiencies in FTA and further develop methods for collision risk analysis which can model multi-state and non-linear causation relationships between accident contributing factors, the Bayesian approach has been introduced into research and drew much attention from the academia.

Bayesian network is a graphical inference network based on Bayesian theorem. Three elements composed Bayesian network:

directed acyclic arc, which demonstrates causation relationships between accident contributing factors; node, which indicates accident contributing factors, and Conditional Probability Table (CPT), which contains conditional probabilities of each state of the variables. For the details of the Bayesian network, interested readers may refer to Langseth and Portinale (2007). Compared with FTA, the Bayesian network allows factors to have multiple states and the probabilities of each state under different conditions are given by Conditional Probability Table (CPT) of each node. The joint probability of the network can be obtained according to Eq. (5):

$$P(X_1 = x_1, X_2 = x_2, \cdots, X_n = x_n) = \prod_{t=1}^{n} P(X_1 = x_1 \mid X_{pa(t)}) \tag{5}$$

where X_n are the contributing factors considered in the network and $x_n$is the corresponding given state. A simple example of the Bayesian network model is illustrated in Fig. 9.

When applying this method to estimate the causation probability of ship-ship collision accident, several elements need to be clarified. Langseth and Portinale (2007) have pointed out that: "*Decide what to model; Defining variables; Build the qualitative part; Build the quantitative part; Verification*" are the phases necessary to build the Bayesian network model, which have been applied by Montewka et al. (2014) as a framework for risk analysis of collision accident of RoPax vessel. Also, the process of obtaining the accident contributing factors and their causal relationships are benefited from research on HRA. Many HRA methods, e.g. CREAM, HFACS, etc. are incorporated with Bayesian network to analyse, determine the human and organisational factors and their causal relationships in a comprehensive and structured manner, e.g. Martins and Maturana (2013) incorporated HRA analysis and Bayesian network to analyse the probability of ship-ship collision accident. Graziano et al. (2016) proposed a classification system for human errors in ship grounding and accident using Technique for the Retrospective and Predictive Analysis of Cognitive Errors (TRACEr), which can facilitate the establishment of the Bayesian network for causation probability modelling.

With its openness and flexibility in incorporating multiple sources of information, e.g. Expert knowledge, stochastic simulation results, historical data, etc. The Bayesian network has become a popular model under this method. Trucco et al. (2008)) establish a probabilistic model to analyse the risk of human and organisational factors in the ship-ship collision, where the Bayesian network is utilized as to obtain their probabilistic correlations and probability of the accident. Similar researches have also been done by Martins and Maturana (2013), and Sotiralis et al. (2016). Montewka et al. (2014) established a framework for risk analysis of collision involving Ropax ship with the Bayesian network, where multiple sources of information, including simulation results, expert knowledge, etc. are included to obtain the probability of collision with certain consequence. Apart from obtaining the probability of collision accident, the Bayesian network can also be utilized to determine the influence of contributing factors to the accident because of its characteristic of two-way inference. Sensitivity analysis of the method to achieve that. Hanninen and Kujala (2012) conducted research on identifying the influence of the contributing factors to collision accident and proposed three methods to implement.

Apart from the advantages of utilizing the Bayesian network to model causation probability and analysing their inter-relationships, when in the practices, there are several issues concerning Bayesian network. Hanninen (2014) and Zhang and Thai (2016) have conducted a review on this method in regards to its benefits, challenges, and procedures of expert knowledge elicitation, where scarceness of accident data, the complicated dependency and causation relationship between contributing factors and uncertainty among the models are considered complicate for model construction. To alleviate the influence of incomplete data when building the Bayesian network, Zhang et al. (2018a) introduced Credal Network, which is an extension of Bayesian network by Antonucci et al. (2010) and Antonucci and Zaffalon (2008) to conduct probabilistic inference of Bayesian network with uncertainty. In this manner, the probability of collision will be obtained in the form of interval instead of point estimates. Besides, expert knowledge is still an indispensable source of information when identifying the factors and their probability. How to elicit the knowledge from expert properly and diminish bias will be one of the critical problems.

5. Discussion

5.1. Relations of collision risk analysis methods for individual ships and macroscopic risk analysis

Analysing and estimating collision candidate is one of the critical elements for probabilistic collision risk analysis. The number of collision candidate, its spatiotemporal characteristics, etc. can provide constructive insights to stakeholders such as maritime safety authorities to understand the current risk situation and facilitate them to propose corresponding risk mitigation measures.

The critical element for geometric collision probability is how to define and identify collision candidate or near miss, i.e. to adopt what criteria to determine which encounter is dangerous. To do this, variables such as DCPA and TCPA, Collision Diameter, MDTC, Ship Domain, Velocity Obstacle, etc. are introduced as the basis to construct various approaches of candidate detection by measuring proximity between ships in spatiotemporal domain. The knowledge and experience from individual collision risk analysis have facilitated the development of the topic in a macroscopic perspective to a large extent. Such finding is based on three facts: (1) The strong similarities between these criteria and collision risk detection method for individual ships; (2) Determination of collision candidate is usually conducted between two ships, where multiple-ship encounters will be decomposed into multiple two-ship encounter scenarios; and (3) The results of collision candidate detection are usually the summation of the identified dangerous ship pairs. In the meantime, the results of macroscopic risk analysis can also facilitate risk analysis and prevention for the individual ship. The risk mitigation measures based on spatiotemporal characteristics of collision candidate in certain waterways could act as background knowledge for OOWs onboard. Besides, as Mou et al. (2010) argued, for research utilizing CPA parameters, prioritizing collision avoidance for multiple targets could be improved.

However, in practices current approaches to obtain the number of collision candidate as geometric collision probability and its characteristics usually analyse pair of ships in encounter situations. During such process, encounters, where more than two ships involved, will be intentionally divided into multiple sub-situations, which could lead to potential overestimate of results. To obtain results which could better reflect safety level in waterways, approaches that can consider multiple encounters should be improved.

5.2. Comparison among collision candidate detection methods

Among the literature, model-based data analysis, stochastic process model, and computer simulations, etc. can be frequently found to estimate the geometric probability for ship-ship collision. Combined with additional information, e.g. causation probability, etc. collision risk and its insights can be obtained for certain waterways. Although the implementations are different from one another, the common element for them is that it is critical to adopt certain criteria to determine dangerous encounters, i.e. collision candidate.

Proximity is the key element to perform the task, either in spatial, temporal domain or both, which can be considered introduced from individual ship perspective. The traditional synthetic indicators criteria e.g. CPA-based approaches are to measure spatial and temporal proximity between ships using DCPA and TCPA, distance, speeds, etc., respectively, under the assumption that both ships will maintain their kinematic status throughout the whole process. However, since some models provide separate estimations on the parameters, in certain situation it could give contradictory results, e.g. small DCPA value but large TCPA value, which make the determination of collision candidate difficult. Some scholars have proposed criteria combining DCPA, TCPA using the linear/non-linear equation to improve it to some extent. As for safety boundary-based criteria, they are utilized to estimate spatial proximity at the certain time interval for the data-driven mathematical model, stochastic model, and computer simulation approaches.

Among the various approaches for geometric collision probability, the reliability of them is questioned by some scholars. Goerlandt and Kujala, 2014) have conducted a comprehensive analysis of the reliability of collision candidate detection methods. The results indicate a significant difference due to the different criteria introduced and methods parameter settings. As for the inter-methodological difference of the results, such difference is reasonable since different criteria are introduced for the task.

In general, when in comparison, the issues of these approaches focus on two aspects: (1) low inter-methodological reliability; and (2) high influence of parameter choices for the adopted method. Involvement of time interval for collision candidate detection can be one of the reasons. During the encounter process, the value of indices which are utilised as criteria can fluctuate due to the interactions between ships. Such fluctuation, combined with the involvement of the time interval, could lead to over/underestimation of the results. For inter-methodological reliability issue, it is very challenging to propose which one is accurate due to the lack of standard labelled datasets for benchmarking. However, the reliability of results in terms of parameter settings, when in application, can be improved by considering the whole process of the encounter as proposed in (Chen et al., 2018), rather than analysing traffic data with an interval of time.

5.3. Human and organisational factors in collision risk analysis

The maritime transportation system is a complex system where human and organisational factors are highly involved. The behaviours of ships are governed by the officers on board, based on regulations, their perceptions, and experiences. During the process of decision making and execution, failure of human reliability, errors from human and organisational aspects could contribute to the occurrence of collision accident to a large extent.

For research on causation probability of collision accident, three major approaches can be identified from the literature: (1) probabilistic analysis, which aims at obtaining collision probability caused by human and operational errors; (2) accident contributing factors analysis, which is to identify the contributing factors of ship-ship collision, to analyse their causal relationships and to determine major factors that can be utilized for risk reduction; and (3) human reliability analysis, which is to systematically identify and analyse the cause and consequences of human errors (Groth and Swiler, 2013). These approaches are closely intertwined with each other as the goals of such analyses in probabilistic risk analysis of ship-ship collision are to find the mechanism of human and organisational factors that caused a collision, to quantify such probability and propose risk mitigation measures with respects to the factors.

Statistical analysis on historical collision accident is one of the fundamental techniques for the approaches aforementioned, e.g. (Bye and Aalberg, 2018; Graziano et al., 2016; Zhang et al., 2018b), etc. Accident investigation reports contain detailed information about the process of the accident, and the identified causes for the accident by the investigation authority, e.g. loss of watch keeping, mechanical failure, etc. Such information can be utilized directly to identify the influence of human and organisational factors on the collision, but also be processed to estimate collision risk in the forms of probability. Besides, research on accident mechanism and decision-making procedure, etc. have been widely applied in this field. FTA and Bayesian network, etc. are introduced to analyse the structure of system failure and the causation relationships between accident contributing factors, to obtain the causation probability and identify significant factors for risk mitigation. During the process of FTA and Bayesian network modelling, works from HRA research have facilitated them by providing guidelines for factors and causation relationships determination (e.g. (Martins and Maturana, 2013)), classification (e.g. Yıldırım et al., 2017), and expert elicitation (e.g. Harrald et al., 1998).

When applying such methods to get insights about human and organisational risk of collision, due to the scarce nature of collision accident, it is difficult to perform data-driven approaches, therefore, additional information, e.g. expert knowledge is important to be included, especially for determining the causal relationship between the contributing factors and establishing the structures of Fault/Event tree and Bayesian network. However, during the procedure, the uncertainty and elicitation process is often discussed (Zhang and Thai, 2016). To improve the reliability of causation probability, methods that deals with uncertainty and expert knowledge elicitation process should be improved and integrated into the process. For example, Zhang et al. (2018a) introduced “Credal Network (Antonucci et al., 2010; Antonucci and Zaffalon, 2008)” to conduct probabilistic inference with the interval to consider epistemic uncertainty in the causation probability model.

5.4. The model choice for different stakeholders

For different stakeholders in the maritime traffic system, due to their various and different interest of concerns, which have been analysed in Section 3.1, the applicability of the methods mentioned in the previous sections for them are different. Therefore, it is necessary to discuss which methods can be utilized for different stakeholders.

For maritime safety authorities, their interests of concerns is concluded as: (1) frequency of accident or near miss occurrence, which are important KPI to evaluate the performance of maritime authorities (Mou et al., 2019; Valdez Banda et al., 2016); (2) potential consequence of accident, e.g. oil spill, etc.; and (3) Human and organisational factors. All the interests concern different components of the risk analysis of ship-ship collision accident. For frequency problem, the statistics-based approach (e.g. Kujala et al., 2009; Yip, 2008, etc.) is one of the fundamental approaches that can be utilized. Besides, methods utilized to obtain geometric and causation probability, e.g. synthetic indicator, and safe boundary approach, etc. are now the mainstream of research for obtaining the frequency of accident. For the potential consequence estimation, probabilistic approach such as Bayesian network is an effective tool to estimate the consequence of ship-ship collision accidents (e.g. Goerlandt and Montewka, 2015a). However, since the details on accident consequence research are out of the scope of this paper, methods for this type of interests is not included. For human and organisational factors, methods for HRA, e.g. CREAM, HFACS, etc. can be utilized as guidelines to identify accident contributing factors from multiple sources of information, and act as a taxonomy to facilitate the determination of causal relationships among the factors. To probabilistically quantify the influence of them on the occurrence of ship-ship collision accidents, Bayesian network, FTA etc. can be incorporated.

For individual ships, risk detection and resolution are the main interests of concern of collision risk during navigation, e.g. to detect the risk of collision and perform proper collision avoidance manoeuvre. From this perspective, approaches illustrated in Section 4.1 can be incorporated into risk detection process, e.g. CPA-based approach (Wang et al., 2017), ship domain approach (Szlapczynski and Szlapczynska, 2017a), and velocity-based approach (Huang et al., 2019; Huang et al., 2018), etc. As for risk resolution, since it is out of the scope of this paper, the approaches for this is not included.

For ship designers, design, operation, and regulation are three major interests of concern. Ship design is of great importance for safe navigation, crashworthiness and human performance. However, since the research on ship design is out of the scope of this paper, for interested readers please refer to literature such as Deeb et al. (2017) and Liu et al. (2018). For ship operation, it concerns how to improve human performance during navigation and encounters, hence, to improve safety and avoid the occurrence of the accident. Methods for HRA, e.g. CREAM, HFACS, etc. can be incorporated to facilitate the process. Besides, the Bayesian network and FTA are effective tools to analyse the influence of ship design factors on human performance, e.g. Montewka et al. (2017). For risk-based regulations, since it concerns multiple aspects of the system, e.g. traffic management, ship operation, etc., it requires many approaches from different aspects to facilitate the regulation formation process. Therefore, all the approaches mentioned in the paper can be incorporated with risk-based regulations, depending on its goals and scope.

6. Conclusions

In this paper, a systematic review and analysis of quantitative risk analysis on ship-ship collision accident are presented with the focus on macroscopic perspective for maritime safety management. Major stakeholders and their preferences in risk analysis have been analysed, as well as the risk analysis methods under the framework proposed by Fujii and Shiobara (1971) and Macduff (1974) to provide an overview on the topic.

A classification and introduction of probabilistic risk analysis methods for ship-ship collision have been provided. Detailed analysis of research methods is conducted for the elements of the probabilistic risk analysis framework: geometric and causation probability. For geometric probability, research is classified into the synthetic indicator, safe boundary, and velocity-based approaches respectively according to different criteria utilized when determining encounters that have the potential for collision. For causation probability analysis, statistical analysis, Fault tree analysis, and Bayesian network models are chosen as major categories of approaches.

A discussion is presented and the main findings are as follows: (1) Research on collision risk analysis from individual ship perspective, especially criteria to evaluate ship encounters, have facilitated the research in macroscopic perspective, and in turn, results from macroscopic research can also facilitate individual risk analysis by providing regional risk characteristics, etc. However, among the literature, the geometric probability is usually obtained by evaluating simple encounters where only two ships are involved. To improve the accuracy of the results, methods that can consider multiple-ship-encounter scenarios should be developed; (2) Although different criteria are utilized to propose various approaches, proximity in the spatial temporal domain is the common element to determine the geometric probability for collision. However, current approaches usually estimate geometric probability by analysing data at certain intervals, which could lead to over/underestimation of the results. To improve related research, methods that can consider the whole process of encounters should be proposed; (3) For causation probability induced by human and organisational factors in a collision accident, lack of data and uncertainty is a problem to obtain accurate and reliable estimation. To obtain reliable results, methods which could conduct probability inference considering uncertainty should be further developed. 4) For each stakeholder and their interests of concern, the possible choices of methods are also suggested.

Risk analysis and management is an important element for the maritime transport system to prevent the occurrence of accidents, related consequences and their influence on the individuals and societies and to improve the efficiency of the maritime traffic operations in the system. The findings of this work and systematically analysed risk analysis approaches for ship-ship collision accident can provide more insights to peer researchers and risk assessors, to better grasp the merits of current research methods, inter- and intra-categorical relationships and technical characteristics of risk analysis methods, as well as the challenges that need further efforts. The relationship between risk analysis for individual ships and macroscopic perspective provides an opportunity to stakeholders such as maritime safety authorities to propose safety mitigation measures concerning both aspects. The comparison among collision candidate detection methods offers new understanding to researchers of current methods and their advantages and disadvantages when applied. The analysis of human and organisational factors in collision risk analysis concludes the challenges in practices. Based on these findings, we hope that this work can act as a reference for future research.

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Appendix A. Overview of probabilistic risk analysis of ship-ship collision[3]

Nr.	Research name	Synthetic estimation	
		Geometric probability	Causation probability
1	Pedersen (1995)	**SB**	**FTA**
2	Bukhari et al. (2013)	**SI**	**–**
3	Chen et al. (2018)	**VB**	**–**
4	Dong and Frangopol (2015)	**SI**	**LS**
5	Goerlandt and Kujala (2011)	**SI**	**LS**
6	Hanninen and Kujala (2012; Hänninen and Kujala (2009)	**–**	**BN**
7	IALA (2009)		**LS + EJ**
8	Lušić and Čorić (2015)	**SB**	**–**
9	Goerlandt et al. (2012)	**SB**	**–**
10	Qu et al. (2011)	**SI**	**–**
11	Ren et al. (2008)	**–**	**BN**
12	Rong et al. (2015)	**SB**	**–**
13	Uğurlu et al. (2013)	**–**	**FTA**
14	Wu et al. (2016)	**SB**	**–**
15	Zhang et al. (2018a)	**–**	**BN**
16	Friis-Hansen and Simonsen (2002)	**SB**	**BN**

[3] This table only illustrates the models which explicitly performs probabilistic risk analysis on ship-ship collision accident for either geometric or causation probability, or both. The works which contribute to the details of methods utilized in these researches are not included.

17	COWI (2008)	**SB**	**SA**
18	Kujala et al. (2009)	**SB**	**LS**
19	Debnath and Chin (2010)	**SI**	**–**
20	Trucco et al. (2008)	**–**	**FTA + BN**
21	Martins and Maturana (2010)	**–**	**FTA**
22	Montewka et al. (2010)	**SB**	**LS**
23	Mou et al. (2010)	**SI**	**SA**
24	Debnath et al. (2011)	**SI**	
25	Montewka et al. (2012)	**SB**	**LS**
26	Martins and Maturana (2013)	**–**	**FTA + BN**
27	Silveira et al. (2014; Silveira et al. (2013)	**SB**	**LS**
28	Montewka et al. (2014)	**SB**	**BN**
29	Lenart (2015)	**VB**	**–**
30	Li et al. (2015)	**SI**	**–**
31	Weng and Xue (2015)	**SB**	**LS**
32	Zhang et al. (2015b)	**SI**	**–**
33	Debnath and Chin (2016)	**SI**	**–**
34	Sotiralis et al. (2016)	**BN**	**–**
35	Zhang et al. (2016)	**SI**	**–**
36	Chai et al. (2017)	**SI**	**FTA**
37	Christian and Kang (2017)	**SB**	**LS**
38	Cucinotta et al. (2017)	**SB**	**LS**
39	Szlapczynski and Szlapczynska (2016)	**SB**	**–**
40	van Westrenen and Ellerbroek (2017)	**VB**	**–**
41	Zhang et al. (2017)	**SI**	**–**
42	Zhen et al. (2017)	**SI**	**–**
43	Szlapczynski and Krata (2018)	**VB**	**–**

SI: Synthetic indicator approach; **SB**: Safety Boundary approach; **VB**: Velocity based approach.
FTA: Fault Tree Analysis; **BN**: Bayesian Network; **SA**: Statistical Analysis; **EJ**: Expert Judgement; **LS**: Literature sources.

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