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REVIEW ARTICLE

A review of ship collision risk assessment, hotspot detection and path planning for maritime traffic control in restricted waters

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Abstract
The three research topics, ship collision risk assessment, ship traffic hotspot detection and prediction, and collision-avoidance based ship path planning, are vital for next-generation vessel traffic management and monitoring systems. The system development is closely related to big data analytics and artificial intelligence for restricted waters. This study, therefore, aims to analyse the state-of-the art of these three topics over the latest decade, identify research gaps, and shed light on future research avenues. To achieve these three objectives, we critically and systematically review related articles that were published during the period between 2011 and 2021. We believe that this comprehensive and critical literature review would have a significant and profound impact on the formal safety assessment and vessel traffic management, and monitoring studies because it is not only an extension but also an essential continuity work of the literature review on maritime waterway risk assessment and prediction, as well as ship path guidance for ship collision risk mitigation in accordance with current automation vessels development and modern intelligent port construction.

1. Introduction

The current vessel traffic management and monitoring systems developed for restricted/confined waters such as port waters, fairways and straits should be migrated to the intelligent systems with e-navigation function in the era of big data analytics and artificial intelligence. The maritime sectors and port authorities, as well as information technology companies, have already collaborated to develop next-generation vessel traffic management and monitoring systems.[1] Ship collision risk assessment, ship traffic hotspot detection and prediction, and collision-avoidance-based ship path planning are essential for such systems, as shown in Figure 1. This is because a collision between ships could result in severe consequences, especially in the restricted waters with a high ship traffic density. Ship collision risk identification and estimation are at the core of ship collision avoidance processing. For example, a ship with high collision risk is a warning signal for the ship to take action for collision avoidance

[1] https://www.mpa.gov.sg/web/portal/home/media-centre/news-releases/detail/f48f9c64-633a-4143-bec3-83f4c0315036

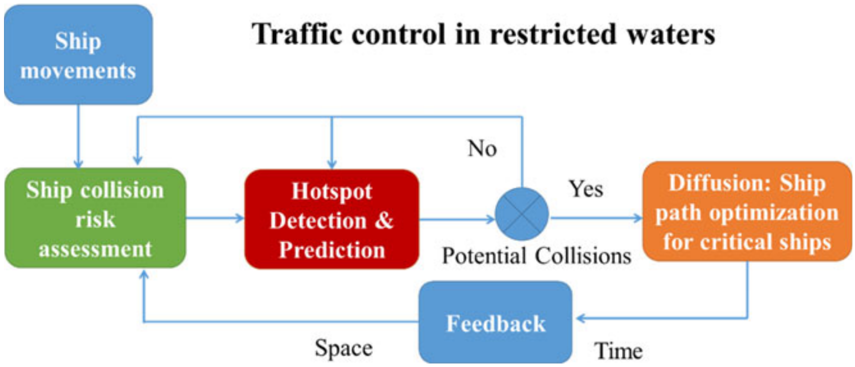

Figure 1. *Traffic control in restricted waters.*

by means of the navigation systems. A smart navigation system can forecast possible ship collision locations, times and collision hotspots, and it can also guide ship path optimisation to avoid a crash and support ship traffic management. The dynamic ship collision risk estimation should consider physical navigation conditions and crew behaviours associated with vessel manoeuvrability, velocity variation and course adjustment. Determination of a ship-collision-risk-averse navigation path for a critical ship is a complicated and essential task when multiple vessels turn in proximity to one another.

This study aims to review the relevant articles focusing on the three research topics for vessel traffic management and monitoring in restricted waters over the latest decade (2011–2021): (i) ship collision risk assessment, (ii) ship traffic hotspot detection and prediction, and (iii) collision-avoidance-based ship path planning. Ship collisions are frequent in confined waters and cause disastrous consequences. As for maritime safety authorities, the ship collision risk estimation for the encountered ships is essential to understand the current ship collision risk level, recognise the most dangerous individual ship, and evaluate the performance of ship collision risk mitigation and safety management. Historical ship travel data can be applied to determine the hierarchical geographical distribution for the vessel collision risk in restricted areas and to identify the high-ship-collision-risk places (same as precautionary areas). Nowadays, with the emergence of modern unmanned ships and ports, more attention is needed on the real-time ship movement-based ship collision risk hotspot prediction to further guide safe navigation in ports. With these advanced sensor and communication technologies, automatic vessels and intelligent ports are the trends for the near future. Therefore, collision-avoidance-based ship path planning for restricted waters is significant for assessing the effect of the trajectory adjustment actions that a critical ship takes for reducing the ship collision risk. Furthermore, it also can guide the automatic vessels sailing at the safest and most efficient path in confined waters. Therefore, this paper systematically analyses the models, formulation and approaches for ship collision risk assessment, ship traffic hotspot detection and prediction, and collision-avoidance-based ship path optimisation to better grasp the advantages of current research and their inter- and intra-categorical relationships, as well as to identify gaps and future effort directions. These findings will offer more insight to the related researchers and navigation industry.

2. Methods and materials

This study was conducted through the following steps: (1) define the research questions and objectives; (2) determine the eligibility criteria and data source; (3) perform the search strategy on relevant databases; (4) perform a data extraction process to screen relevant documents and (5) conduct analysis to answer the predefined questions and objectives.

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2.1. Data source

Scopus is one of the largest abstract and citation databases of peer-reviewed literature, covering both journal and conference articles. *Web of Science* (WoS) *SCI-EXPANDED* is also a commonly accepted database of abstracts and references from high-quality scientific papers (Van Nunen et al., 2018). Google Scholar is unsuitable for bibliometric analysis due to its publication without checking originality, quality and quantity (Ampah et al., 2021). Furthermore, Scopus and WoS are complementary (Kołakowski et al., 2022a, 2022b). We, therefore, merge the publications from both WoS and Scopus to minimise the limitation of potentially omitting significant papers by only using either of these two databases.

2.2. Eligibility criteria

The paper focuses on three research areas: (i) ship collision risk estimation, (ii) ship traffic hotspot detection and prediction, and (iii) collision-avoidance-based ship path planning in Scopus and WoS up to the year 2021. As the year 2022 was incomplete, publications indexed after December 31, 2021 in both databases are not included.

2.3. Search strategy

This paper uses keywords 'ship collision risk' or 'vessel collision risk' or 'collision risks of the vessel' or 'collision risk of ships' for searching the research on ship collision risk estimation, collects papers on the second research area based on keywords 'hotspots detection' and 'maritime' (or 'port' or 'waterway'), and employs the keywords 'ship path planning' or 'ship route planning' or 'ship trajectory planning' or 'path planning of vessel' or 'route planning of vessels' or 'trajectory planning of vessel' to search the research on collision-avoidance-based ship path planning.

2.4. Extraction process

After reading over the abstracts of these 150 articles including keywords associated with ship collision risk in Scopus, we identified 84 articles related to the first research area. However, there are only 14 papers on the second research area, and these mostly focus on historical data-driven hotspots analysis, so the real-time data motivated hotspots detection has rarely been considered. These findings indicate that the real-time data access, storage, processing and implementation are challenging tasks in maritime transportation. This could be a future avenue and is meaningful to identify critical ships and the implementation of ship path optimisation as the diffusion measures to mitigate the possibility of disastrous accidents.

For the third research area, we found 39 journal papers and 18 conference papers after refinement by careful inspection. Maritime navigation has gained increasingly more attention recently, as have vessel collision risk estimation and path optimisation. Ship traffic hotspot detection and prediction has attracted attention since 2010, which may be related to the access to massive historical data derived from an advanced navigation communication system, as shown in Table 1.

3. Major research focuses and developments on ship collision risk assessment

3.1. What is the ship collision of encounter ships sailing in restricted waters?

Ship collision is the physical impact that occurs in encounter ships leading to a damaging accident. The damage may go beyond that measured by a monetary cost. The development of huge and heavy ships with a large speed, in accordance with the increase in maritime traffic and technological advancements, will also increase the risk of such collision accidents. As for maritime safety authorities, the collision risk analysis for the encountered ships is essential to understand the current ship collision risk level, recognise the most dangerous individual ship, and evaluate the performance of ship collision risk

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Table 1. *Details for keyword strategy and extraction process.*

	Search strategy and extraction process
Database	Scopus and WoS
Timespan	Up to 2021, mainly focussed on 2011–2021
Document types	Articles, review papers and conferences papers in English language
Eligibility criteria	Only focus on these three areas: (i) ship collision risk estimation, (ii) ship traffic hotspot detection and prediction, and (iii) collision-avoidance based ship path planning
Paper search	*ship collision risk estimation*: keywords 'ship collision risk' or 'vessel collision risk' or 'collision risks of the vessel' or 'collision risk of ships' *ship traffic hotspot detection and prediction*: keywords 'hotspots detection' and 'maritime' (or 'port' or 'waterway') *collision-avoidance based ship path planning*: the keywords 'ship path planning' or 'ship route planning' or 'ship trajectory planning' or 'path planning of vessel' or 'route planning of vessels' or 'trajectory planning of vessel'
Validation methods	The front page and introduction, as well as expert validity methods
Total numbers of articles using for analysis	*ship collision risk estimation*: 84 *ship traffic hotspot detection and prediction*: 14 *collision-avoidance based ship path planning*: 57

mitigation and safety management. The ship collisions are associated to various encounter situations, as shown in Figure 2, where regions B, C and E are the crossover encounters, region A is the head-on encounter, and region D is the overtaking encounter. The various encounters can be identified based on the course of both ships. Ship collisions associated to various encounters will result in different consequences, for example, the damage to the ship hull in the head-on situation may be more serious than other types of encounters.

3.2. What is the consequence of the ship collision?

The potential consequences connected with collision accidents include social, economic and environmental influences, such as human injuries, fatalities, downtime, cargo damage, economic loss and oil spillage (Dong and Frangopol, 2015; Sotiralis et al., 2016; Christian and Kang, 2017; Luo and Shin, 2019; Zhang et al., 2019d). Also, there may be indirect impacts derived from ship collision accidents, for example, collision leading to an oil spill, the oil spill causing pollution in an aquaculture area and the polluted aquatic products subsequently affecting the health of humans. The real consequences are very hard to determine, and some of them use the simplified method to present the associated consequence, such as adopting the amount of oil spilt to represent the environmental consequences of tanker collisions (Pedersen, 1995), the total amount of energy loss (Asmara et al., 2014) or the damage penetration area of ships and repair costs (Dong and Frangopol, 2015), to characterise the potential consequence. Current consequence assessment is often based on the ship's structural response model (Ståhlberg et al., 2013) and qualitative methods with the linguistic state, such as the fuzzy model (Zaman et al., 2014) and

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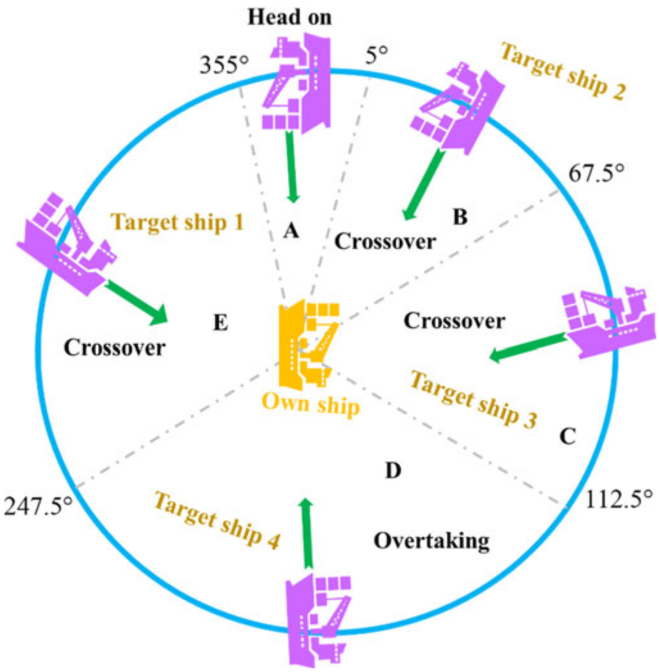

Figure 2. *Ship collisions connected with various encounters.*

Bayesian Belief Network (BBN) (Goerlandt et al., 2014). The ship structural response model is associated with the scenario where the collision leads to a breach of the hull, subsequent flooding occurs, which in turn causes ship loss (Ståhlberg et al., 2013), as well as another scenario where no significant hull damage occurs but the ship becomes disabled and drifts before subsequent obvious rolling, and finally to the ship capsizing. Qualitative analysis can identify the influence of ship collision on safety, environment and property, and can be further applied to the cost–benefit evaluation of control options in maritime transportation and be developed as a tool to assess the probability of accidents reduction associated with the mitigation measures. However, the qualitative methods often integrate linguistic terms and likelihood score or probability rank to figure out damage severity and occurrence possibility that may include the subjective view of the author and experts (Goerlandt et al., 2014; Zaman et al., 2014).

As declared by Kang et al. (2019), there is no way to access the full complete dataset that has the potential to determine the accident probability, and associated accident severity and fatality rate. Thus, the simulation methodology incorporating a huge amount of big empirical data is trying to provide convincing results through conducting several potential collision scenarios. The validity and applicability of the proposed methodology may be questioned. For example, the expected fatalities are almost 0·01 per collision according to COWI (2008), which is problematic in covering restricted navigation areas because of the high dynamics in waterways and operation conditions. The potential consequence analysis remains interesting and challenging, and there is great need of a combination of tangible quantitative and qualitative robust methodologies to obtain a more reliable assessment. There are epistemic and aleatory uncertainties in consequences assessment due to the inaccuracies in estimation and the natural randomness (Mei et al., 2019; McKay et al., 2000), see Figure 3.

3.3. How to define and evaluate the collision risk between encounter ships sailing in restricted waters

Current ship collision risk measurement can be grouped into ship safe boundary and ship collision risk level estimation, the synergetic ship collision risk function definition based on manoeuvrability parameters, and ship collision risk identification based on intelligent algorithms or systems.

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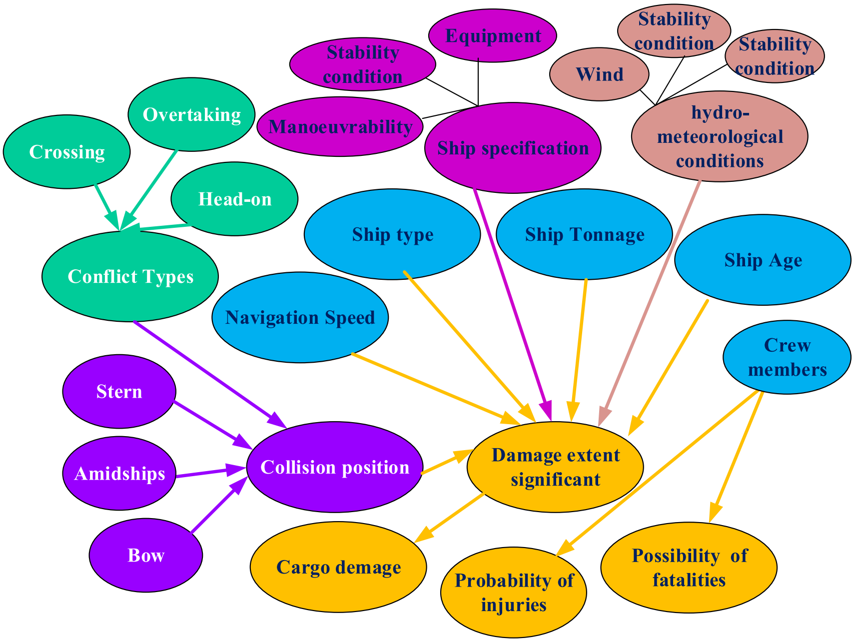

Figure 3. *Generic framework of potential consequences analysis.*

Newer approaches integrating the new technologies have been proposed since 2013, such as artificial intelligence (Mohamed-Seghir et al., 2021) and big data science (i.e. AIS) (Iphar et al., 2020).

Ship safe boundary can be grouped into collision diameter and ship domain model, and its research development is shown in Figure 4. The ship domain can be characterised into various types, such as circular, empirical, elliptical, fuzzy, projected, quaternion, probability, and seafarers' awareness-based types (Liu et al., 2016; Yu et al., 2019b; Zhang and Meng, 2019; Lee et al., 2021), and guides navigators to keep away from nearby vessels in a determined space. The shapes of different ship domains are illustrated in Figure 5. The classical Fujii, Goodwin and Davis ship domains are described by a circle, ellipse and fan-shape. The fuzzy ship domain can be defined as the degree of membership for an encounter situation to the fuzzy set of 'dangerous navigation' (Pietrzykowski, 2008). The quaternion ship domain comprises four elements, namely the longitudinal radius in aft and fore directions and the lateral radius in port and starboard directions (Wang, 2010). The projected ship domain is to predict the following violation according to the current navigation status, and the shape can be a circle or other shapes. The probabilistic ship domain with a series of contours can be defined as follows (Goerlandt and Kujala, 2014):

$$S_\alpha = \left\{(\mathrm{r}_{\min}(\theta) + \delta(\theta), \theta) | \int_0^{\delta(\theta)} f_{\Delta(\theta)}(\omega) d\omega \leq \alpha, 0 \leq \delta(\theta) \leq l(\theta) - r_{\min}(\theta), 0^\circ \leq \theta \leq 360^\circ \right\} \quad (1)$$

where α is the probability with $0 \leq \alpha \leq 1$, $l(\theta)$ is equal to 2 nautical miles, $f_{\Delta(\theta)}(\omega)$ is the probability density function and $\delta(\theta)$is the continuous random variable. Recently, a fuzzy quaternion ship domain was proposed for quantifying ship collision risk of inland ships near bridge-waters (Jinyu et al., 2021). Ship domain models can be used to detect collision candidates (Chen et al., 2017), such as using a minimum safety passing domain boundary (with ship collision risk equal to one) and an early warning ship domain (with ship collision risk equal to zero) to define the synergy ship domain (risk between zero and one) (Zhou et al., 2018) and applying the product of lateral and longitudinal ship collision risk (Ren et al., 2011), safety domain violation and overlap (Tam and Bucknall, 2010a; Qu et al., 2011; Teixeira and Guedes, 2018; Svanberg et al., 2019; Wang et al., 2020a) to define the spatial ship collision risk.

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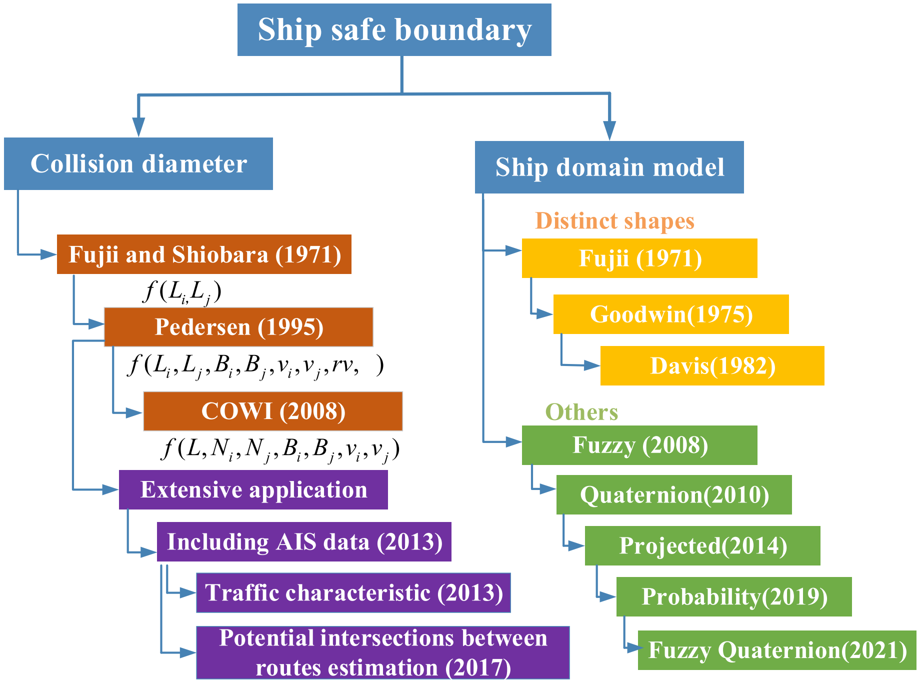

Figure 4. *Research development of ship safe boundary.*

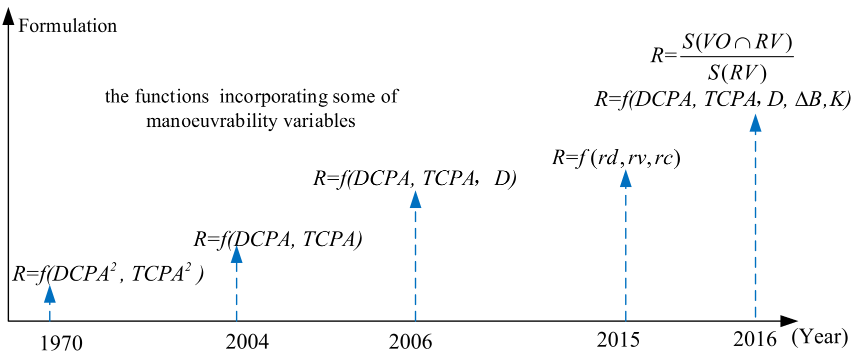

Figure 5. *Shapes of different ship domains.*

The ship domain model determined based on the big statistical data and AIS trajectory data depend on certain water areas with particular navigational situations and it is very difficult to isolate the influence of multiple parameters. The ship domain is highly connected with the expert knowledge, for example, the choice of surveyed crew, and leads to subjectivity. In terms of collision diameter, Li et al. (2012) conducted a detailed review for the research before 2012, and it is easy to see that a new model has rarely been proposed since 2013 but extensive applications have been performed (Weng et al., 2012; Silveira et al., 2013; Asmara et al., 2014), such as the traffic characteristics based on Pedersen's model (Silveira et al., 2013) or Kristiansen's method (Asmara et al., 2014) and integrating AIS data, as well as potential intersections between routes estimation (Christian and Kang, 2017).

The synergetic ship collision risk function definition integrating manoeuvrability variables can be applied to measure the vessel collision risk. The ship collision near-miss index (Kim and Jeong, 2016) is often calculated by the function incorporating some of the variables, including Distance (DCPA) and Time (TCPA) to the Closest Point of Approach, and course deviation, relative distance and azimuth

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between the own and target ships (Lisowski and Seghir, 1970; Szłapczyński and Śmierzchalski, 2009; Yang and Yang, 2013; Gang et al., 2016; Nguyen et al., 2018; Mohamed-Seghir et al., 2021). We also can use the Grey correlation formula to define the key collision avoidance ship (Liu and Liu, 2016) combining with the ship collision risk index estimation. The research trend of vessel collision risk estimation based on manoeuvrability variables is as shown in Figure 6. It is obvious that the researcher first only considers DCPA and TCPA, and more parameters are considered with the development of ship collisions risk estimation. The formula of ship collision risk index integrating primary variables and its development is described as follows. The ship collision risk calculation only including DCPA and TCPA first proposed by (Lisowski and Seghir, 1970) is as follows:

$$r = r_{\mathrm{RD}}\mathrm{DCPA}^2 + r_{\mathrm{RT}}\mathrm{TCPA}^2 \tag{2}$$

where r is the ship collision risk, and r_{RD} and r_{RT} are the subjective parameters dependent on the navigator. Then, the function for the ship collision risk calculation connected with DCPA, TCPA and D (distance between ships) is first performed using (Szlapczynski, 2006)

$$r = \left[a_1\left(\frac{\mathrm{DCPA}}{D_s}\right)^2 + a_2\left(\frac{\mathrm{TCPA}}{T_s}\right)^2 + a_3\left(\frac{D}{D_s}\right)^2\right]^{-1/2} \tag{3}$$

where D is the distance between encounter ships, D_s is the safe distance for approaching ships, T_s is the necessary time to manoeuvre collision avoidance successfully and a_1, a_2, a_3 are the coefficients of weights. The ship collision risk calculation based on DCPA, TCPA, D, θ_T and K can be formulated as follows (Gang et al., 2016):

$$r = (\omega_{\mathrm{DCPA}}, \omega_{\mathrm{TCPA}}, \omega_{D_R}, \omega_{\theta_T}, \omega_K)\begin{bmatrix}\mu_{\mathrm{DCPA}}\\ \mu_{\mathrm{TCPA}}\\ \mu_D\\ u_{\theta_T}\\ u_K\end{bmatrix} \tag{4}$$

where $\mu_{\mathrm{DCPA}}, \mu_{\mathrm{TCPA}}, \mu_D, u_{\theta_T}$ and u_K are the ship collision risk based on DCPA, TCPA, D, the direction of the target ship ϕ_T and the ratio of the speed of the target vessel and the own vessel K, respectively. Additionally, ω_{DCPA}, ω_{TCPA},ω_{D_R},ω_{θ_T} and ω_K are the corresponding weights. Some other models have been proposed by integrating other manoeuvrability parameters, such as by Huang et al. (2016) and Huang and van Gelder (2019), as well as Li et al. (2020) using the overlap of velocity obstacle VO and reachable velocity RV to define ship collision risk, and Zhang et al. (2015a) applied the function of relative speed, relative course and relative distance to characterise the near-miss ship collision risk. Fang et al. (2018a) integrated the location for the ship to start collision avoidance to calibrate the model of Zhang et al. (2015a) to reveal the regional ship collision risk inside ports. Recently, Yu et al. (2019b) proposed the direction-constrained space–time prism-driven approach that includes current ship movement characteristics and the subsequent manoeuvrability prediction for estimating potential multi-ship collision risks. It is obvious that there is increased development in ship collision risk analysis for obtaining more accurate results and providing them more intuitively to navigators. However, current existing models describe the linear and nonlinear relationship between factors and collision in a function that has various formulae and different considered variables. In addition, some ship collision risk estimation based on these parameters highly depends on the target ship, such as the encounter angle and distance to the target vessel.

Comprehensive consideration of ship safe boundary and manoeuvrability parameters can be achieved by potential collision risk definition based on manoeuvrability parameters and then using it to define the potential ship domain (Im and Luong, 2019) or using the ship domain (calculating the safety distance (Yang and Yang, 2013; Wang et al., 2017) and dangerous margin (Liu et al., 2019a)) to support

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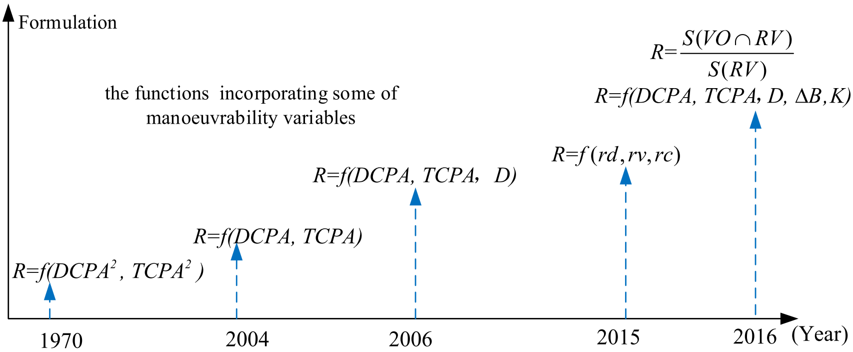

Figure 6. *Changes of functions of ship collision risk estimation based on manoeuvrability variables over time.*

collision risk value calculation. With the development of artificial intelligence technology, collision risk identification based on intelligent algorithms or systems is attracting increasingly more attention. For example, fuzzy logic inference (Bukhari et al., 2013; Chen et al., 2014), Dempster–Shafer (D-S) evidence theory (Li and Pang, 2013), improved BP neural network (Lin and Yuan, 2018), artificial neural network (Namgung et al., 2019) and artificial potential field can be used to obtain the collision risk in the open sea with multi-source observation data. These models make it more convenient to deal with ship collision risk estimation associated with multi-source big data. It needs further improvement to discriminate against the collision risk change derived from unstable state and near-collision situations to improve the efficiency of decision-making.

Quantitating ship collision risk estimation has gained more interest, while the real-time ship collision risk estimation incorporating dynamic navigation environment and uncertain human behaviours is still challenging. First, the current near-miss index does not consider the correlation between different parameters, ignores the effects of vessel type and size, weather, and hydrodynamic conditions, and even the dynamic characteristics of the target ship. Second, the majority of simulation analyses, from the aspect of own-to-one target or own-to-many targets with the assumption the target ship does not change its speed and course and neglect the loss of speed in the turning phase of the vessel (Szłapczyński and Śmierzchalski, 2009), maintain significant differences between real navigation. Third, navigational situations estimation considering different factors such as speed, course, manoeuvring capability and International Regulations for Preventing Collisions at Sea (COLREGS) rules may determine ship domains in various shapes and types, and cannot be modified dynamically in different water areas and adapt to complex traffic environment. Finally, most of the current research says that their ship collision risk estimation is suitable for both the open sea and restricted waters, but mostly implement experiments in the open sea with constant sailing speed for the target ship and assuming obstacles with a regular shape or with certain ship pair encounters, and only a few involved legs in the marine strait, restricted water areas and inside ports.

3.4. Ship collision risk assessment for restricted waters

Vessel traffic safety is one of the dominant concerns in restricted waters and has attracted much attention from the transportation, scientific and management domains. With the increase of high speed and larger ships and the continued construction of the offshore structure, the ship collisions would result in a catastrophic consequence. Thus, ship collision risk estimation, collision risk mitigation and collision prevention become significant in confined areas. Ship collision risk for restricted waters can be achieved through summarisation of the ship collision risk from all individual encounters, statistical analysis of historical collision accidents, and the product of geometrical near-miss collision avoidance frequency and causation probability, as shown in Table 2.

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Table 2. *Ship collision risk assessment for restricted waters.*

Category	Key topics	Methodology
Summary of the ship collision risk from all individual encounters	Collision risk modelling for individual encounter and then summarising the collision risk for all the encounter scenarios in the confined waters	Modelling: the closest point of approach driven methods (Zhang et al., 2015b; Li et al., 2019a; Yoo and Lee, 2019); the ship domain model (such as Fujii and Shiobara, 1971; Fujii and Tanaka, 1971; Goodwin, 1975; Davis et al., 1982; Śmierzchalski, 2005; Wang, 2012) combined with other measurable indicators (Hampel, 1985; Miyake et al., 2017); relative speed, relative course and relative distance-based method (Zhang et al., 2015a; Fang et al., 2018a); space-time prism-based method (Yu et al., 2019b), etc. Behaviour-directed simulation: Simulators (e.g. a fuzzy system or ontology-based semantic knowledge simulator) and simulation approaches (e.g. colony intelligence optimisation, etc.) (Li et al., 2014; Nguyen et al., 2018; Wang et al., 2018a; Tan et al., 2019)
Statistical analysis of historical collision accidents	Analysis collision frequency associated with risk factors (i.e. ship attributes and weather) (Arima et al., 2008; Zhang et al., 2014; Shinoda and Uru, 2016; Shinoda and Uryu, 2016)	Statistical analysis
Product of geometrical near-miss collision avoidance frequency and causation probability	Collision occurrence probability and the corresponding damage seriousness	Geometrical near-miss collision avoidance frequency: Pedersen's model (1995), speed dispersion, degree of acceleration and deceleration, and ship domain overlap (Qu et al., 2011) etc.; Probability estimation approaches: parametric (e.g. multinomial, mixed logic and molecular collision theory (Altan and Otay, 2018)) and non-parametric methods (e.g. Bayesian networks); Damage severity: Ordered Probit models, etc. (Qiu et al., 2010; Wang et al., 2016; Li et al., 2018; Wei, 2018; Zhang et al., 2019a)

The ship collision risk in restricted waters can be derived by summarising the ship collision risk from all individual encounters, for example, Fang et al. (2018a) first calculated the collision risk between individual encounter ships based on relative distance, relative speed and relative course, and then adopted the maximum, total and mean ship collision risk values for all the encounter ships to reveal the hierarchical spatiotemporal ship collision risk distribution in the port areas. Therefore, the methodologies in Section 2.3 can promote the accuracies and capabilities of ship collision risk estimation in restricted waters, and in turn, outcomes from research on ship collision risk assessment in restricted regions could also provide traffic characteristics and ship collision risk distributions to facilitate individual collision risk modelling (Chen et al., 2019b). These two perspective types of research mutually facilitate each other.

Statistics of historical ship collisions mostly are involved in detecting the causal factors on crash accidents in different confined waters. For instance, the amount of draft of the ships can easily lead to collision in confined waters. Also, the product of geometrical near-miss collision avoidance frequency and causation probability can be used to characterise the ship collision risk in waterways, such as speed dispersion, degree of acceleration and deceleration, and ship domain overlap (Qu et al., 2011), which can be used to evaluate the ship collision risk of waterways from the statistical perspective.

The research topic on ship collision risk estimation in restricted waters remains popular. Assessing the availability of collision risk definitions and modelling methodologies, as well as improving their applicability and efficiency in actual vessel collision probability estimation, is promising.

3.5. Causes of ship collisions

The causes of collision can be grouped into human elements, ship and equipment factors, environmental issues, and management factors (Wang et al., 2020b; Zhang et al., 2021). Human elements include navigation facilities misuse, fatigue and false diagnosis of the navigation situation at the perception stage; deficient consideration of hydrodynamic and weather conditions, ignorance of signals, unsuitable selection in route, and error assessment of collision risk at the decision-making phase; and incorrect ship operation, improper collision avoidance, delay action and excessive speed at the action stage. Ship and equipment factors comprise instrument failure, navigation aid system failure, uncoordinated communication system and improper display of electronic chart. Environmental issues include heavy traffic, poor visibility, serious weather and a bad channel environment (Liu et al., 2021). Management factors consist of inappropriate regulation, improper shifting of duty, incomplete navigation information, inadequate training experience and lack of certification (Montewka et al., 2014a).

Most of the current research using the accident report to support the collision cause analysis through a back-propagation neural network (Wang et al., 2020b), the event tree (Montewka et al., 2014b), Bayesian analysis (Qu et al., 2012; Wu et al., 2020) and text mining (Shi et al., 2019). The event tree methods follow Boolean logic that cannot reveal the reality of events with more than two states that limit the practicability in systematic ship collision risk estimation and management. Bayesian analysis allows inference in both directions, which means the back-propagation of collision probabilities can be used in the ship collision risk assessment phase and can determine the most important nodes and point out the valid way to improve the results of the model through multi-scenario thinking. Test mining is the emerging new technology with the development of artificial intelligence and machine learning, which facilitates information extraction from the text material.

These methods have provided effective tools to analyse collision causation probability, as shown by the generic framework in Figure 7. It can be applied to analyse the causal factors of ship collisions and their characteristics, which can act as the reference for regional maritime safety management. However, there are still some upcoming issues that need to be dealt with in future research. For example, Wang et al. (2020b) said that delay action and incorrect collision estimation are more likely to cause accidents compared to other reasons. Shi et al. (2019) hold the opinion that lack of enough rest and inappropriate lookout and pilotage are the primary causes, followed by error collision risk estimation. Such findings indicate that collision causation analysis may be highly relevant to the data included,

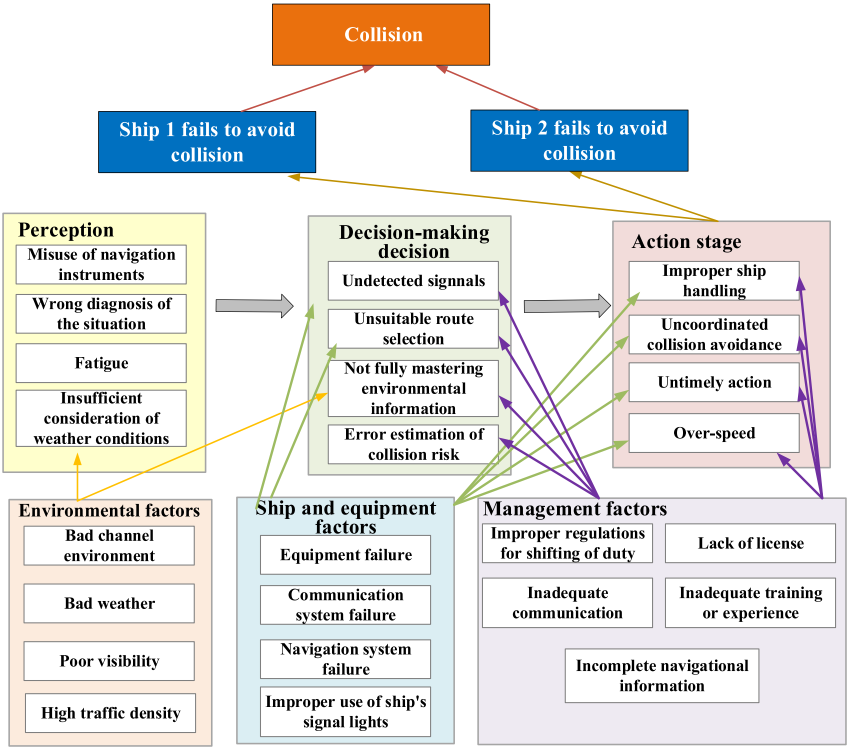

Figure 7. *A generic framework for causation probability analysis.*

estimation methods and chosen research areas, and even cause contradictory conclusions. Improving the accuracy and adaptability of collision risk causes analysis is essential in the maritime transportation industry. Spatiotemporal factors including navigation strategy, ship manoeuvrability, traffic features, and dynamic environment corresponding to real collisions and truly reflecting the dangerous conditions ship encountered are useful to determine more precise ship collision risk value and implement suitable mitigation strategies.

3.6. Research gaps and future research directions

Owing to the development of more intelligent vessels, the increasing dangerous cargo transportation and increasing volume of maritime traffic, collision risk estimation and traffic management are the valid measures and practical solutions to reduce ship collision risk. Ship collision risk modelling and prediction considering spatiotemporal movements of multiple vessels have barely been approached to date. There are frequent and risky multi-ship encounters in restricted waters. In such scenarios, a series of interactions among multiple encountered ships make collision risk estimation more complicated. For instance, a ship can simultaneously act as a give-way or stand-on ship. The simplified ship-pair circumstances for multi-ship encounters can be enhanced to image practical scenarios by considering continuous interactions of the ships' navigation. Ship collision risk estimation and prediction is therefore advanced when the vessels' behaviour for collision avoidance is taken into account and the quantitative models considering various complex situations are essential to optimise the ship collision risk modelling.

Most of the current research estimate the collision from the perspective of encounter ships. However, determining the whole spatially differential real-time ship collision risk for all the approaching ships is more important for the vessel traffic service management centre. This challenging task is involved in the interaction of encountering ships, mitigation measures the give-way ships take, traffic network

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and regulations, as well as the real-time efficiency of ship collision risk estimation. Allocating ship collision risk factors to specific contributory conditions is affected by the perception of navigators and environmental conditions, especially for more critical, confined and hostile conditions with high traffic density, narrow channels, and wind, rain and fog (Wennink, 1992). Even though there are certain unsolved issues in ship collision risk estimation, it is believable that the new ideas and research are derived from the old ones. The development of a good and reliable method and system to deal with ship collision risk analysis and prediction to provide a true ship collision risk level for maritime operators is a potential topic for the future, especially with the increasing attention associated with the occurrence of serious accidents, and the emergence of huge vessels and increasing carriage of dangerous products.

4. Major research focuses and developments on ship traffic hotspot detection and prediction

4.1. What are the ship traffic hotspots in restricted waters?

Ship traffic hotspots are the locations or areas with the highest collision probabilities or highly frequent vessel conflicts, rather than the regions with a large amount of traffic. The importance of regional maritime risk has attracted increasingly more attention in multiple ship collision risk estimation and potential conflict hotspots predictions. The detection of high-ship-collision-risk areas (named as hotspots) can help maritime transportation authorities to plan key monitoring regions to ensure safe movement for a huge number of ships.

Historical ship travel data can be applied to figure out the hierarchical geographical distribution for the vessel collision risk in restricted areas to identify the high-ship-collision-risk places (same as precautionary areas). Real-time ship movement data can be employed to predict the following hotspots that are efficient for maritime transportation managers to diffuse the critical ships to cut down high-ship-collision-risk areas. The spatial-temporal ship collision risk maps highlighting changing hotspots provide guidance and bases for the deployment of control actions and implementation of counterpart strategies as parts of disastrous accident prevention and management.

4.2. What is hotspot detection based on historical data analysis?

Historical data-driven high-ship-collision-risk area analysis assumes the locations with the highest collision probabilities (Christian and Kang, 2017; Fang et al., 2018a) and areas detected with high regional Vessel Collision Risk Operators (Zhang et al., 2019a; Luong et al., 2021), as well as regions experiencing highly frequent vessel conflicts between different vessels (Wu et al., 2016; Rong et al., 2021) termed as ship collision risk hotspots. The methodologies to detect ship collision risk hotspots from historical data comprise the density complexity (Meng et al., 2014; Zhang et al., 2019a), traffic fundamental diagram (Kang et al., 2018b), spatial clustering method (Liu et al., 2019b; Zhen et al., 2021), a tangible analytical approach (Zhang et al., 2019c), etc. These findings can be useful to the operators and managers in maritime traffic surveillance and management to maintain a better understanding of the high-ship-collision-risk area distribution and develop corresponding strategies to enhance navigational safety. These methods can work well for the proposed specific case studies, however, whether they are practical for other research areas is unknown. Because of the diversity of historical data sources, the proposed approach may show inconsistency and lose its advantages in different types of data and exhibit inaccuracy by the bias derived from sample selection. However, the ship collision risk hotspots are static, which may have some contradictions with spatial-temporal changeable traffic patterns along the complex waters.

4.3. What is the real-time ship movement-based collision risk hotspot prediction?

Nowadays, with the emergence of modern automatic vessels and ports, more attention is paid to the real-time ship movement-based collision risk hotspot prediction to further guide safe navigation in ports. The real-time ship movement-based collision risk hotspot prediction works on how to detect the following potential ship collision risk hotpots according to a huge number of real-time ship movements. Recently, the framework combining a spatial clustering process (DBSCAN) and a multi-ship collision risk index model has been proposed to rank vessel collision risk in nearly real-time, and automatically identify high collision risk vessels on the west coast of Sweden (Zhen et al., 2017). Also, a fuzzy inference system considering spatial traffic patterns and near collision situations illustrates that the density-based spatial clustering and the long short-term memory method can be adopted to make timely optimal decisions in vessel traffic service (Namgung and Kim, 2021). However, it is neglected that the ships close to the boundaries of clusters may also be risky to the ships inside nearby clusters and have not considered the traffic regulation, maneuverer behaviour and complex encounter situation inside the ports. Furthermore, the diffusion strategy in maritime transport based on the detected ship collision risk hotspots is hard to be implemented in the current research.

4.4. Research gaps and future research directions

Once the important confined shipping water areas are blocked by traffic congestion or an accident, it will bring serious costs for the maritime logistics industry. To ensure the safety and operational efficiency of significant ports in maritime transportation, deep insight into the real-time traffic situation and hotspots prediction is indispensable. The AIS can automatically provide the sailing speed, navigating course, dynamic location and other static messages, and then transmit this information to the nearby base stations with the time interval of several seconds to three minutes (Yu et al., 2021b), which can support fundamental traffic diagram study, real-time hotspots detection, predict congestion and potential collision, and further aid strategies implementation to improve maritime traffic conditions (Fang et al., 2018b; Yu et al., 2019c).

The real-time ship collision risk hotspot detection and prediction should incorporate various information associated with the surrounding environment and navigation situation that provides advice about the needed collision avoidance and path adjustment to reduce collision accidents. How to incorporate the historical hotspots analysis results in effective real-time traffic management will be interesting and attractive. Furthermore, robust technology enables us to predict the locations of ships in advance with high time resolution necessary for real-time prediction. The advanced data collection methods and machine learning technologies not only guarantee the efficiency and reliability of shipping traffic information, but also lead to real-time precisely capturing ship activities and analysing traffic character. Finally, it will be interesting to investigate the optimisation of the ship path and port operation strategy to mitigate the potential following collision hotspots for efficiency and safety purposes.

5. Major research focuses and developments on collision-avoidance-based ship path planning

5.1. What is collision-avoidance-based ship path planning in restricted waters?

In the era of big data science and artificial intelligence, e-navigation, the unmanned ship and the semi-automatic ship have become increasingly more popular under the advanced technologies. Therefore, collision-avoidance-based ship path planning for restricted waters is significant for assessing the effect of the trajectory adjustment actions that a critical ship takes for reducing the ship collision risks. Furthermore, it also can guide the automatic vessels sailing at the safest and most efficient path in confined waters.

Generally, safety acts as the priority in path optimisation, and other aspects such as the economy and fuel efficiency have a lower priority (Tam and Bucknall, 2010b). Path planning is to calculate the optimal path connected with the predetermined start and end waypoints that should avoid a collision with obstructions, complying with traffic rules, considering changeable environments, accounting for collision avoidance behaviours and improve the efficiency as much as possible, as well as successfully provide near real-time solutions to ensure the applicability (Ni et al., 2018). An appropriate ship path

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cannot only reduce uncoordinated human operation related accidents by providing navigators with sailing recommendations, but can also enhance the efficiency of traveling through saving fuel consumption and optimising sailing time (Xie et al., 2019).

5.2. What are the significant differences between the static and dynamic collision-avoidance-based ship path planning problems?

The dynamic collision-avoidance-based ship path planning problems are much more complicated than only considering a stable obstruction because moving vessels may need maneuverer adjustments and strategy changes for collision avoidance. Another reason is that dynamic collision-avoidance-based ship path planning not only needs to be optimised from a global perspective through introducing all the accessible environmental information, but also local adjustment according to the dynamic obstacles. These reasons indicate that increasing the efficiency of solving a more complicated path problem is needed to support a real-time optimal navigation strategy when dynamic collision-avoidance is considered.

The static collision-avoidance-based ship path planning problems ensure the avoidance of a collision with any stable obstacles, such as an island, buoys, shallows, rocks and fishing nets. It can be solved by the traditional algorithms including a spatial structural model, approaches based on raster grids, the line-of-sight method and the potential field approach, as well as artificial intelligence-based algorithms and simulations such as particle swarm, evolutionary, neural networks and fuzzy logic, as stated by Yan et al. (2009), Tsou and Hsueh (2010), Szłapczyński (2012), Chen et al. (2016), Kolendo and Śmierzchalski (2016), Deng et al. (2017), Hinostroza et al. (2017), Witkowska et al. (2017), Zhou et al. (2017), Wang et al. (2018b) and Tang et al. (2019).

The dynamic collision-avoidance-based ship path planning problems comprehensively consider the applicability and safety of the ship's path through introducing the changeable encounter scenarios and changeable environment and adapting to waterways and navigation conditions (Li-Jia and Li-Wen, 2012; Kang et al., 2018a; Yu et al., 2021a). The dynamic collision-avoidance-based ship path planning problems are hard to solve by the traditional methods, and are always in need of the artificial intelligence-based algorithm and simulation-driven approaches.

In addition, some path planning problems considering both static and dynamic collision-avoidance are more complex and complicated, and will require a long computation time to obtain useful and reliable results (Smierzchalski, 2000; Xue et al., 2011; Mei and Arshad, 2015; Kuczkowski and Śmierzchalski, 2017; Lazarowska, 2017; Lyu and Yin, 2017). The recently proposed solving methods such as the multi-behaviour fusion-based potential field method and the new deterministic approach are targeting these problems. The optimal path determination for a vessel in the complex dynamic scenario remains challenging. How the optimisation path for critical ships reversely affects the ship collision risk for encounter ships has rarely been considered in the current research.

5.3. What is the model formalisation for ship path planning?

Path planning in different circumstances can be reduced to the optimisation task with static and dynamic constraints through considering the available manoeuvring region with the determined boundary derived from obstacles and the surrounding moving ships. The area-based static obstructions such as shallow regions and shorelines can be represented as polygons or convex hulls (Smierzchalski, 1999a) and then the ship collision risk is checked through the intersections with the polygon. The moving ships can be represented as the ship domain shape or the occupied grids or circles (Lyu and Yin, 2019).

In common, the optimisation model should be formulated with the explicit optimisation model with decision variable, objective and constraints for ship movement to support the selection of appropriate approaches to solve these formulated models and further satisfy the purposes of enhancing the automation, improving efficiency, aiding the navigation mission planning and on-board revision to avoid a collision, as well as reduce the ship collision risk (Tam and Bucknall, 2013). However, as shown in

Table 3, current research simply describes trajectory planning as the determination of a set of waypoints that enable ships to avoid a collision with each other, as well as away from the static obstacles, while keeping the smallest potential deviation from the given path (Lazarowska, 2015b). The safety objective can be represented as the turning and speed of the vessel, and the economic objective is associated with the distance of navigation. The navigation areas can be discretised into grids and the trajectory planning is to pick up the optimal adjacent cells by moving the occupying cell in the left, right, up and down directions (Zhu et al., 2013). These approaches are implemented from spatial perspectives and will ignore the dynamic movement characteristics of ships, as well as be easily affected by the size of grids.

Usually, the movement environment can be represented as the discrete configuration space that comprises a lot of nodes, such as the initial and end positions, as well as other waypoints. The static obstructions (i.e. land) and other surrounding ships occupied nodes are unavailable for the own ship path. Therefore, the general model for ship path optimisation to avoid a collision with static and moving obstacles and comply with COLREGS for normal encounter situations is illustrated in Table 4. The full implementation of the reactive ship path planning that not only considers the COLREGS and manoeuvrability characteristics but also an emergency is challenging. Ship navigation is a very complicated system and hard to be described through an accurate simple mathematical model. Even though the mathematical model has been proposed, the feasibility and applicability are not easy to ensure.

5.4. What methods have been proposed for ship path planning?

There are several methods to solve the path optimisation in the current research that can be categorised as the deterministic, heuristic and hybrid methods. The deterministic methods, including ordinary differential equations (Soltan et al., 2011), the trajectory-based method (Lazarowska, 2016, 2017), the policy gradient based deterministic path planning (Xu et al., 2019) and the artificial potential field method (Mei and Arshad, 2015; Lazarowska, 2018; Fu et al., 2019; Lyu and Yin, 2019), use a set of defined rigorous steps to make the feasible solutions converge to the optimal one, and has the advantage of the repeatability of solutions for every run with the same input in the same amount of calculation time due to its deterministic nature. The deterministic methods can obtain a smooth trajectory planning with regular shape obstacles (Soltan et al., 2011) or dynamic regular obstacles with constant velocity (Lazarowska, 2018; Fu et al., 2019; Lyu and Yin, 2019; Mei et al., 2019), sort all candidate trajectories according to the fitness function to obtain the optimal path (Lazarowska, 2016, 2017) and make the ship behaviour continuous (Xu et al., 2019). However, they hypothesised ship movement parameters that are unchangeable and will be time-consuming with the fine-grained candidate trajectories definition, as well as being problematic when it is applied in a complex navigation environment with irregular moving obstacles due to resulting in a trap area with unreachable near obstacles.

The heuristic methods use the guidance information (i.e. collective behaviour and membership function) to narrow the whole search space to the subset one and obtain the optimal solution that meets the design requirements quickly for the complex situation. The heuristic approaches include artificial intelligence algorithms (i.e. neural network (Mohamed-Seghir, 2016; Mohamed-Seghir et al., 2021), evolutionary algorithm (Szlapczynski and Szlapczynska, 2012; Li et al., 2019b; Zhang et al., 2019b; Mohamed-Seghir et al., 2021), A*algorithm (Xie et al., 2019), the particle swarm optimisation (Yujie et al., 2018)) and their respective characteristics, as shown in Table 5. Most of the heuristic methods can be applied to solve multi-objective optimisation and maintain parallelism and scalability, but they may have low efficiency, slow convergence, long search time and stagnation that lead to a sub-optimal solution (Xu et al., 2021). The optimal solution may be the suboptimal path, and the optimal trajectory may consist of multiple course changes that are not compliant with a real evasive manoeuvre and common practice. It attracts increasingly more attention to how the final result derived from the heuristic methods can be reproduced and applied on-board a ship (Lazarowska, 2015a; Candeloro et al., 2017).

The hybrid methods and super-hybrid to some extent can improve the accuracy of the current trajectory planning by introducing other mature technology or heuristics information, as shown in Table 6. The

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Table 3. Exemplified formulae for the objective of path optimisation.

Objective	Formula
The course deviation of adjacent genes must be smaller than $\pi/3$(Ni et al., 2018)	$\varphi_i \rightarrow \begin{cases} \pi/12 < \lvert\varphi_i\rvert > \pi/12 \\ \lvert\lvert(\varphi_{i+1}+\varphi_1)\rvert - \lvert(\varphi_i+\varphi_1)\rvert\rvert \\ \le \pi/3(i=2,3,\ldots,N) \end{cases}$ φ_i the course of gene i
Smierzchalski (1999a, 1999b) proposed the evolutionary algorithm to solve the trajectory planning model that assumed the speed of ships is constant	$Total\_Cost(S) = Safe\_Cost(\mathrm{S}) + Econ\_Cost(S)$ $Safe\_Cost(\mathrm{S}) = w_c \cdot clear(S)$ $Econ\_Cost(S) = w_d \cdot dist(S) + w_s \cdot smooth(S) + w_t \cdot time(S)$ where w_c, w_d, w_s and w_t are the coefficients of weights, $clear(S)$ is the largest difference between the safe distance and the distance to the closest turning point. Here, $dist(S)$, $smooth(S)$ and $time(S)$ are respectively the total length, maximum turning and time
Tsou et al. (2010) structured the shortest route considering collision avoidance	Distance = $\min_{i=1}^{n}\{Ds_i + Dr_i\}$ $Ds_i = f^3(X_1)V_O$ $Dr_i = f^3(X_2)V_O$ where Ds_i and Dr_i are the distance after collision avoidance and navigational restoration distance. Here, min $f^3(X_1)$and min $f^3(X_2)$ are the turning angle after collision avoidance and of navigational restoration
Tam and Bucknall (2013) formulated the ship path model	$collision\_risk_{ij}$: $= \exists \mathrm{t}, p_i(t) - p_j(t)\rvert\rvert \le d_{safe}, t \in [t_{\min}, t_{\max}]$ $d_{safe} := f(\mathrm{dw}_i,\mathrm{dw}_j,\mathrm{min_safe_distance})$$t_{\min}$ (the start time), $t_{\max}$(the duration of the simulation), d_{safe} the minimum allowable distance and dw_i (the weights)
The navigation path optimisation based on the evolution algorithm (Tam and Bucknall, 2010b)	$\Phi_{p,i} = \cup_{s=1}^{\tau_{p,i}} \phi_{p,i,s}$ where $\phi_{p,i,s}$ is the waypoint along $\Phi_{p,i}$,$s \in [1, \tau_{p,i}]$ is the index
The ship path associated with the coordinates and heading based on the Q-learning algorithm (Chen et al., 2019a)	$[(x_1, y_1, \psi_1), (x_2, y_2, \psi_2), \cdots, (x_n, y_n, \psi_n)]$; $L = \sqrt{(x - x_{goal})^2 + (y - y_{goal})^2}$ where x,y and $\psi$are respectively the x-coordinate, y-coordinate and heading. Here, L represents how the path close to the goal, and the reward for each step equal to $r = 1 - -0 \cdot 003 \times L$
The optimality criterion for the shortest path (Lazarowska, 2015b)	$\min[I = \sum_{\mathrm{i}=1}^{N-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}]$
The security and economic objectives (Li et al., 2019b)	$F_{\mathrm{safe}} = \ln\left(\frac{1}{1 - \max_{i=1,2,3}(r_i)}\right)$, $F_{economy} = \sum_i \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$ where i represents the sailing time and (x_i, y_i) is the coordinates of the ship at the time i. Here, r_i indicates the ship collision risk

Table 4. *Objective and constraints for general path optimisation.*

General model for ship path optimisation
Objective: minimising safety cost and minimising economic cost Constraints. 1. The ship trajectories should originate from the start points 2. The ship trajectory should direct at destination points 3. The distance between the ship and obstacles should larger than the critical distance at the closest point of approach 4. The navigation space occupied by static and moving obstacles is not available for the travelling ship 5. The successive small course or speed changes are not allowed 6. The sailing speed should be located at a set of permissive speed 7. There is no sharp course change that indicates course changes should be located between 15 and 60 degrees 8. The depth of water should larger than the draft and squat of ships

hybrid methods include nonlinear programming (gradient descent + the genetic algorithm (Ni et al., 2017), tangent graph (represent obstacles) + the swarm optimisation algorithm (Shen et al., 2019), A* (global path planning) + artificial potential field (complete obstacle avoidance) (Yu et al., 2019a) and discrete artificial potential field (a collision-free path) + optimisation algorithm (achieve the optimal path). The super-hybrid methods include genetic algorithm + particle swarm optimisation (Zhao et al., 2021), dynamic optimal control + particle swarm acceleration calculation (Wang et al., 2021), dynamic programming + behaviour learning (Yu et al., 2021a) and artificial neural network + particle swarm optimisation (Yu et al., 2021b). Usually, the mixed algorithms show wonderful ability in avoiding a collision with obstacles, reducing distance cost, accomplishing path optimisation in unknown complex scenarios and reducing the sailing time. However, they do not consider the ship manoeuvrability and feedback mechanism among the multiple interacting ships with more complicated collision avoidance actions and emergency actions when the give-way ship cannot change course and speed successfully. Furthermore, the implementation of ship path planning may be computation consuming. For example, the searching space will increase exponentially with the fine-grained definition of environment and the frequent course changes of the give-way ships.

The acceptable solution derived from every scenario in the complex environment considering the uncertainty of both environment and ship behaviour within the low computation time is necessary for the application in the on-board collision avoidance decision-making system in Figure 8.

5.5. Research gaps and future research directions

The current research proves the ability in solving the ship path planning considering both static and dynamic obstacles and simplified marine traffic rules and dynamic characteristics of vessels (Kaminski and Smierzchalski, 2001; Lu et al., 2018). There are still some unsolved challenges as stated as follows. The proposed research only considers some of the criteria and rarely cover all of them, including safe distance, traveling time, sailing speed, turn rate, collision avoidance manoeuvre and changeable environment. The currently proposed methods primarily consider smoothness, distance and accessibility of the ship path but easily ignore the dynamic characteristics such as the interaction of the motion for encounter ships. It is problematic in the application of guiding ship navigation in the implementation of the region of a traffic separation scheme, execution of coastal fishing as well as other activities.

The external environmental factors, including weather conditions, hydrodynamics and visibility, are usually be neglected in path optimisation. The uncoordinated actions of the give-way ship and the effect of wind and currents are potentially involved in a collision. The robustness of the proposed path

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Table 5. *Characteristics of heuristic methods.*

Methods	Characteristics	Advantages	Deficiency
Neural network	Inputs: minimum distance to obstacles, the speed of moving objects, the boundary and location of obstacles; Outputs: steering angle, deceleration, and acceleration to control moving ships (Mohamed-Seghir, 2016)	Local trajectory planning in a dynamically changing environment (Mohamed-Seghir, 2016; Xie et al., 2019)	Black-box relationship between the input and output layers; easy to be affected by the number of inputs and layers and included training data
Evolutionary algorithm	Evolves gradually according to the objective function until finding a satisfactory solution (Szlapczynski and Szlapczynska, 2012; Li et al., 2019b; Zhang et al., 2019b)	Appropriate for the open sea ship path planning with one destination	Cannot be applied to scenarios with multiple destinations
A* algorithm	A grid-based method (Xie et al., 2019)	Using the distance from the starting point to the current grid, and the predicted following cost to the destination to obtain the optimal trajectory	The larger grid and the less neighbourhood sacrifice the performance of the trajectory
Fuzzy logic model	Constructs the relationship between environment and ship trajectory planning	Using 'IF-THEN' rules explained with fuzzy indicators	Case-sensitive means parameters should be adjusted carefully to characterise the specific scenario
Particle swarm algorithm	Global path optimisation	Based on the collective behaviour of diverse populations and the guidance of velocity adjustment	May be problematic in convergence and trapped into local optima (Yujie et al., 2018)

Table 6. *Characteristics of hybrid methods.*

Hybrid methods	Advantages	Deficiency
Nonlinear programming (gradient descent) + the genetic algorithm (Ni et al., 2017)	Reduces the course deviation; enhances practicality and consistency of the solution obtained by a genetic algorithm	Simulation-based on the simplified encounter situation
Tangent graph (represent obstacles) + the swarm optimisation algorithm (Shen et al., 2019)	Increases the precision and convergence speed	The tangent map cannot model a complex environment
A* (global path planning) + artificial potential field (complete obstacle avoidance) (Yu et al., 2019a)	Reduces the path distance and solving time	The computation time fast-growing with the size of the map grid
Discrete artificial potential field (a collision-free path) + optimisation algorithm (achieve the optimal path) (Lazarowska, 2020)	Enhances efficiency	Ignorance of the course change of the target ship and speed changes of encounter ships; the collision-free results may have obvious effects on the final optimal path; the comparison with non-combination results is missing

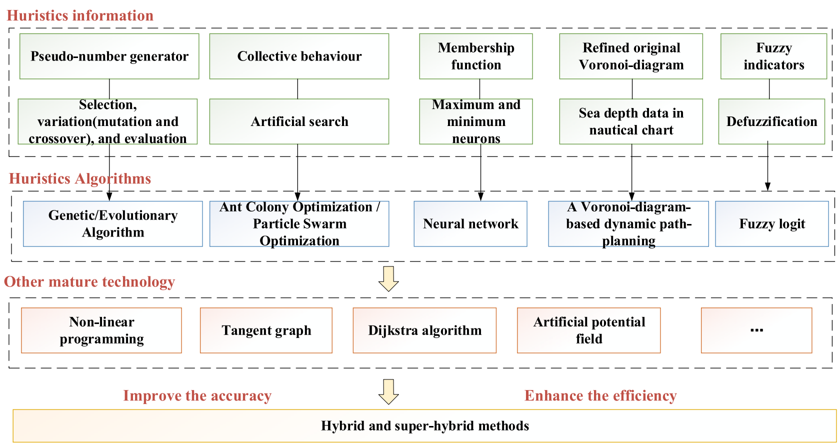

Figure 8. *Heuristics and hybrid methods.*

planning in uncertain sailing strategies and environmental disturbance needs to be further confirmed. It is impossible to get the complete prior information, which indicates the pre-generated approach and reactive method should be combined to take advantage of the advanced accessible information to generate path prior and also can adjust in accordance with the unidentified surrounding information. Recent tendencies are simultaneous quantitative assessment of the ship collision risk, fuel consumption, sailing time, waiting time as well as the anti-collision manoeuvres in reducing the ship collision risk.

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6. Conclusions

With the increasing demand for maritime transportation, collisions are the major accidents when ships are navigating in the maritime industry. Once collisions happen, serious economic loss, environmental pollution and even fatality are probable. Particularly for the ships including liquefied petroleum gas (LPG) and liquefied natural gas (LNG), as well as an oil tanker, nuclear ship and chemical tanker, collisions will result in a serious ecological disaster and environmental pollution. As for the authority of restricted waters, they need to gain accurate ship collision risks and provide information on collision risk hotspots, as well as identify critical ships to adjust the path to mitigate the occurrence of an accident.

This study has reviewed the literature on ship collision risk assessment, ship traffic hotspot detection and prediction, and collision-avoidance-based ship path optimisation for restricted waters. Based on this review, the current ship collision risk models can support quantitating collision risk assessment and prediction, while the real-time collision risk estimation incorporating a dynamic navigation environment and uncertain human behaviours is still challenging. The real-time ship movement-based collision risk hotspot prediction has barely been approached to date, which could be an essential future avenue and be meaningful for identifying critical ships and the implementation of ship path optimisation as the diffusion measures to mitigate the possibility of disastrous accidents. The deterministic, heuristic and hybrid methods can solve the static and dynamic collision-avoidance-based ship path planning problems; however, the robustness of the proposed path planning both models and solving the approaches in uncertain sailing strategies and environmental disturbance need to be further confirmed.

The completion of the whole process, including real-time collision risk estimation, risk hotspots detection, collision-avoidance-based path optimisation and critical vessel diffusion, is the key avenue for filling up the current research gap. This requires designing a solid and efficient ship collision risk estimation method to identify critical vessels and predict upcoming hotspots and figure out collision-avoidance-based path optimisation for the critical vessel to finish diffusion, which is meaningful for port authorities to monitor massive vessel movements in busy waters and implementation of counterpart actions to avoid significant accidents. Even though this is a challenging research topic in maritime transportation, it will be helpful to learn from the comprehensive methodologies and technologies from urban transportation.

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References

Altan, Y. C. and Otay, E. N. (2018). Spatial mapping of encounter probability in congested waterways using AIS. *Ocean Engineering*, **164**, 263–271.

Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C. and Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. *Journal of Cleaner Production*, **320**, 128871.

Arima, T., Harada, S., Rahim, A. M. and Uraguchi, Y. (2008). Trial application of FE simulation on ships collision within the risk assessment on oil spills from oil tankers. *ClassNK Technical Bulletin*, **26**, 29–34.

Asmara, I. P. S., Kobayashi, E., Artana, K. B., Masroeri, A. A. and Wakabayashi, N. (2014). Simulation-Based Estimation of Collision Risk During Ship Maneuvering in Two-Lane Canal Using Mathematical Maneuvering Group Model and Automatic Identification System Data. In *International Conference on Offshore Mechanics and Arctic Engineering*, Vol. **45424.** American Society of Mechanical Engineers, V04AT02A055.

Bukhari, A. C., Tusseyeva, I. and Kim, Y. G. (2013). An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system. *Expert Systems with Applications*, **40**(4), 1220–1230.

Candeloro, M., Lekkas, A. M. and Sørensen, A. J. (2017). A Voronoi-diagram-based dynamic path-planning system for underactuated marine vessels. *Control Engineering Practice*, **61**, 41–54.

Chen, S., Ahmad, R., Lee, B. G. and Kim, D. (2014). Composition ship collision risk based on fuzzy theory. *Journal of Central South University*, **21**(11), 4296–4302.

https://doi.org/10.1017/S0373463322000650 Published online by Cambridge University Press

Chen, L., Negenborn, R. R. and Lodewijks, G. (2016). Path Planning for Autonomous Inland Vessels Using A* BG. In *International Conference on Computational Logistics*. Cham: Springer, 65–79.

Chen, P., Mou, J. and van Gelder, P. H. A. J. M. (2017). Risk assessment methods for ship collision in estuarine waters using AIS and historical accident data. *Maritime Transportation and Harvesting of Sea Resources*, 213–221.

Chen, C., Chen, X. Q., Ma, F., Zeng, X. J. and Wang, J. (2019a). A knowledge-free path planning approach for smart ships based on reinforcement learning. *Ocean Engineering*, **189**, 106299.

Chen, P., Huang, Y., Mou, J. and van Gelder, P. H. A. J. M. (2019b). Probabilistic risk analysis for ship-ship collision: state-of-the-art. *Safety Science*, **117**, 108–122.

Christian, R. and Kang, H. G. (2017). Probabilistic risk assessment on maritime spent nuclear fuel transportation (part II: ship collision probability). *Reliability Engineering & System Safety*, **164**, 136–149.

COWI, A. (2008). Risk Analysis of Sea Traffic in the Area around Bornholm. Kongens Lyngby, Denmark: COWI AS. Report# P-65775-002.

Davis, P. V., Dove, M. J. and Stockel, C. T. (1982). A computer simulation of multi-ship encounters. *The Journal of Navigation*, **35**(2), 347–352.

Deng, W., Gan, L., Zhou, C., Zheng, Y., Liu, M. and Zhang, L. (2017). Study on Path Planning of Ship Collision Avoidance in Restricted Water Based on AFS Algorithm. In *The 27th International Ocean and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

Dong, Y. and Frangopol, D. M. (2015). Probabilistic ship collision risk and sustainability assessment considering risk attitudes. *Structural Safety*, **53**, 75–84.

Fang, Z., Yu, H., Ke, R., Shaw, S. L. and Peng, G. (2018a). Automatic identification system-based approach for assessing the near-miss collision risk dynamics of ships in ports. *IEEE Transactions on Intelligent Transportation Systems*, **20**(2), 534–543.

Fang, Z., Yu, H., Lu, F., Feng, M. and Huang, M. (2018b). Maritime network dynamics before and after international events. *Journal of Geographical Sciences*, **28**(7), 937–956.

Fu, M. Y., Wang, S. S. and Wang, Y. H. (2019). Multi-behavior fusion based potential field method for path planning of unmanned surface vessel. *China Ocean Engineering*, **33**(5), 583–592.

Fujii, Y. and Shiobara, R. (1971). The analysis of traffic accidents. *The Journal of Navigation*, **24**(4), 534–543.

Fujii, Y. and Tanaka, K. (1971). Traffic capacity. *The Journal of Navigation*, **24**(4), 543–552.

Gang, L., Wang, Y., Sun, Y., Zhou, L. and Zhang, M. (2016). Estimation of vessel collision risk index based on support vector machine. *Advances in Mechanical Engineering*, **8**(11), 1687814016671250.

Goerlandt, F. and Kujala, P. (2014). On the reliability and validity of ship–ship collision risk analysis in light of different perspectives on risk. *Safety Science*, **62**, 348–365.

Goerlandt, F., Montewka, J. and Kujala, P. (2014). Tools for an Extended Risk Assessment for RoPax Ship-Ship Collision. In *Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management*, 2292–2302.

Goodwin, E. M. (1975). A statistical study of ship domains. *The Journal of Navigation*, **28**(3), 328–344.

Hampel, B. (1985). The minimum manoeuvering range as a criterion to evaluate the risk of collision between ships. In: Heller, M. R. (ed.). *Maritime Simulation*. Berlin, Heidelberg: Springer, 242–253.

Hinostroza, M. A., Xu, H. T. and Guedes Soares, C. (2017). Path-planning and path following control system for autonomous surface vessel. *Maritime Transportation and Harvesting of Sea Resources*, 991–998.

Huang, Y. and Van Gelder, P. H. A. J. M. (2019). Measuring ship collision risk in a dense traffic environment. *TransNav, International Journal on Marine Navigation and Safety od Sea Transportation*, **13**(4), 737–744.

Huang, Y., Van Gelder, P. H. A. J. M. and Mendel, M. B. (2016). Imminent Ships Collision Risk Assessment Based on Velocity Obstacle. In *ESREL*, 693–700.

Im, N. and Luong, T. N. (2019). Potential risk ship domain as a danger criterion for real-time ship collision risk evaluation. *Ocean Engineering*, **194**, 106610.

Iphar, C., Napoli, A. and Ray, C. (2020). An expert-based method for the risk assessment of anomalous maritime transportation data. *Applied Ocean Research*, **104**, 102337.

Jinyu, L., Lei, L., Xiumin, C., Wei, H., Xinglong, L. and Cong, L. (2021). Automatic identification system data-driven model for analysis of ship domain near bridge-waters. *The Journal of Navigation*, **74**(6), 1–22.

Kaminski, R. and Smierzchalski, R. (2001). An evolutionary method of ship's anti-collision trajectory planning: new experiments. *WIT Transactions on The Built Environment*, **53**, 125–132.

Kang, Y. T., Chen, W. J., Zhu, D. Q., Wang, J. H. and Xie, Q. M. (2018a). Collision avoidance path planning for ships by particle swarm optimization. *Journal of Marine Science and Technology*, **26**(6), 777–786.

Kang, L., Meng, Q. and Liu, Q. (2018b). Fundamental diagram of ship traffic in the Singapore strait. *Ocean Engineering*, **147**, 340–354.

Kang, L., Lu, Z., Meng, Q., Gao, S. and Wang, F. (2019). Maritime simulator based determination of minimum DCPA and TCPA in head-on ship-to-ship collision avoidance in confined waters. *Transportmetrica A: Transport Science*, **15**(2), 1124–1144.

Kim, K. I. and Jeong, J. S. (2016). Visualization of Ship Collision Risk Based on Near-Miss Accidents. In *2016 Joint 8th International Conference on Soft Computing and Intelligent Systems (SCIS) and 17th International Symposium on Advanced Intelligent Systems (ISIS)*. IEEE, 323–327

Kołakowski, P., Ampah, J. D., Wróbel, K., Yusuf, A. A., Gil, M., Afrane, S., Jin, C., and Liu, H. (2022a). Alternative fuels in shipping: discussion on the findings of two recently published, independent bibliometric studies. *Journal of Cleaner Production*, **338**, 130651.

Kołakowski, P., Gil, M., Wróbel, K. and Ho, Y. S. (2022b). State of play in technology and legal framework of alternative marine fuels and renewable energy systems: a bibliometric analysis. *Maritime Policy & Management*, **49**(2), 236–260.

Kolendo, P. and Śmierzchalski, R. (2016). Experimental comparison of straight lines and polynomial interpolation modeling methods in ship evolutionary trajectory planning problem. In: Kacprzyk, J. (ed.). *Advanced and Intelligent Computations in Diagnosis and Control*. Cham: Springer, 331–340.

Kuczkowski, Ł and Śmierzchalski, R. (2017). Path Planning Algorithm for Ship Collisions Avoidance in Environment with Changing Strategy of Dynamic Obstacles. In *Polish Control Conference*. Cham: Springer, 641–650.

Lazarowska, A. (2015a). Parameters Influence on the Performance of an Ant Algorithm for Safe Ship Trajectory Planning. In *2015 IEEE 2nd International Conference on Cybernetics (CYBCONF)*. IEEE, 140–145.

Lazarowska, A. (2015b). Ship's trajectory planning for collision avoidance at sea based on ant colony optimisation. *The Journal of Navigation*, **68**(2), 291–307.

Lazarowska, A. (2016). A trajectory base method for ship's safe path planning. *Procedia Computer Science*, **96**, 1022–1031.

Lazarowska, A. (2017). A new deterministic approach in a decision support system for ship's trajectory planning. *Expert Systems with Applications*, **71**, 469–478.

Lazarowska, A. (2018). A new Potential Field Inspired Path Planning Algorithm for Ships. In *2018 23rd International Conference on Methods & Models in Automation & Robotics (MMAR)*. IEEE, 166–170.

Lazarowska, A. (2020). A discrete artificial potential field for ship trajectory planning. *The Journal of Navigation*, **73**(1), 233–251.

Lee, H. J., Furukawa, Y. and Park, D. J. (2021). Seafarers' awareness-based domain modelling in restricted areas. *The Journal of Navigation*, **74**(5), 1172–1188.

Li-Jia, C. and Li-Wen, H. (2012). Ship collision avoidance path planning by PSO based on maneuvering equation. In: Zhang, Y. (ed.). *Future Wireless Networks and Information Systems*, Berlin, Heidelberg: Springer, 675–682.

Li, B. and Pang, F. W. (2013). An approach of vessel collision risk assessment based on the D–S evidence theory. *Ocean Engineering*, **74**, 16–21.

Li, S., Meng, Q. and Qu, X. (2012). An overview of maritime waterway quantitative risk assessment models. *Risk Analysis: An International Journal*, **32**(3), 496–512.

Li, W., Ma, W., Yang, J., Shi, G. and Desrosiers, R. (2014). The Assessment of Risk of Collision Between two Ships Avoiding Collision by Altering Course. In *International Conference on Algorithms and Architectures for Parallel Processing*. Cham: Springer, 507–515.

Li, Y., Guo, Z., Yang, J., Fang, H. and Hu, Y. (2018). Prediction of ship collision risk based on CART. *IET Intelligent Transport Systems*, **12**(10), 1345–1350.

Li, S., Liu, J., Wang, X., Guan, H. and Yan, Q. (2019a). Optimizing the Anti-Collision Decisions Between Multiple Ships Based on Predictive Risk Evaluations. In *2019 5th International Conference on Transportation Information and Safety (ICTIS)*. IEEE, 1395–1399.

Li, J., Wang, H., Zhao, W. and Xue, Y. (2019b). Ship's trajectory planning based on improved multiobjective algorithm for collision avoidance. *Journal of Advanced Transportation*, **2019**, 1–12.

Li, J., Wang, H., Guan, Z. and Pan, C. (2020). Distributed multi-objective algorithm for preventing multi-ship collisions at sea. *The Journal of Navigation*, **73**(5), 971–990.

Lin, X. and Yuan, Y. (2018). Algorithm of Ship Collision Risk Based on Improved BP Neural Network. In *2018 IEEE International Conference on Mechatronics and Automation (ICMA)*. IEEE, 57–61.

Lisowski, J. and Seghir, M. M. (1970). The safe ship control with minimum risk of collision. *WIT Transactions on Ecology and the Environment*, **31**, 125–134.

Liu, H. and Liu, S. (2016). Application of grey relational decision-making on determination of ship collision risk degree. *Revista Tecnica De La Facultad De Ingenieria Universidad Del Zulia.*, **39**(3), 359–365.

Liu, J., Zhou, F., Li, Z., Wang, M. and Liu, R. W. (2016). Dynamic ship domain models for capacity analysis of restricted water channels. *The Journal of Navigation*, **69**(3), 481–503.

Liu, Z., Wu, Z. and Zheng, Z. (2019a). A cooperative game approach for assessing the collision risk in multi-vessel encountering. *Ocean Engineering*, **187**, 106175.

Liu, Z., Wu, Z. and Zheng, Z. (2019b). A novel framework for regional collision risk identification based on AIS data. *Applied Ocean Research*, **89**, 261–272.

Liu, K., Yu, Q., Yuan, Z., Yang, Z. and Shu, Y. (2021). A systematic analysis for maritime accidents causation in Chinese coastal waters using machine learning approaches. *Ocean & Coastal Management*, **213**, 105859.

Lu, Z., Kang, L., Gao, S. and Meng, Q. (2018). Determination of minimum distance to obstacle avoidance in the Singapore strait. *Transportation Research Record*, **2672**(11), 73–80.

Luo, M. and Shin, S. H. (2019). Half-century research developments in maritime accidents: future directions. *Accident Analysis & Prevention*, **123**, 448–460.

Luong, T. N., Hwang, S. and Im, N. (2021). Harbour traffic hazard map for real-time assessing waterway risk using marine traffic hazard index. *Ocean Engineering*, **239**, 109884.

https://doi.org/10.1017/S0373463322000650 Published online by Cambridge University Press

Lyu, H. and Yin, Y. (2017). Ship's Trajectory Planning for Collision Avoidance at sea Based on Modified Artificial Potential Field. In *2017 2nd International Conference on Robotics and Automation Engineering (ICRAE)*. IEEE, 351–357.

Lyu, H. and Yin, Y. (2019). COLREGS-constrained real-time path planning for autonomous ships using modified artificial potential fields. *The Journal of Navigation*, **72**(3), 588–608.

McKay, M. D., Beckman, R. J. and Conover, W. J. (2000). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, **42**(1), 55–61.

Mei, J. H. and Arshad, M. R. (2015). A hybrid artificial potential field method for autonomous surface vessel path planning in dynamic riverine environment. *Indian Journal of Geo-Marine Sciences*, **44**(12), 1980–1994.

Mei, J. H., Arshad, M. R. and Tang, J. R. (2019). Collision risk assessment based artificial potential field approach for multi-ships avoidance. *Indian Journal of Geo-Marine Sciences*, **48**(7), 1037–1047.

Meng, Q., Weng, J. and Li, S. (2014). Analysis with automatic identification system data of vessel traffic characteristics in the Singapore strait. *Transportation Research Record*, **2426**(1), 33–43.

Miyake, R., Fukuto, J. and Hasegawa, K. (2017). Evaluation Method of Collision Risk Based on Actual Ship Behaviours Extracted From AIS Data. In *Marine Navigation* CRC Press, 161–166.

Mohamed-Seghir, M. (2016). Computational Intelligence Method for Ship Trajectory Planning. In *2016 21st International Conference on Methods and Models in Automation and Robotics (MMAR)*. IEEE, 636–640.

Mohamed-Seghir, M., Kula, K. and Kouzou, A. (2021). Artificial intelligence-based methods for decision support to avoid collisions at Sea. *Electronics*, **10**(19), 2360.

Montewka, J., Goerlandt, F., Innes-Jones, G., Owen, D., Hifi, Y. and Porthin, M. (2014a). Quantifying the Effect of Noise, Vibration and Motion on Human Performance in Ship Collision and Grounding Risk Assessment. In *PSAM 12th Probabilistic Safety Assessment and Management Conference*.

Montewka, J., Ehlers, S., Goerlandt, F., Hinz, T., Tabri, K. and Kujala, P. (2014b). A framework for risk assessment for maritime transportation systems—a case study for open sea collisions involving RoPax vessels. *Reliability Engineering & System Safety*, **124**, 142–157.

Namgung, H. and Kim, J. S. (2021). Regional collision risk prediction system at a collision area considering spatial pattern. *Journal of Marine Science and Engineering*, **9**(12), 1365.

Namgung, H., Jeong, J. S., Kim, J. S. and Kim, K. I. (2019). Inference model of collision risk Index based on artificial neural network using ship near-collision data. *In Journal of Physics: Conference Series*, **1357**(1), 012044. IOP Publishing.

Nguyen, M., Zhang, S. and Wang, X. (2018). A novel method for risk assessment and simulation of collision avoidance for vessels based on AIS. *Algorithms*, **11**(12), 204.

Ni, S., Liu, Z., Cai, Y. and Wang, X. (2017). A Nonlinearity-Based Genetic Algorithm for Ship Path Planning. In *2017 29th Chinese Control And Decision Conference (CCDC)*. IEEE, 1743–1748.

Ni, S., Liu, Z., Cai, Y. and Wang, X. (2018). Modelling of ship's trajectory planning in collision situations by hybrid genetic algorithm. *Polish Maritime Research*, **25**(3), 14–25.

Pedersen, P. T. (1995). Collision and grounding mechanics. *Proceedings of WEMT*, **95**(1995), 125–157.

Pietrzykowski, Z. (2008). Ship's fuzzy domain–a criterion for navigational safety in narrow fairways. *The Journal of Navigation*, **61**(3), 499–514.

Qiu, Y., Chen, W., Wang, W. and Zhang, G. (2010). A Model for Assessment Collision Risk Degree of Ships in Sight of Another. In *ICCTP 2010: Integrated Transportation Systems: Green, Intelligent, Reliable*, 867–874.

Qu, X., Meng, Q. and Suyi, L. (2011). Ship collision risk assessment for the Singapore strait. *Accident Analysis & Prevention*, **43**(6), 2030–2036.

Qu, X., Meng, Q. and Li, S. (2012). Analyses and implications of accidents in Singapore strait. *Transportation Research Record*, **2273**(1), 106–111.

Ren, Y., Mou, J., Yan, Q. and Zhang, F. (2011). Study on Assessing Dynamic Risk of Ship Collision. In *ICTIS 2011: Multimodal Approach to Sustained Transportation System Development: Information, Technology, Implementation*, 2751–2757.

Rong, H., Teixeira, A. P. and Soares, C. G. (2021). Spatial correlation analysis of near ship collision hotspots with local maritime traffic characteristics. *Reliability Engineering & System Safety*, **209**, 107463.

Shen, Y., Wang, F., Zhao, P., Tong, X., Huang, J., Chen, K. and Zhang, H. (2019). Ship Route Planning Based on Particle Swarm Optimization. In *2019 34rd Youth Academic Annual Conference of Chinese Association of Automation (YAC)*. IEEE, 211–215.

Shi, S., Zhang, D., Su, Y., Zhang, M., Sun, M. and Yao, H. (2019). Risk Factors Analysis Modeling for Ship Collision Accident in Inland River Based on Text Mining. In *2019 5th International Conference on Transportation Information and Safety (ICTIS)*. IEEE, 602–607.

Shinoda, T. and Uru, K. (2016). Establishment of Risk Assessment Model for Ship Collision Using Applied Bayesian Network-Collision Accidents Between Fishing Vessels and Cargo Vessels. In *2015 SNAME Maritime Convention, SMC 2015*. Society of Naval Architects and Marine Engineers, 207–217.

Shinoda, T. and Uryu, K. (2016). Risk Assessment Model for Ship Collisions in Consideration of Human Factors. In *RINA, Royal Institution of Naval Architects-International Conference on Human Factors 2016*. Royal Institution of Naval Architects.

Silveira, P. A. M., Teixeira, A. P. and Soares, C. G. (2013). Use of AIS data to characterise marine traffic patterns and ship collision risk off the coast of Portugal. *The Journal of Navigation*, **66**(6), 879.

Smierzchalski, R. (1999a). An Intelligent Method of Ship's Trajectory Planning at sea. In *Proceedings 199 IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems (Cat. No. 99TH8383)*. IEEE, 907–912.

Smierzchalski, R. (1999b). Evolutionary trajectory planning of ships in navigation traffic areas. *Journal of Marine Science and Technology*, **4**(1), 1–6.

Smierzchalski, R. (2000). Ships' domains as a collision risk at sea in the evolutionary trajectory planning. *WIT Transactions on Ecology and the Environment*, **45**, 43–52.

Śmierzchalski, R. (2005). Ships' Domains as Collision Risk at sea in the Evolutionary Method of Trajectory Planning. In *Information Processing and Security Systems*. Boston, MA: Springer, 411–422.

Soltan, R. A., Ashrafiuon, H. and Muske, K. R. (2011). ODE-based obstacle avoidance and trajectory planning for unmanned surface vessels. *Robotica*, **29**(5), 691–703.

Sotiralis, P., Ventikos, N. P., Hamann, R., Golyshev, P. and Teixeira, A. P. (2016). Incorporation of human factors into ship collision risk models focusing on human centred design aspects. *Reliability Engineering & System Safety*, **156**, 210–227.

Ståhlberg, K., Goerlandt, F., Ehlers, S. and Kujala, P. (2013). Impact scenario models for probabilistic risk-based design for ship–ship collision. *Marine Structures*, **33**, 238–264.

Svanberg, M., Santén, V., Hörteborn, A., Holm, H. and Finnsgård, C. (2019). AIS in maritime research. *Marine Policy*, **106**, 103520.

Szlapczynski, R. (2006). A unified measure of collision risk derived from the concept of a ship domain. *The Journal of Navigation*, **59**(3), 477.

Szłapczyński, R. (2012). Evolutionary approach to ship's trajectory planning within traffic separation schemes. *Polish Maritime Research*, **19**, 11–20.

Szłapczyński, R. and Śmierzchalski, R. (2009). Supporting navigator's decisions by visualizing ship collision risk. *Polish Maritime Research*, **16**(1), 83–88.

Szlapczynski, R. and Szlapczynska, J. (2012). On evolutionary computing in multi-ship trajectory planning. *Applied Intelligence*, **37**(2), 155–174.

Tam, C. and Bucknall, R. (2010a). Collision risk assessment for ships. *Journal of Marine Science and Technology*, **15**(3), 257–270.

Tam, C. and Bucknall, R. (2010b). Path-planning algorithm for ships in close-range encounters. *Journal of Marine Science and Technology*, **15**(4), 395–407.

Tam, C. and Bucknall, R. (2013). Cooperative path planning algorithm for marine surface vessels. *Ocean Engineering*, **57**, 25–33.

Tan, X., Tao, J. and Konovessis, D. (2019). Preliminary design of a tanker ship in the context of collision-induced environmental-risk-based ship design. *Ocean Engineering*, **181**, 185–197.

Tang, K., Yang, Y., Zhao, M., Li, M. and Hao, Z. (2019). Cooperative Trajectory Planning and Trajectory Tracking Control for Multiple Surface Vessels System. In *2019 Chinese Control Conference (CCC)*. IEEE, 6100–6105.

Teixeira, A. P. and Guedes Soares, C. (2018). Risk of Maritime Traffic in Coastal Waters. In *International Conference on Offshore Mechanics and Arctic Engineering*, Vol. **51326**. American Society of Mechanical Engineers, p. V11AT12A025

Tsou, M. C. and Hsueh, C. K. (2010). The study of ship collision avoidance route planning by ant colony algorithm. *Journal of Marine Science and Technology*, **18**(5), 746–756.

Tsou, M. C., Kao, S. L. and Su, C. M. (2010). Decision support from genetic algorithms for ship collision avoidance route planning and alerts. *The Journal of Navigation*, **63**(1), 167–182.

Van Nunen, K., Li, J., Reniers, G. and Ponnet, K. (2018). Bibliometric analysis of safety culture research. *Safety Science*, **108**, 248–258.

Wang, N. (2010). An intelligent spatial collision risk based on the quaternion ship domain. *Journal of Navigation*, **63**(4), 733–749.

Wang, N. (2012). Intelligent quaternion ship domains for spatial collision risk assessment. *Journal of Ship Research*, **56**(3), 170–182.

Wang, Y., Huang, L. and Fan, Y. (2016). Research on Inland Ship Collision Risk Entropy Model-Based-Complex System. In *The 26th International Ocean and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

Wang, T., Yan, X., Wang, Y. and Wu, Q. (2017). A Distributed Model Predictive Control Using Virtual Field Force for Multi-Ship Collision Avoidance Under COLREGS. In *2017 4th International Conference on Transportation Information and Safety (*ICTIS*)*. IEEE, pp. 296–305.

Wang, Y., Huang, L., Xiong, X., Wang, M., Yuan, H. and Wang, L. (2018a). Collision Risk Prediction and Quantification Method for Multi-Ship Encountered Situation with Multi-Factors in Inland Water. In *The 28th International Ocean and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

Wang, C., Zhang, X., Li, R. and Dong, P. (2018b). Path Planning of Maritime Autonomous Surface Ships in Unknown Environment with Reinforcement Learning. In *International Conference on Cognitive Systems and Signal Processing*. Singapore: Springer, 127–137.

Wang, N., Chang, D., Yuan, J., Shi, X. and Bai, X. (2020a). How to maintain the safety level with the increasing capacity of the fairway: a case study of the Yangtze estuary deepwater channel. *Ocean Engineering*, **216**, 108122.

Wang, Y. F., Wang, L. T., Jiang, J. C., Wang, J. and Yang, Z. L. (2020b). Modelling ship collision risk based on the statistical analysis of historical data: a case study in Hong Kong waters. *Ocean Engineering*, **197**, 106869.

Wang, X., Feng, K., Wang, G. and Wang, Q. (2021). Local path optimization method for unmanned ship based on particle swarm acceleration calculation and dynamic optimal control. *Applied Ocean Research*, **110**, 102588.

Wei, X. (2018). Risk assessment model of vessel collision based on fuzzy decision. *Journal of Coastal Research*, **83**, 916–920.

Weng, J., Meng, Q. and Qu, X. (2012). Vessel collision frequency estimation in the Singapore strait. *The Journal of Navigation*, **65**(2), 207–221.

Wennink, C. J. (1992). Collision and grounding risk analysis for ships navigating in confined waters. *The Journal of Navigation*, **45**(1), 80–90.

Witkowska, A., Śmierzchalski, R. and Wilczyński, P. (2017). Trajectory Planning for Service Ship During Emergency STS Transfer Operation. In *Polish Control Conference*. Cham, Springer, 514–523.

Wu, X., Mehta, A. L., Zaloom, V. A. and Craig, B. N. (2016). Analysis of waterway transportation in southeast Texas waterway based on AIS data. *Ocean Engineering*, **121**, 196–209.

Wu, B., Yip, T. L., Yan, X. and Mao, Z. (2020). A mutual information-based Bayesian network model for consequence estimation of navigational accidents in the Yangtze river. *The Journal of Navigation*, **73**(3), 559–580.

Xie, L., Xue, S., Zhang, J., Zhang, M., Tian, W. and Haugen, S. (2019). A path planning approach based on multi-direction A* algorithm for ships navigating within wind farm waters. *Ocean Engineering*, **184**, 311–322.

Xu, H., Wang, N., Zhao, H. and Zheng, Z. (2019). Deep reinforcement learning-based path planning of underactuated surface vessels. *Cyber-Physical Systems*, **5**(1), 1–17.

Xu, L., Chen, N., Chen, Z., Zhang, C. and Yu, H. (2021). Spatiotemporal forecasting in earth system science: methods, uncertainties, predictability and future directions. *Earth-Science Reviews*. **222**, 103828.

Xue, Y. Z., Han, D. F. and Tong, S. Y. (2011). Automatic trajectory planning and collision avoidance of ships in confined waterways. *Sustainable Maritime Transportation and Exploitation of Sea Resources*, **167**, 167–172.

Yan, F., Zhao, L., Pan, M. and Inaishi, M. (2009). A Path Planning Algorithm for Autonomous Ship Agents. In *International Conference on Transportation Engineering 2009*. 1402–1407.

Yang, G. and Yang, Z. (2013). Research of Computing the Vessels' Collision Risk Index by Multiple Parameters Based on Neural Network with Genetic Algorithm. In *2013 Third International Conference on Instrumentation, Measurement, Computer, Communication and Control*. IEEE, 712–714.

Yoo, Y. and Lee, J. S. (2019). Evaluation of ship collision risk assessments using environmental stress and collision risk models. *Ocean Engineering*, **191**, 106527.

Yu, J., Deng, W., Zhao, Z., Wang, X., Xu, J., Wang, L., ... and Shen, Z. (2019a). A hybrid path planning method for an unmanned cruise ship in water quality sampling. *IEEE Access*, **7**, 87127–87140.

Yu, H., Fang, Z., Murray, A. T. and Peng, G. (2019b). A direction-constrained space-time prism-based approach for quantifying possible multi-ship collision risks. *IEEE Transactions on Intelligent Transportation Systems*, **22**(1), 131–141.

Yu, H., Fang, Z., Lu, F., Murray, A. T., Zhang, H., Peng, P., ... and Chen, J. (2019c). Impact of oil price fluctuations on tanker maritime network structure and traffic flow changes. *Applied Energy*, **237**, 390–403.

Yu, H., Murray, A. T., Fang, Z., Liu, J., Peng, G., Solgi, M. and Zhang, W. (2021a). Ship Path Optimization That Accounts for Geographical Traffic Characteristics to Increase Maritime Port Safety. IEEE *Transactions on Intelligent Transportation Systems*, 1–12.

Yu, H., Fang, Z., Fu, X., Liu, J. and Chen, J. (2021b). Literature review on emission control-based ship voyage optimization. *Transportation Research Part D: Transport and Environment*, **93**, 102768.

Yujie, L., Yu, P., Yixin, S., Huajun, Z., Danhong, Z. and Yong, S. (2018) Ship Path Planning Based on Improved Particle Swarm Optimization. In *2018 Chinese Automation Congress (*CAC*)*. IEEE, 226–230.

Zaman, M. B., Kobayashi, E., Wakabayashi, N., Khanfir, S., Pitana, T. and Maimun, A. (2014). Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca strait: based on AIS data. *Journal of Simulation*, **8**(1), 91–104.

Zhang, L. and Meng, Q. (2019). Probabilistic ship domain with applications to ship collision risk assessment. *Ocean Engineering*, **186**, 106130.

Zhang, W., Montewka, J. and Goerlandt, F. (2014). Semi-qualitative method for ship collision risk assessment. In: Mlynczak, M. and Nowakowski, T. (eds.). *Safety and Reliability: Methodology and Applications*. UK: CRC Press, 1599–1608.

Zhang, W., Goerlandt, F., Montewka, J. and Kujala, P. (2015a). A method for detecting possible near miss ship collisions from AIS data. *Ocean Engineering*, **107**, 60–69.

Zhang, L., Wang, H. and Meng, Q. (2015b). Big data–based estimation for ship safety distance distribution in port waters. *Transportation Research Record*, **2479**(1), 16–24.

Zhang, W., Feng, X., Qi, Y., Shu, F., Zhang, Y. and Wang, Y. (2019a). Towards a model of regional vessel near-miss collision risk assessment for open waters based on AIS data. *The Journal of Navigation*, **72**(6), 1449–1468.

Zhang, Q., Li, C., Lu, X. and Huang, S. (2019b). Research on Complete Coverage Path Planning for Unmanned Surface Vessel. In *IOP Conference Series: Earth and Environmental Science*, Vol. **300**(2). IOP Publishing, 022037.

Zhang, L., Meng, Q. and Fwa, T. F. (2019c). Big AIS data based spatial-temporal analyses of ship traffic in Singapore port waters. *Transportation Research Part E: Logistics and Transportation Review*, **129**, 287–304.

Zhang, L., Wang, H., Meng, Q. and Xie, H. (2019d). Ship accident consequences and contributing factors analyses using ship accident investigation reports. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, **233**(1), 35–47.

Zhang, J., He, A., Fan, C., Yan, X. and Soares, C. G. (2021). Quantitative analysis on risk influencing factors in the Jiangsu segment of the Yangtze river. *Risk Analysis*, **41**(9), 1560–1578.

Zhao, W., Wang, Y., Zhang, Z. and Wang, H. (2021). Multicriteria ship route planning method based on improved particle swarm optimization–genetic algorithm. *Journal of Marine Science and Engineering*, **9**(4), 357.

Zhen, R., Riveiro, M. and Jin, Y. (2017). A novel analytic framework of real-time multi-vessel collision risk assessment for maritime traffic surveillance. *Ocean Engineering*, **145**, 492–501.

Zhen, R., Shi, Z., Shao, Z. and Liu, J. (2021). A novel regional collision risk assessment method considering aggregation density under multi-ship encounter situations. *The Journal of Navigation*, **75**(1), 1–19.

Zhou, H., Zhao, D. and Guo, X. (2017). Global Path Planning of Unmanned Surface Vessel Based on Multi-Objective Hybrid Particle Swarm Algorithm. In *International Conference on Bio-Inspired Computing: Theories and Applications*. Singapore: Springer, 82–91.

Zhou, X. Y., Liu, Z. J., Wang, F. W. and Ni, S. K. (2018). Collision Risk Identification of Autonomous Ships Based on the Synergy Ship Domain. In *2018 Chinese Control and Decision Conference (CCDC)*. IEEE, 6746–6752.

Zhu, M., Wang, Y. and Wen, Y. (2013). A Global Path Planning Algorithm of Unmanned Vessel in Inland Waterway. In *ICTIS 2013: Improving Multimodal Transportation Systems-Information, Safety, and Integration*. 2106–2113.

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