

Review

Review of Probabilistic Risk Assessment Models for Ship Collisions with Structures

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Abstract: Researchers have always been concerned about collision risks between ships and structures on busy waterways, as the consequences can be catastrophic. The models for determining the probabilities of these accidents, however, vary widely, with discrepancies between different model results in the same assessment. The models sometimes lack critical elements or are inherently flawed, and therefore do not represent reality. This paper aims to review the existing probabilistic risk models for ship and structure collisions. The advantages and disadvantages of each model are discussed, which leads to a better method for future model development. This paper reviews the existing literature for the probabilistic risk assessment (PRA) between nautical traffic and offshore infrastructures. This paper differentiates the existing models into three categories: statistics of collision rates, statistical models, and simulation models, as the models are evolving from statistical models to simulation models to derive more accurate results. The advantages and disadvantages of the statistical models were evaluated by comparing the details of the elements contributing to risk. Simulation models with virtual autonomous ships can better reflect the reality and include more risk elements than those described in the existing models. The cores of simulation models and the advantages of different models are elaborated and compared, thus supporting future work in this area.

Keywords: ship collision; risk assessment; statistical models; simulation models

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1. Introduction

Researchers have always been concerned with risks on busy waterways. From the perspective of the shippers, a vessel collision with a bridge or berth may cause property loss and casualties. The enormous energy of a ship collision can cause great damage to a bridge and even bridge collapse. Those huge potential losses have brought together engineers of transportation and infrastructure systems to conduct risk assessments during the design process for waterway structures. They also take measures to reduce the risk of accidents in operations.

Normally, the two dimensions for a risk analysis are probability and consequence. Models were developed for calculating ship collision probabilities and predicting consequences [1–5]. Probabilistic research of ship collisions with structures is a part of the research on risk assessment and the design of structures (such as a bridge span or a bridge pier) [6]. However, the predictions are not always satisfactory due to various uncertainties during validation [7,8]. Therefore, a better probabilistic prediction model is still needed.

This paper aims to review the existing probabilistic risk models for ship collisions with structures. The advantages and disadvantages of each model are discussed, which might lead to a better method for future model development. Consequently, improved designs and measurements can be applied for both the infrastructure and waterway structure to mitigate the risks.

This paper is organized as follows. Section 2 introduces the method of this review. Section 3 introduces statistical models, which are primitive and used to tentatively derive a probability. Section 4 presents statistical models that have been widely used in calculating the probability of ship collision with bridges, and compares the elements considered in each statistical model. Section 5 presents different waterborne traffic simulation models and highlights their advantages and limitations. The paper is summarized in Section 6. The contents of this review have been published in a Ph.D. thesis [9]. However, the authors decided to modify the work and publish it in this journal to gain broader attention.

2. Method

This paper aims to review the existing models. A survey of the advantages and disadvantages of each model might lead to recommendations for developments in future models. This paper differentiates the models into three categories: statistics of collision rates, statistical models, and simulation models. The advantages and disadvantages of the models are compared in order to gain a full overview of the risk elements for more advanced models.

Risk assessment for the probability of collision between ship traffic and structures has been evolving over time. Statistical probability results can be derived from historical accident databases. Nevertheless, when the accident databases are not available, statistical models are used for probabilistic assessments. A successful probabilistic assessment depends on proper consideration of the elements that significantly contribute to the risk.

The scope of this review consists of two dimensions. First, this research yields insights into the historical background, procedures, and advantages and disadvantages of each statistical model for ship collisions with structures. Afterwards, comparisons of risk elements in the models are considered. Second, this paper examines the existing simulation models designed for probabilistic risk assessment. The simulation models mimic the autonomous individual ship collision avoidances and uncertainties that are not so evident in statistical models, as Goerlandt [10] found that few waterway risk analysis applications reflect uncertainty. The advantages and disadvantages are discussed in relation to typical existing simulation models. This review will shed light on the way to retain the advantages in the next generation of probabilistic risk assessment models. The methods for model improvement are also discussed.

This literature review was conducted by searching the digital library of Wuhan University of Technology, including ScienceDirect®, Scopus®, Google Scholar, other databases, and relevant journals. There are some important materials that are not presented as electronic versions, e.g., three random models [11] are also included to gain a full picture of the development of models.

The search of the databases consisted of combinations of key words such as “risk”, “probabilistic”, “safety”, “collision”, “assessment”, “ship”, “bridge”, “structure”, “maritime”, and “marine”. The references in the relevant literature reviews [12,13] were also included in the examination of the existing research. The last resources were the relevant standards (e.g., ASSHTO model) and models introduced by experienced experts [14]. As a result, there were a total of 245 references considered; however, this overview only selected representative or innovative models, as some of the papers were applications or minor discussions.

3. Statistics of Collision Rates

Normally, accident statistics are derived from historical accident databases to acquire the probability of disasters. A typical example was conducted by the World Association for Waterborne transport, Navigation, Ports, and Waterways (PIANC) to derive the probability of bridge collision by ships [15]. The accident rates were obtained by dividing the number of accidents by the total number of ship passages. An international database becomes a valuable source for statistics. Collisions for each year between 1960 and 1995 and collision rates were collected. These statistics show that human error is the main cause of collisions.

The causes of the collisions are also derived from statistical analysis, and it was found that the causes of collisions can be divided into three main groups: human error (approximately 64%), technical failure (21%), and extreme circumstances (15%) [16]. Human error is the main cause of ship position aberrancy. However, collisions often stem from a combination of human error, technical failure, and extreme circumstances.

The advantage of the field of statistics is that it is easy to understand and simple to apply. However, the disadvantage is that consistent databases are not always available, as small accidents are not always recorded, and the reports may not mention every useful detail of the accidents. Even if the historical data is available, this simple and direct model may not reflect what could happen in the future with different conditions. This is because the rules and the design of the bridges and ships navigating underneath are different.

The human factor is so complex that it is not adequately taken into consideration in the existing models for risk analysis. There are studies that try to interpret human factors statistically, as an element in risk analyses. The human element is studied in collision events [17], maneuvering behavior [18], human performance with different environmental conditions [19], and ship operation [20,21].

4. Statistical Models

When the databases of accidents are not available, statistical models are substitutes for probabilistic risk assessment (PRA). Given a causational factor, the probability of accidents can be calculated with a statistical distribution that describes the spatial positions of the ship traffic. This model has been widely used in calculating the probability of incidents [22–24]. Most of the models are widely applied in the probabilistic risk assessments of ship and bridge collisions.

4.1. AASHTO Model

As described in the AASHTO (American Association of State Highway and Transportation Officials) report, the annual frequency of a bridge collapse [25] is expressed as:

$$AF = (N)(PA)(PG)(PC) \quad (1)$$

where, AF = annual frequency of the collapse of a bridge element due to a given N; N = annual number of vessels, classified by type, size, and loading condition, that can strike a bridge element; PA = probability of vessel aberrancy; PG = geometric probability of a collision between an aberrant vessel and a bridge pier; and PC = probability of bridge collapse due to a collision with an aberrant vessel. The geometric probability, PG, is taken as the area under the normal distribution bounded by the pier width and the width of the vessel [25].

4.2. Kunz's Model

Kunz [26] introduced another simplified mathematical model to calculate the probability of a collision event, based on the relative position between vessel and a bridge pier. The random variables are the course deviation with angle φ and the stopping distance, x (see Figure 1).

4.3. Eurocode Model

The Eurocode model [27] is similar to the AASHTO model. This model is based on a co-ordinate system (x, y) (Figure 2). The probability of a collision event is expressed by:

$$P_c(T) = nTP_{na} \int \int \lambda(x)P_c(x, y)f_s(y)dx dy \quad (2)$$

where T = period of time under consideration; n = number of ships per time unit; P_{na} = the probability that a collision is not avoided by human intervention; $\lambda(x)$ = probability of

failure per unit travelling distance; $P_c(x, y)$ = conditional probability of collision, given initial position (x, y) ; and $f_s(y)$ = distribution of the initial ship position in direction y .

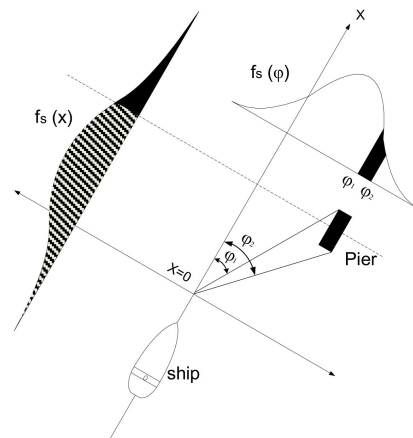


Figure 1. Kunz's Mathematical collision model [26].

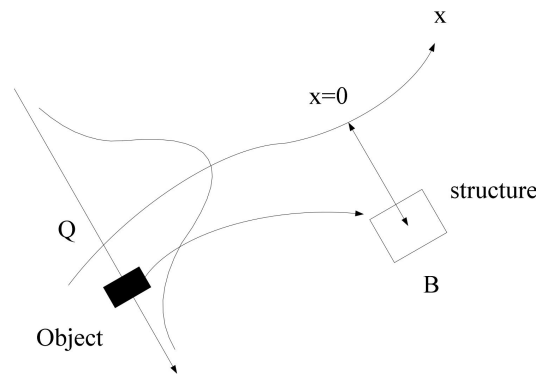


Figure 2. Illustration for probabilistic collision model in Eurocode (Based on [27]).

4.4. Pedersen's Model

Pedersen's model [28] is evolved from Larsen's model [29]. The model applied in calculating the expected rate ($F_{Cat,1}$) of serious collisions [28]:

$$F_{Cat,1} = \frac{1}{T} \sum_i \frac{1}{V_{a,i}} \int_0^{V_{max,i}} \int_A^B \int_0^T P_{c,i} q_i V_i B_i R_i dt dx dV_i \quad (3)$$

where $V_{a,i}$ = average speed of ship class, i ; $V_{max,i}$ = maximum speed of ship class, i ; and $P_{c,i}$ = causation factor, i.e., the probability of a collision if the ship is on a collision course [30]. The value q_i = traffic density function of the ships given by the number of ships and the Gaussian distribution as described; the unit is the number of ships per unit area; and V_i = distribution of speed of the ships. The value B_i = simple geometrical collision indicator function, which is 1 when the ship strikes a pier or a girder and 0 when the ship either passes through the bridge line without collision or grounds before it reaches the bridge line, and R_i = severity of the collision. This factor depends on the crushing force, i.e., type, ship size, ship velocity, the strength of the bridge structure, and several other parameters. T = time and x = axis along the bridge line. In Pedersen's model, the collision frequencies are categorized and studied individually. Similar categories were also applied to the risk of collision with offshore wind farms [31]. The accident category 4 assumes that the ships drift uniformly over 360° around the bridge [28] (see Figure 3).

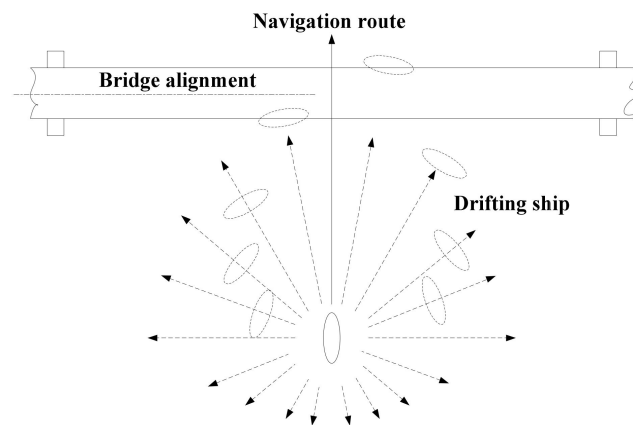


Figure 3. Ship drifts towards the bridge line (based on [28]).

4.5. Drift Model

In the process of designing the Su-Tong Bridge in China, drift model was developed to calculate the probability of collisions between ships and the bridge pier [14]. The movement of an out-of-control ship is illustrated in Figure 4, where V is ship instantaneous speed, U is current speed, and V_S is the ship speed over ground. When a ship is out of control, the ship's motion can be divided into two steps. The first step is from Point G_0 (initial position when a ship is out of control) to G_1 , where the ship is moving with inertia under the forces from wind and currents. From Point G_1 to point G_2 (position of a bridge pier), only wind and currents are the major factors for the movements. Whether a collision happens or not depends on the fairway condition, currents, wind, and the positions of the piers, etc. There are formulas to calculate the lateral distances ($B_1 + B'_1 + B_2 + B'_2$) in Figure 4, in which B_1 is the drift on axis x caused by the current within the stopping period, B'_1 is the drift on axis x caused by wind within the stopping period, B_2 is the drift on axis x caused by the current without inertia, and B'_2 is the drift on axis x caused by the wind without inertia. There are empirical formulas to calculate the lateral drifts. The stopping distance and stopping time are constant, and these can be found in the ship particulars. After numerous calculations of drift tracks from different ships with different initial speeds and positions in the waterway, the dangerous collision areas can be determined (shadowed areas in Figure 5).

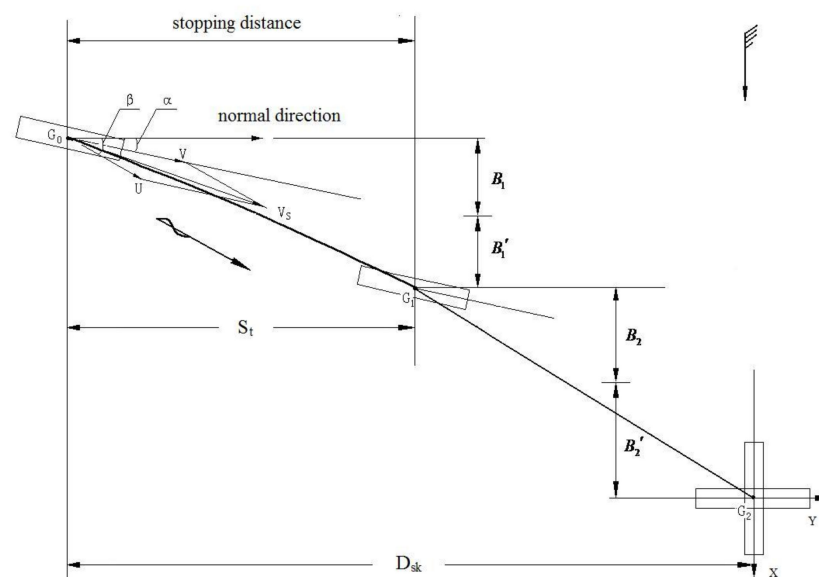


Figure 4. Drifting stages of the ship that is out of control [14].

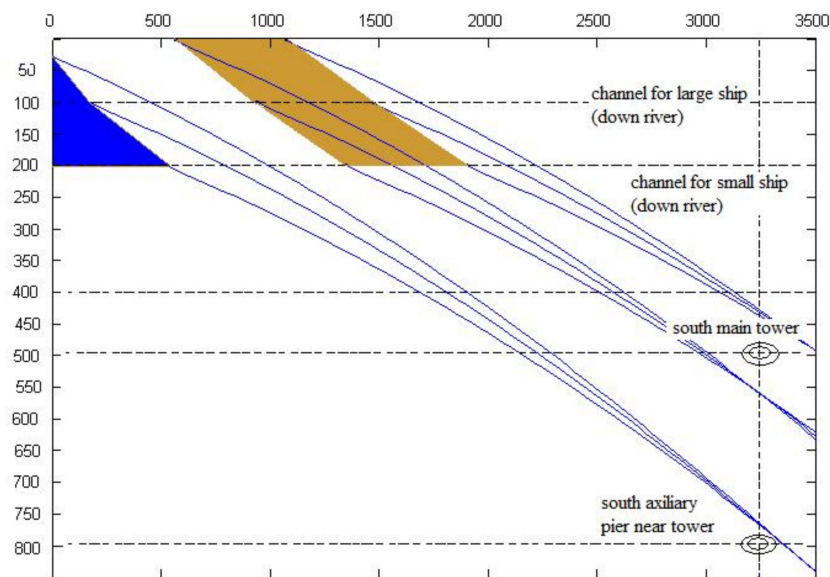


Figure 5. An example for dangerous areas in the drift model (based on [14]).

The dangerous areas will be formed via various ship tracks, where out-of-control ships have a chance to collide with the bridge. Then the collision probability is:

$$P_{collision} = \frac{A_{danger}}{A_0} \quad (4)$$

where, A_0 is the area in which the ship navigates and A_{danger} is the dimension of the dangerous area in which the ship may collide with the bridge. This area is determined by factors including wind, currents, and ship speed.

4.6. Three Random Variables Model

Based on the AASHTO model and Kunz's model, Geng et al. [11] developed a new model for the collision problems between ships and bridges [11,32,33]. There are two additional parameters comparable to those in Kunz's model. Firstly, the frequency of a certain water level in a year is multiplied by the probabilities of collision events for the specific water level. Secondly, the aberrant vessel distribution perpendicular to the centerline of vessel sailing path is taken into consideration, adopted from the AASHTO model.

The coordinate system (x, y) is as indicated in the Figure 6. The x coordinate is the horizontal distance perpendicular to the centerline of the vessel sailing path. The y coordinate is the distance parallel to the centerline of the vessel sailing path. Therefore, the collision model is:

$$P_{wi} = \sum_{j=1}^n N_j \int_{\mu_x - 3\sigma_x}^{\mu_x + 3\sigma_x} f(x) \int_0^D \lambda(s) [1 - F(s)] \int_{\theta_1}^{\theta_2} g(\theta) d\theta ds dx \quad (5)$$

where N_j = annual number of vessels in category j ; $f(x)$ = the distribution of vessel position in the x direction; $\lambda(s)$ = probability of aberrancy per unit travelling distance; $F(s)$ = the probability of the ship stopping before the collision; and $g(\theta)$ = the distribution of the deviation angle θ .

4.7. Comparisons of the Statistical Models

This section compares the statistical models introduced in previous sections. The most reasonable and reliable approach to determine PA (probability of vessel aberrancy) should be based on long-term accidental statistics. However, when there is no adequate database, as stated by Wang and Geng [33], the AASHTO model is the most widely used model for

calculating the probabilities of collisions, because of its simplicity and practicality. The AASHTO predefined estimates of PA are derived from American data. The worldwide applicability could be the problem.

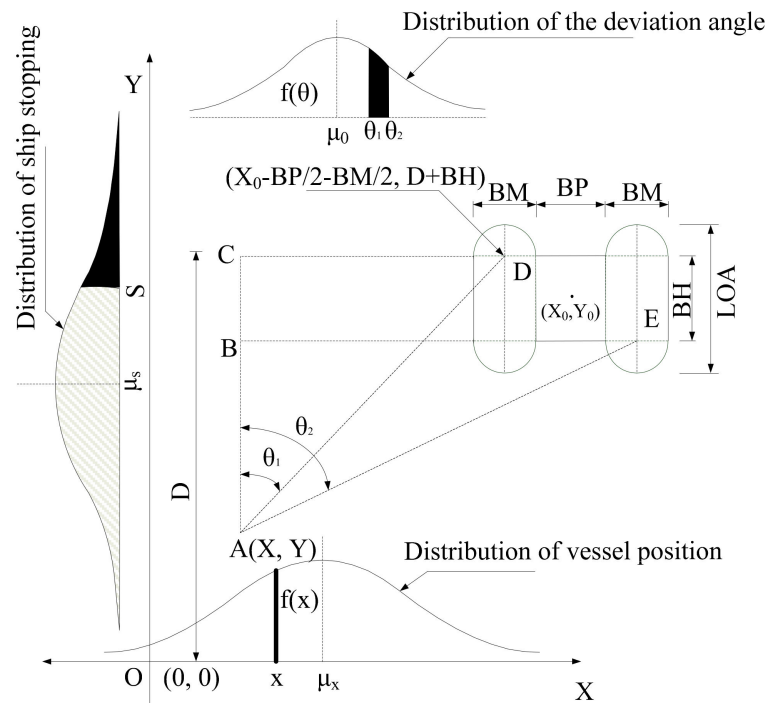


Figure 6. Three random variables collision model [11].

Most of the models do not fully consider wind, visibility, navigational aids, or other factors of navigational circumstances. A comparison of the elements considered in each statistical model is given in Table 1. The elements in the table are derived from the models mentioned above. It is pointed out that these models are lacking in detailed descriptions of ship movements [12,34]. The advantages and disadvantages of each model are discussed as follows.

Kunz's model, the Eurocode model, and the Three Random Variables model can mimic the critical steps for a ship collision. For a vessel that is completely out of control, the drift model can reflect the movement processes. However, the models show weaknesses in describing the dynamic behaviors of a nautical traffic system, such as describing ship behaviors such as collision avoidance, speed change, or course alteration.

The ship distribution is considered in all three models. However, the formula of $P_c(x, y)$ is not provided, which makes the model less practical than the AASHTO model. Further, only single ship routes are considered in the models. The problem with this is that these models may not be applicable in other areas. To overcome the deficiencies, the Three Random Variables model has the advantage of being able to consider more elements.

Pedersen's model is applied in the design process of a large span bridge situated in the sea. However, there are disadvantages compared with other models. Firstly, the model does not consider overtaking encounters. Secondly, the effects of wind and currents are not considered. Further, the model assumes that the ship's drifting direction is evenly distributed over 360° . These are simplifications compared with the Drift Model, in which the drifting ship moves under the force of wind and currents.

The human factor is fully understood as an element in the probabilistic risk analysis. Human factor analysis should be studied and can be built into the model to calculate the probability of incidents.

Table 1. Comparison of the factors considered in the models.

Risk Factors	Risk Elements	AASHTO Model	Kunz's Model	Eurocode Model	Pedersen's Model	Drift Model	Three Random Variables Model
Structure Factor	Pier/Object Positions	✓	✓	✓	✓	✓	✓
	Span of Bridge	✓	✓	-	✓	✓	✓
	Pier/Object Dimensions	✓	✓	-	✓	✓	✓
Navigational Circumstances	Wind	-	-	-	-	✓	-
	Current	✓	-	-	-	✓	-
	Tide	-	-	-	-	✓	-
	Water Depth	✓	-	-	✓	✓	✓
	Visibility	-	-	-	-	-	-
	Channel Bends	✓	-	✓	-	-	-
	Ship Traffic Density	✓	-	✓	✓	-	-
	Ship Dimension	✓	-	-	✓	✓	✓
Ship Factor	Probability of Vessel Aberrancy	✓	-	✓	✓	-	-
	Distribution of Vessel Position Perpendicular to Normal Route	✓	-	✓	✓	-	✓
	Ship Deviation Angle	-	✓	-	-	✓	✓
	Distribution of Stopping Distance	-	✓	-	-	✓	✓
	Failure Rate Per Travel Unit	-	✓	✓	-	-	✓
	Speed of The Ships	-	-	✓	✓	✓	-
	Ship Classification	✓	-	✓	✓	✓	✓
	Human Error	-	-	✓	✓	-	-

This section has presented an overview of several models for calculating the probability of ship collisions with structures. The other kinds of probabilistic risks, such as collisions with wind farms, are based on the statistical models introduced in Section 4. After treatment of historical background, procedure, and the advantages and disadvantages of each model, comparisons are made for the risk elements that are considered in the existing statistical models. Consequently, the following discussions are made for further research: Firstly, more risk elements should be taken into consideration. Further research should consider all risk elements listed in Table 1. Moreover, it would be better to describe the ship movements in more detail. Secondly, the categories of ships based on ship types, ship tonnages, and ship dimensions, as well as ship maneuverability, need to be considered to make the model more accurate. Thirdly, different encountering situations must be included. Fourthly, the effects of wind and currents need to be considered. The wind and currents are not only the cause of position aberrance and a larger swept path, but can also drive the ships into collision (e.g., Drift Model). Therefore, the influence of the wind and currents needs to be examined and considered.

5. Simulation Models as a Substitute

5.1. Simulation Models

Goerlandt and Montewka [35] pointed out that uncertainty treatment is needed in the risk analysis applications for maritime transportation, and also pointed out that simulation models are able to propagate the uncertainty of the input variables into the outputs for further consideration [13]. In most cases, simulation programs are performed in the risk analysis. It is very possible that simulation models have the potential to better reflect the influence of the various risk elements (listed in Table 1). There are two different simulation approaches for risk analysis: individual ship simulation and ship traffic simulation. This

section tries to explain the advantages as well as the limitations of the existing simulations and gives insights regarding the future models for probabilistic risk assessments.

For individual ships, the interaction with other ships and the role of human interventions are important. Dynamic ship movements can be simulated with manned ship-handling simulators (e.g., the Mermaid 500 at MARIN). One of the drawbacks of this is that normally only scenarios with certain extreme circumstances are simulated using the system. This relies too much on expert judgments. Another disadvantage is that different traffic patterns and uncertainties in the waterway are difficult reflected using this system. Different cases of ship encounters should be performed, and a single case of a ship-handling simulation is time consuming and the equipment is expensive [36]. Other cheaper options are the simulation of ship movements based on Fuzzy Logic [37], Bayesian Networks [38], and Neural Networks [39]. Nevertheless, these models remain dependent on expert opinions or other human interventions, otherwise proper vessel behavior in different situations is still missing [40].

Ship traffic simulation exceeds the ship-handling simulator's ability to consider different ship traffic conditions and situations at the same time. Besides representing single ship behavior, it automatically performs collision avoidances and regulation conformities that are more relevant to collision risks. This enables a safety assessment process in calculating all the possible probabilities in a much shorter time compared to ship-handling simulators. However, a model for automatic collision avoidance is the key to performing various ship behaviors in different situations, rather than the use of expert opinion. Therefore, the successfulness of a collision avoidance model become very important for the simulation model, and it plays a key role in the following risk assessments.

There are domain-based models developed for automatic collision avoidances that mimic real ship behaviors. The first traffic simulation model utilizes the widely discussed domain theory for automatic collision avoidance in the model. Ship domain is a predefined area around a ship that should remain clear of other ships. In ship traffic simulations, if the domain of the ship is invaded, action should be taken to avoid collisions. Davis, Dove [41], Goodwin [42], Liu [43], and Pietrzykowski and Uriasz [44] gave good examples of various shapes of ship domains. Domain-based ship traffic simulations can count the number of invitations and near misses, which are parameters in a risk estimation. A traffic simulation model using the safety domain for qualitatively analyzing maritime safety in restricted waters, named MARTRAM (Marine Traffic Risk Assessment Model), has been presented by Pimontel [45], using FoxPro and MapInfo. MARTRAM counts the number of safety domain invasions (encounters) as an indication of collision risk.

The OFI (opportunity for incident) model uses a dynamic simulation model to count the occurrences of the various incident scenarios that could happen in the waterway concerned [46]. The simulation platform generates ships on the map and simulates the movements of the ships in the area concerned. The function of the platform is to count the possible incidents by simulating ship encounters on a map [47]. The saved scenarios and the counted data will be further processed by expert judgments in the safety assessment of the number of accidents. Traffic simulation forms an element for counting the incidents. However, the dynamic ship traffic behavior and collision avoidance is not addressed, which makes the model greatly dependent on expert judgment and Bayesian networks [48]. The complete procedure, the model of the system simulation, and the role of the simulations can be found in the Prince William Sound Risk Assessment [49–51], the Washington State Ferry Risk Assessment [46,52], and other literature published subsequently based on the previous projects [47,48,53,54].

Ship interactions are simply addressed in SMARTS (Ship Auto-navigation Fuzzy Expert System) [55]. The ship navigation, including collision/grounding avoidance maneuvers, are governed by a fuzzy expert system. This nautical traffic simulation provides ship interactions. However, the interactions based on fuzzy expert system are not described in detail. Therefore, the ability to represent real-world multi-encountering and collision

avoidance is unknown. Moreover, the route of the ships is predetermined, while the real ship tracks conform to a lateral spatial distribution rather than a fixed line of route.

The Istanbul Strait simulation model investigates ship integrations from a traffic management perspective. Ship traffic behavior is examined based on different scenarios, including ship arrival and waiting time [56]. One important feature is that the passage of a big ship (with a length larger than 200 m) will prevent the opposite traffic from passing the strait. On the whole, this traffic simulation is a good tool to determine the strategy for ship entry into the Istanbul Strait. Ulusçu [57] presents more details on using a mathematical risk model to estimate the risks of the Strait of Istanbul. This simulation solved a local problem in quantifying and managing risks. It is designed for traffic management. However, it is not capable of simulating realistic ship behavior and ship avoidance behavior in the strait.

Generating different collision candidates for encounter scenarios and ship behavior in various circumstances is not a simple task. The MDTC (minimum distance to collision) model gives a clue regarding simulating detailed ship integrations for risk analysis. Different types of ship are generated based on AIS data analysis, with different spatial distributions, speed distributions, and course distributions. Collision candidates can be computed and counted in different encounter situations and areas. Estimation of the collision frequency can be calculated with the MDTC-based model, Pedersen's model, and AIS data [28,58]. The MDTC model uses discs to represent vessels, which looks similar to the Arenas model [58,59]. The MDTC values (Collision Diameter) are computed based on a series of ship encountering simulations and ship maneuvering simulations. What is innovative in the model is determining the Minimum Distance To Collision, which is a substitute for the parameter "collision diameter" (CD) in Pedersen's model [60]. This enables a more accurate and reasonable calculation of collision candidates. The MDTC is a parameter related to the ship type and encountering angle. If the distance between two vessels is less than a certain specific value of MDTC, a collision accident happens, no matter what evasive action is taken on board. In conclusion, the MDTC-based model gave a good indication of the least distance needed for evasive action in a certain encounter situation. It also provides a CD value, which can be used in Pedersen's model. However, as the author indicates, the assumption of blind navigation in the geometrical model does not reflect the fact that the ships can avoid each other in real traffic. Furthermore, there are many assumptions in the simulation. For instance, the model assumes vessels start maneuvers simultaneously.

5.2. Comparisons of The Simulation Models

This section compares the simulation models mentioned in this chapter. Different models perform different functions in the risk assessments. The simulations are used to generate the parameters that are more appropriate for further assessments. This paper only takes the contributions and limitations for risk assessment as factors for comparing the models (Table 2). The following passages discuss the contributions and limitations of each model.

Domain-based simulations can provide the invasion counts (ship encounters), which is a very important parameter for statistical models for risk analysis. Researchers have developed different shapes for more reasonable and accurate results. However, the invasion counts in the simulation are significantly larger than AIS observations [58,59,61]. This discrepancy also shows the limitation of the model. Pimontel [45] attests that, in the MARTRAM model, predefined ship courses result in a "narrow route" in the simulation, which limits the reality of the simulation. Moreover, vessels carrying hazardous cargo are not treated differently. Furthermore, the vessel avoidance behavior is modeled only by speed change, which is not realistic. A dynamic change of speed and course in an encounter situation would be more realistic. On the other hand, simulations can also be used to determine a ship domain [62].

Table 2. Comparison of the simulation models.

Pros and Cons	Factors	Ship-Handling Simulators	MARTRAM	OFI Model	SMARTS	Istanbul Strait Model	MDTC Model	CA Model
Contributions for Risk Assessment	Collision Avoidances	✓	✓	-	✓	-	-	-
	Considering Extreme Circumstances	✓	✓	-	-	-	-	-
	Ship Hydrodynamics	✓	-	-	-	-	✓	✓
	Widely Recognized	✓	-	-	-	-	-	-
	Considering Ship Traffic Conditions	-	✓	✓	✓	-	-	✓
	Automatic Behavior	-	✓	-	✓	-	-	✓
	Fast	-	✓	✓	✓	✓	✓	✓
	Encounter Counts	-	-	✓	✓	✓	✓	✓
	Distribution of Vessel Position	-	-	-	-	-	✓	✓
	Distribution of Ship Arrival	-	-	✓	✓	✓	✓	✓
	Various Ship Speed	✓	-	✓	✓	✓	✓	✓
	Crossing Encounters	✓	✓	-	✓	-	✓	-
Limitations for Risk Assessment	Human Intervention	✓	-	✓	-	-	-	-
	Time Consuming	✓	-	-	-	-	-	-
	Expensiveness	✓	-	-	-	-	-	-

With the help of the simulation, the OFI model can count occurrences of the various incidents' scenarios. The default settings of ship interactions may not be reasonable and accurate. Expert judgments are involved in the safety assessment of the number of accidents. Bayesian networks, the results of which are sometimes biased, are also applied in the safety assessment. In other words, current simulation models are only part of the risk analysis. Human intervention and statistical method are also applied for the final assessment.

The SMARTS model applies a fuzzy expert system for automatic ship navigation and collision avoidance. Statistical data for ship arrival is applied for ship traffic. The ship traffic is the most vivid in the SMARTS model. However, multi-encounter and collision avoidance is not introduced in detail. The predetermined route choice of the ships is still a limitation in this model. The core of the Istanbul Strait simulation model is similar to the SMARTS model. The traffic control feature enables traffic management.

The MDTC model is the first model to apply ship dynamics to generate more accurate ship behavior that guarantees more accurate results. Spatial distributions and various ship speeds enables vivid ship traffic and various encountering situations, as in reality. However, the “blind navigation” to determining MDTC weakens the performance of the model. Pedersen's model [28] has a significant effect on the model.

A CA (cellular automata) model reflects micro scale ship traffic well, as it can simulate traffic formation based on the change of waterway width [63]. The velocity fluctuations of the individual ship can be described by randomized accelerations, considering weather and sea conditions [64]. Hydrodynamic ship interactions, especially in narrow channels, can be reflected [65]. Therefore, a CA model can be used to study the relationship between ship lengths and the traffic capacity of the waterway area.

Human factors, which are not fully reflected in the statistical models, have been included in the simulation models. Simulated ship behaviors, such as ship courses and speeds, present encounters that are more realistic. The automatic collision avoidance module decreases the workload of the experts.

There are also disputes regarding the uncertainty propagation problem [13], although some of the model is able to reflect parts of the uncertainties using random probabili-

ties [64,66]. This is true for the simulation models at this stage, as the models are lacking in calibration and verification. The uncertainty would be minimized if the models provide more accurate ship behavior and results. This depends on model development and systematic verification. A worldwide application of ship traffic simulation could help with the process, as ship-handling simulators are widely accepted and applied across the globe.

The statistical model does not explain the fact that ships are able to take active evasive behavior to avoid collisions. The simulation models successfully fill in this gap by reproducing vivid ship traffic and various encounter situations as in reality. Although the simulation models have various limitations, we can still look forward to their future developments. This chapter tries to explain the function of the simulation model in safety assessments and gives a clue as to future developments.

This section compares the simulation models mentioned in this chapter. Different models have different functions in the risk assessments. The assessments are performed in different geographical locations of the globe, with different purpose. Therefore, comparing the models is not an easy task. This paper only takes the contributions and limitations for risk assessment as factors for comparing the models. There are other factors, such as accuracy, technics, popularity, and worldwide applicability, etc., that are not included.

This section introduces the simulation models that perform an indispensable role in the risk analysis models. There are several advantages for the simulation models compared to the statistical models. First, the collision candidates can be generated using random variables derived from AIS data analysis. The underlying uncertainties in traffic formation and collision avoidances can be more realistic compared to the historic data derived from simple statistics. Second, the ship traffic simulation provides the possibility to consider all the conditions and situations that can happen in reality. Both single ship behavior and ship traffic behavior can be properly represented. Third, the ship movements in collision avoidances can be vividly displayed on the screen. Therefore, researchers can observe and modify incorrect representations of the ship behavior. This helps to form a verification process that statistical models lack. Finally, theoretically, every risk element in Table 1 can be properly considered in the simulation model. More risk elements and uncertainties have been considered in recent models. However, as has been pointed out, there is still a need for validation of the models [7,67].

6. Conclusions

This paper reviewed existing models for the probabilistic risk assessments of ship collision with structures. Those models include statistical models. The statistics are simple and are widely used in other models. Most of the statistical models are developed for bridges and ports. The statistics and statistical models can either provide parameters for the simulation or serve as sub modules for specific elements in a risk analysis. Simulations are considered an indispensable part in an analysis. Different simulations effectively represent different elements.

After reviewing the existing statistical models, it is concluded that the most desirable model should take into consideration all risk elements and uncertainties that exist to gain results that are more realistic. The ships should be categorized into detailed groups that represent reality more closely. The encounter situations and collision avoidance behavior should consider the effects of wind, currents, and visibility, as ship movements are the result of different impacts. The existing simulation models are either weak in reproducing a realistic traffic level of features or weak in reproducing realistic individual ship movements, especially in collision avoidance.

Notwithstanding the limitations of the existing simulation models, the desired model for maritime risk analysis should be a simulation model that combines both traffic level and details of individual ships, providing fully autonomous ship movements and human factors in the waterway by utilizing as many elements as possible. The validation of the simulation models would decrease latent uncertainties.

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