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# A risk comparison framework for autonomous ships navigation

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## Highlights

- A framework is proposed to compare MASS navigational risk in manual, remote, and autonomous control.
- Three generic accident scenarios are applied along with the heuristics developed by experts.
- Human, organization, ship, environment, technology failure modes are studied in 3 operation modes.
- To account for inherent uncertainty, interval-based RPNs are used as risk indicators.

## ABSTRACT

Maritime autonomous surface ships (MASS) may operate in three predefined operational modes (OM): manual, remote, or autonomous control. Determining the appropriate OM for MASS is important for operators and competent authorities that monitor and regulate maritime traffic in given areas. However, a science-based approach to this respect is currently unavailable. To assist the selection of the proper OM, this study presents a risk-based framework to compare risks in a given situation. To determine the risk level for a given OM, this framework utilizes expected failure modes (FM) related to people, organization, vessel, environment, and technology. FMs and associated accident scenarios (AS) were identified from conventional ship accidents, operating in manual control, in a coastal area in China, based on an extended

24Model. To expand these FMs to other OMs, experts' knowledge elicitation sessions were carried out. Subsequently, a metric for navigation risk of MASS in given OMs was introduced and estimated for the expected AS, using interval-based risk prioritization numbers to convey inherent uncertainty. Finally, by ranking interval-valued metrics in the three OMs, a risk picture was obtained. The feasibility of the proposed framework for risk comparison was verified using grounding in coastal areas where accident data were collected.

*Keywords: Autonomous Ship; Navigational Risk; Operation Mode; Risk Comparison; 24Model; RPN; Interval number; Grounding*

# 1. Introduction

Navigational risks, i.e., collision and grounding, are expected to remain the major risk types in future maritime transportation systems, where autonomous ships are anticipated to operate [1]. When a conventional ship enters into a situation that is difficult for an officer of the watch (OOW) to handle, the captain is called for assistance to mitigate the risks and to bring the ship into safety. However, when an ambiguous situation occurs to an autonomous ship, it cannot be solved autonomously, and assistance may be sought through the change of operational mode (OM), whereby the control is shifted to an operator either on board or ashore. The concept of OMs has been already widely discussed in the literature [2-5], and four main types of OM have been defined: Manual Control (MC); Remote Control (RC); Autonomous Control (AC); and Fail-to-Safe (FtS), as depicted in Figure 1. If none of the first three OMs (i.e., MC, RC, or AC) can be applied to handle an emergency situation, an autonomous ship will enter into FtS, i.e., she will be halted and a steering contingency plan will be executed to mitigate the risks. Although FtS is a potential way to avoid dangerous situations, it seems as a last resort for an autonomous ship to take in adverse conditions for the sake of navigational safety. To mitigate the associated risks, the appropriate OM shall be selected anticipating the potential accident scenarios (AS) associated with a given area and/or operations. For example, the transit through highly trafficked waters may pose significant risk of collision, while the passage through straits with strong currents may be associated with increased risk of grounding. Similarly, altering the course in presence of high waves may expose the ship to a dangerous heel or very high accelerations, which in turn may result in cargo damage or even ship capsizing. Therefore, it is important to define the relevant OMs, the relevant AS, and the risk metric and associated method, in order to describe a given situation in a risk-informed manner and facilitate the process to select an OM with the lowest, however acceptable, value of risk metric.

The aim of this paper is to propose a generic framework that serves this purpose, which is currently missing. The following sub-section presents the state-of-the art literature on this topic.

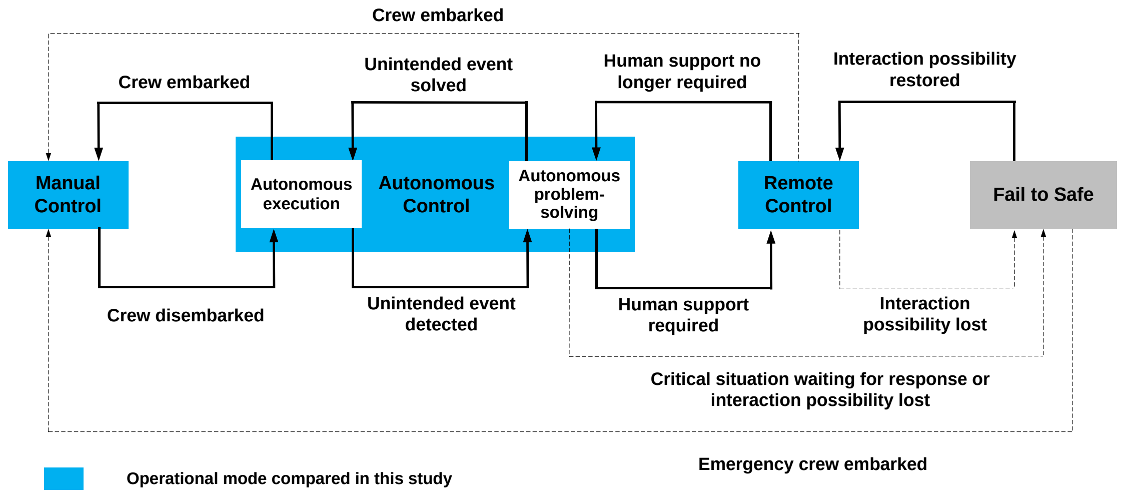



Fig. 1. Operational modes (OMs) for autonomous ships (adapted from [3]).

### 1.1 State of the art

The literature related to operational risk analysis or assessment of Maritime Autonomous Surface Ships (MASS), or autonomous ships, was reviewed chronologically. Rødseth and Burmeister [6] presented some risk analysis results of using a new design and analysis method based on the Formal Safety Analysis (FSA), in the context of the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project. Wróbel et al. [7] applied brainstorming to identify hazards, and created a Bayesian Belief Network (BBN) for risk analysis on unmanned ships that could operate in AC, RC, or MC. Ramos et al. [8, 9] discussed human failures in autonomous ship operations and the factors that could influence the operators onshore. Wróbel et al. [10] applied the System-Theoretic Process Analysis (STPA) to analyse the safety of a remotely controlled, generic merchant vessel. Chong [11] analysed the potential impact of MASS on Vessel Traffic Service (VTS) operations. Kooij and Hekkenberg [12] analysed the effects of automating navigational tasks on crewing levels. Ramos et al. [13] explored how humans can be a key factor for successful collision avoidance in future MASS operations. Bogusławski et al. [14] investigated the worldwide research directions on situational awareness for autonomous transportation. Veitch and Alsos [15] systematically reviewed 42 studies on human supervision and control of autonomous ships. Fonseca et al. [16] developed a new technology adoption model to assess MASS from the point of view of technological innovation, economic factors, e-farers capital, and policy actions. Zghyer et al. [17] discussed the impact of automation on both the safety and the efficiency of ocean operations. Chaal et al. [18] developed a hierarchical control structure to integrate autonomous ships and their control center onshore using the STPA and the System Theoretic Early Concept Analysis. Chang et al. [19] identified the main operational hazards related to MASS from relevant literature, and ranked them by combining Failure Modes and Effects Analysis (FMEA), Evidential Reasoning, and Rule-based BBN. Fan et al. [20] identified the factors influencing navigational risk for remotely controlled MASS without crew on board. Goerlandt [21] contextualized MASS in a risk governance context and provided some recommendation for MASS design and implementation. Ramos et al. [22] considered the human-autonomous ship collaboration and the dynamic Level of Autonomy in operation to analyse MASS collision scenarios as a whole. Utne et al. [23] developed online risk models for supervisory risk control on autonomous ships by combining STPA and BBN. Johansen and Utne [24] extended and integrated STPA and BBN with control systems for MASS to enable supervisory risk control, which can be used to optimize machinery, control model, and speed reference to maintain the safe control of an autonomous ship under changing conditions. Ventikos et al. [25] employed the STPA to determine the hazards for remotely controlled MASS without crew onboard. Wróbel et al. [26] performed a literature review of the operational features of remotely-controlled merchant vessels, assigning references to a safety control structure introduced in their earlier work [10]. Yang et al. [27] utilized the STPA to identify hazards and safety requirements for safe OM transitions in autonomous marine systems. The European Maritime Safety Agency (EMSA) [28] investigated emerging risks for different degrees of MASS using hazard identification (HAZID) and fault tree analysis (FTA). Wróbel et al. [29] listed the leading safety indicators for MASS in three safety-critical operational aspects, i.e., collision avoidance, intact stability, and communication. Wróbel et al. [30] analysed the influence of human factors on the safety of remotely-controlled merchant vessels. Zhou et al. [31] co-analysed safety and security for autonomous ships by proposing an STPA-based analysis methodology that Synthesizes Safety and Security (STPA-SynSS). Bolbot et al. [32] developed a hazard identification process involving operational and functional classification for constrained autonomous crewless ship, where the risk ranking process considers uncertainty, while the risk definition follows the FSA guidance [33]. Størkersen [34] explored how safety management can support core tasks in the operation of remotely controlled vessels without crew onboard. Fan et al. [35] proposed a four-step risk-informed framework to assess operational risk for MASS, in which a MASS model-bank allision was the source of the AS, the 24Model was employed for failure identification, FMEA methods were used for risk definition, and experts' judgement was elicited for risk quantification. Fan et al. [36] prioritized the operational risk for autonomous ships using FMEA and interval numbers, in which grounding was considered as the AS. Guo et al. [37] developed a BBN model based on equipment on a prototype ferry model, and quantified the collision risk between an autonomous ferry and manned vessels in a city canal. BahooToroody et al. [38] proposed a hierarchical Bayesian inference-based reliability framework to prognose the health state of ships assuming a higher degree of autonomy, specifying the acceptable transitions between different degrees of autonomy by determining the defined deterioration ratio. BahooToroody et al. [39] established a probabilistic approach to estimate the trusted operational time of the ship machinery system through different autonomy degrees, in which the associated uncertainty was quantified using Markov chain Monte-Carlo simulation. Vos et al. [40] quantitatively estimated the reduction in loss of life and loss of ships given several scenarios for autonomous ships. Finally, Chou et al. [41] objectively and quantitatively forecast the navigational risks of large MASS without considering uncertainty.

It may be seen that a novel qualitative method, i.e., the STPA, has been widely used in the abovementioned literature [10, 18, 23, 25, 27, 31] to systematically uncover unsafe control actions. The data for these studies rely on experts' knowledge of the future system of autonomous ships. Although Zhou et al. [42] concluded that traditional methods for hazard identification are not applicable to autonomous ships and few works have established a novel model to identify navigational risk influencing factors [20] or modified traditional hazard identification process [31, 32], some studies used literature data and adopted HAZID [28], the Human Factors Analysis and Classification System Maritime Accidents (HFACS–MA) [30], and experts' elicitation or brainstorming [6, 7] to discuss risk in relation to MASS. Yang and Utne [43] found that the collocation of STPA and some traditional methods, such as procedural Hazard and Operability Analysis (HAZOP), could facilitate the online risk modeling of Autonomous Marine Systems. To date, hazards and potential solutions related to autonomous ships operations have been investigated in existing literature [14, 19, 29, 41]. In addition, some studies have employed conventional ship accidents as a source to analyse navigational failures or risks [35, 36, 41]. Moreover, qualitative risk analyses for autonomous ships have provided suggestions for risk management [21, 34], hazards for risk ranking [6, 32], or elements for risk modelling [7, 13, 19, 22-24, 28, 35-37, 41]. Interestingly, uncertainty was also considered in some of these studies [21, 32, 37] from different points of view related to these three aspects. In relation to risk modelling, Thieme et al. [44] examined 64 assessed models, claiming that BBN should be considered as part of a risk model for MASS operation. This conclusion was verified by other studies [7, 15, 19, 23, 24, 37], which considered BBN as the main tool to this respect, while EMSA [28] adopted the FTA. Additionally, other novel frameworks or methods for risk modelling have been proposed in literature [13, 22, 35, 36, 41]. The results of risk quantification clearly appeared in some studies [19, 35-37, 41], while they were missing in others due to either lack of data [7, 28], or methods characteristics [13, 22]. Nevertheless, to a large extent a framework is missing in current literature, which would be suitable for the proactive, risk-informed decision-making process of selection of OMs for MASS in the short-term operational context.

Therefore, the aim of this study was to bridge this knowledge gap by proposing a framework allowing a risk-informed decision-making process for prospective MASS operation. This was done through a comparison of the risk index of a MASS operating under various OMs. To this end, AS were developed comprising of failure modes (FMs) related to human, organization, ship, environment, and technology, and by allowing the assessment and comparison of risk priority numbers (RPN) for the given scenarios and OMs at ship level. The proposed framework can assist remote control centres (RCC) or maritime authorities in defining the advisable OMs for autonomous ships in the sea areas under their surveillance, given the surrounding circumstances and conditions. Therefore, the proposed solution provides a robust and transparent mechanism for the evaluation and comparison of the navigational risks associated with three possible OMs of autonomous ships, thereby contributing to the maritime academy and industry.

The knowledge of anticipated future operational patterns is a prerequisite to develop reliable accident scenarios for MASS. However, this is not available to the wider audience at the moment. Therefore, another approach had to be adopted in this study, utilizing the available data and knowledge. Accordingly, to identify FMs and develop AS, we utilized historical data on merchant ship accidents recorded in a predefined sea area, along with a systematic accident causation model, namely the 24Model, proposed by Fu et al. [45, 46]. This model is a result of the evolution of accident models [47, 48]; it has an advantage in analysing accident causes [48] and has been applied to investigate various modes of transportation [49, 50]. As the structure of autonomous ships and related accidents will be gradually explored in the future, risk analysis of autonomous ships' accidents would be more concrete and generate solid conclusions to promote intelligent navigation safety. In this sense, the advantage of an accident causation approach, such as the 24Model, may gradually emerge. Given sufficient accident data or incident scenarios, some methods, such as FMEA, HAZOP, Cognitive Reliability and Error Analysis Method (CREAM), and HFACS-MA, are appropriate for hazard identification. However, these traditional methods fail to provide confidence in the results of hazards identification [31, 51, 52]; as such, they are less comprehensive or clear in analysing accidents than the 24Model, which explores the cause of an accident at both individual and organizational levels, and along four stages, i.e., immediate cause, indirect reason, radical cause, and root cause (Fig. 2). Moreover, neither some of these traditional methods nor the 24Model may be effective to identify hazards for autonomous ships, since they have not been explicitly developed for such an advanced vehicle with complex characteristics [30, 42, 44]. In addition, similar to HFACS-MA [30, 53-55], the 24Model focuses on human, organizational, and external failures, ignoring failures related to hardware, especially for intelligent facilities or smart systems, e.g., autonomous ships that expected to be humanoid. To overcome this limitation, for the first time the scope of the type of failures in the 24Model was enlarged (see Section 2.1), which is a novelty of this study.

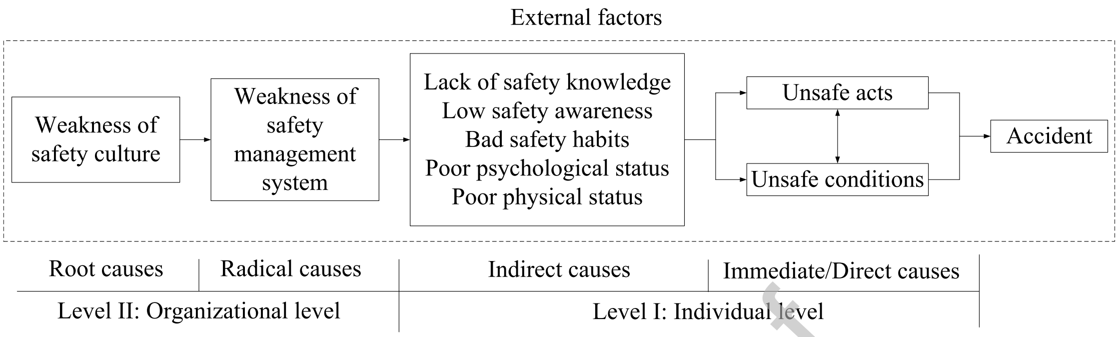



Fig. 2. The 24Model (adapted from [45, 46]).

**1.2 Risk fundamentals**

Risk has been conventionally defined as a product of the probability of an unwanted event and its consequence, [56]. However, over the last decade, the definition of risk and its understanding have gone through an evolution [57] that resulted in a significant paradigm shift. Recognizing the characteristics of intelligent navigation, apart from the aspects of occurrence probability (O) and severity of the consequence (S), the dimension of deficiencies detection ability (D) by the ship herself or by an operator was also found as an important element determining the safety of the analysed system. This capability to monitor relevant, safety-critical circumstances is important for autonomous ships and needs to be enhanced by appropriate solutions [29]. Therefore, in order to combine these three elements into one risk framework we applied RPNs defined by the combination of O, S, and D as a risk metric in a context of FMEA. To develop relevant AS, a set of FMs was defined, based on selected historical accidents. Then, the type of relations among the FMs was defined, adapting the reasoning logic from [58], to obtain a risk index for the AS. For a given AS in each OM, the RPNs were calculated and used for comparative purposes.

The RPN methodology has already been used to assess navigational risk for autonomous ships [19, 35, 36]. Various approaches can be applied to convey epistemic uncertainty, such as linguistic variables [19] or interval numbers [36]. Since this study utilized probabilities, either obtained from the data or elicited from experts, the proper way to convey the associate uncertainties and define the resulting boundaries of RPN was to apply the interval numbers. Moreover, commonly accepted methods and criteria to evaluate navigational risks are lacking in existing literature; therefore, any solution meeting the formal and practical requirements can be useful. In our earlier work [35], we evaluated the navigational risk for a specific OM by using the criterion of crisp numbers; however, this approach ignored the epistemic uncertainty in risk evaluation. Moreover, the logic of risk reasoning presented there is quite simple, since it just sums up the RPNs of the FMs involved, without considering the type of relations in AS. Although in Fan [36] such uncertainty and dependence were considered, standing as a basis for the present study, the question of how to identify FMs and establish the structure of AS was still unclear. Additionally, unlike these studies [35, 36] that analysed only one case, the present study analysed numerous cases to verify the validity of the proposed framework, significantly improving our previous work.

The framework proposed in this study is generic, and its parameters tend to reflect grounding accidents and conditions in a specific geographical region, namely the western Shenzhen Port, in South China. To identify FMs and develop relevant AS based on the 24Model, we analysed historical data, i.e., conventional ship grounding accidents collected from the VTS Centre of the Shenzhen Maritime Safety Administration. In parallel, experts' knowledge was elicited to evaluate the risk parameters of the identified FMs corresponding to three OMs considered. This evaluation was transformed into interval numbers to indicate the epistemic uncertainty in the elicitation. Finally, rules to rank interval numbers were adopted to compare navigational risks in three OMs in terms of interval numbers.

This paper is organized as follows. Section 2 presents the proposed framework, methodology, and parameters. Section 3 illustrates the case study. Section 4 discusses the limitations of this study and future work. Section 5 provides the conclusions of this paper.

## 2. Framework and methodology

### 2.1. A risk comparison framework for MASS

To compare the navigational risks for an autonomous ship in three OMs, i.e., MC, RC, and AC, a scenario was first defined; then, the navigational risks of this scenario were quantified for each of the three OMs. For simplification in the process of risk quantification, we set the following three assumptions upon which the risk comparison framework was based, as depicted in Figure 3:

- Assumption 1: A scenario is composed by one or several FMs linked by various combinations. This scenario is named as accident scenario (AS);
- Assumption 2: In this AS, an autonomous ship can operate in one of three OMs, i.e., MC, RC, or AC;
- Assumption 3: We used three RPN parameters as measures to quantify the risk of each FM, and used RPN as a metric to evaluate navigational risk in an AS for an autonomous ship.

As illustrated in Figure 3, in this framework FMs were identified from five aspects and AS were developed with the use of the 24Model.

Subsequently, each FM and the resulting AS, were assigned three RPN parameters, based on experts' knowledge. To account for subjective uncertainty, the RPN parameters were expressed as interval numbers. To calculate the RPN for the whole AS, comprising of the set of FMs, a risk reasoning method was adapted from [58]. Finally, the ranking rules of interval numbers were adopted to compare the results obtained for the three OMs.

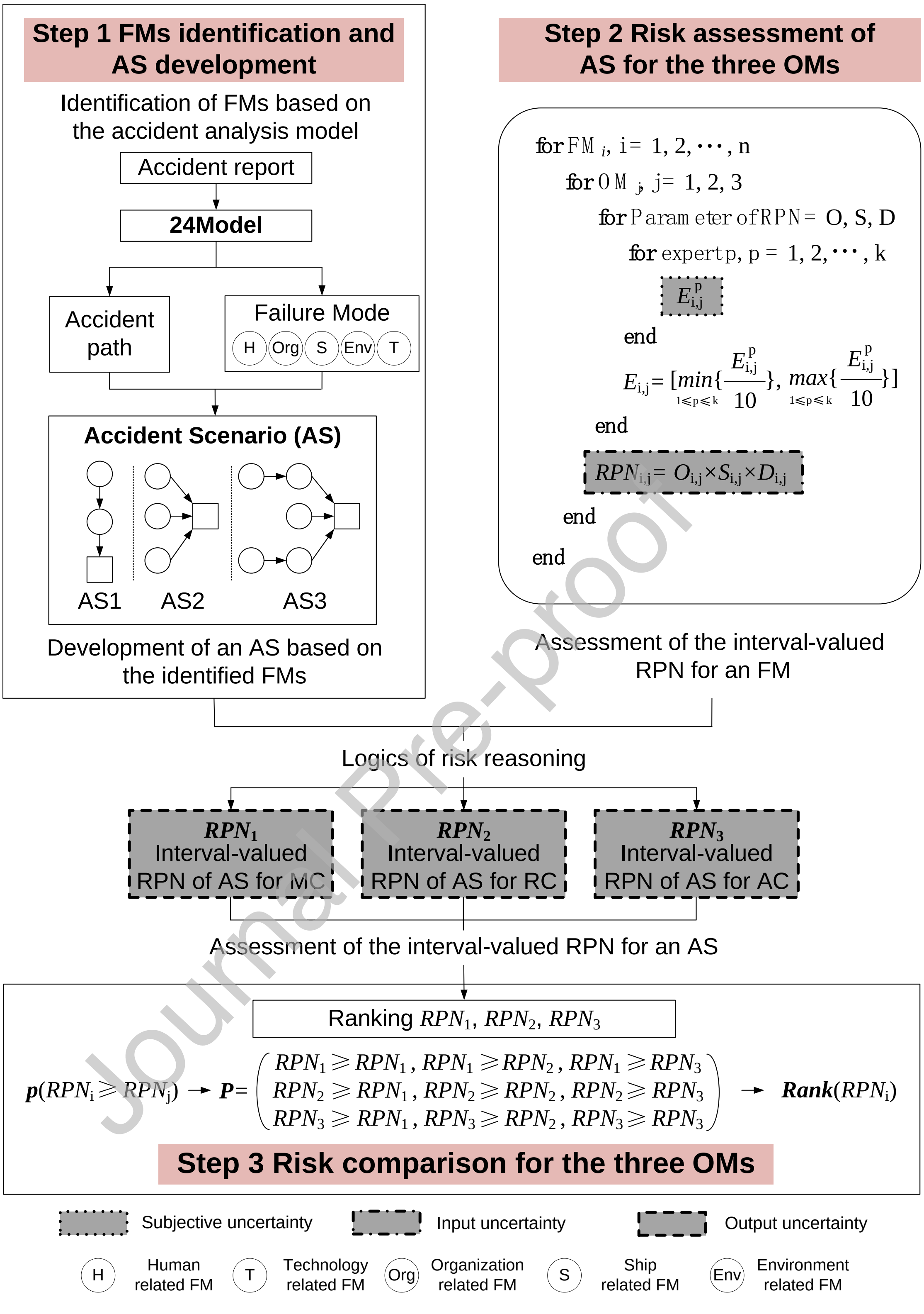



Fig. 3. Process of formulation of the proposed risk comparison framework.

***Step 1: FMs identification and AS development***

***Identification of FMs based on the accident analysis model***

To identify FMs and reveal them in the three OMs, the 24Model was adopted to answer two questions. The first question related to whether or not an accident FM could be categorized into one of five FM/cause types, i.e., human-related, organization-related, ship-related, environment-related, or technology-related. To this respect, it is worth noting that the scope of the cause types was larger than that in the 24Model.

Based on the identified types of FM, the second question aimed to understand what are the unsafe acts or conditions that would be the immediate/direct causes of each FM in either of the three OMs, i.e., MC, RC, and AC. To this respect, it should be noted that the immediate/direct causes analysed in the context of operation were more detailed than that in the 24Model. More importantly, the second question aimed to clarify whether or not the identified FM would exist for autonomous ships and the three OMs considered. If this was the case, the FM could be utilized in the following step to build an AS; otherwise, it could not be utilized. This procedure is shown in Fig. 4.

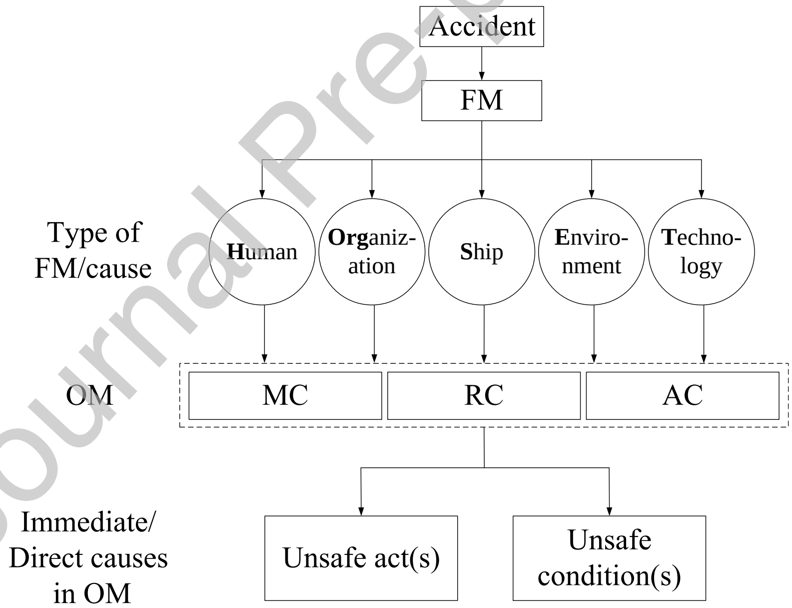
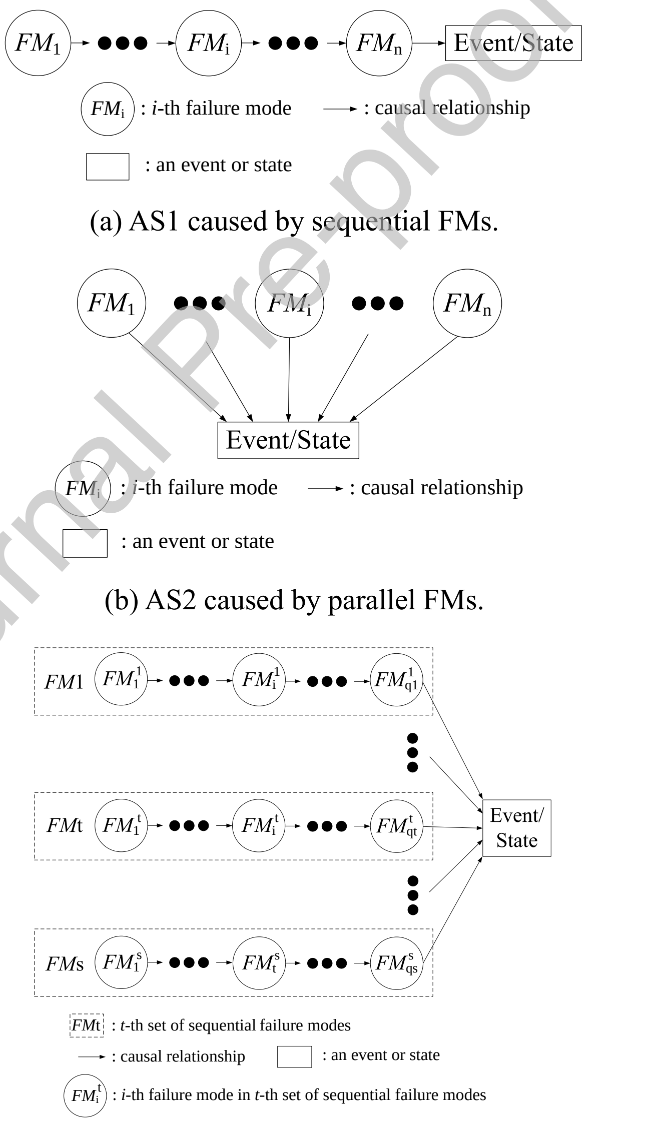



Fig. 4. Procedure followed to analyse failure mode(s) for the three OMs considered.

***Development of an AS based on the identified FMs***

Based on the identified FMs, the 24Model was further used to find the subsequent causal pathways to link these FMs with an adverse event or unfavourable state to develop an AS, given that an AS involves *n* FMs, i.e., $FM_i$, $i = \{1,2,\cdots,n\}$. According to this linear and systematic accident causation model, three general structures of AS were developed as follows: (i) an AS event or state is caused by $n$ FMs connected sequentially, as AS1 in Fig. 5(a); (ii) an AS event or state is caused by $n$ FMs connected in parallel, as AS2 in Fig. 5(b); and (iii) an AS event or state is caused by $s$ sets of FMs connected in parallel. In a set of FMs, i.e., $FM\mathrm{t}$, $\mathrm{t} = \{1,2,\cdots,s\}$, there are $qt$ FMs that are linked sequentially. The $i$-th FM in $FM\mathrm{t}$ was marked as $FM_{\mathrm{i}}^{\mathrm{t}}$, $\mathrm{i} = \{1,2,\cdots,\mathrm{qt}\}$, $n = \sum_{t=1}^{s} \mathrm{qt}$, as AS3 in Fig. 5(c).

Additionally, two levels of dependence among FMs were anticipated, namely high and low dependence [58]. A high dependence means that there is a strong influence among FMs in an AS, while a low dependence implies a weak influence. These two dependences in an AS determine the logic of risk reasoning (see Step 2).




(a) AS1 caused by sequential FMs.

(b) AS2 caused by parallel FMs.

(c) AS3 caused by a set of FMs connected in a mixed manner.

Fig. 5. General structure of potential accident scenario.

***Step 2: Risk assessment of AS for the three OMs***

***Assessment of the interval-valued RPN for an FM***

To quantify the RPN of an FM in a given OM, three parameters needed to be estimated for the FM: the occurrence of failure; its severity; and the chances of not detecting the failure. These are often evaluated using crisp numbers, usually ranging from 1 to 10, as shown in Table 1. For the purpose of this study, these RPN parameters were evaluated in the course of experts' knowledge elicitation, as explained in Section 2.3, thus featuring a natural spread. To account for this result and bound the resulting uncertainty, the parameters were evaluated with the use of interval numbers, defined by lower and upper values based on experts' judgements.

Hence, the product of these three RPN parameters was also consisting of interval numbers, according to the rules explained in Section 2.2.

The interval-valued RPN of an FM in a given OM was defined as follows:

$$RPN_{\mathrm{i,j}} = \prod_{E=\{O,S,D\}} E_{\mathrm{i,j}}, \tag{1}$$

$$\left(E_{\mathrm{i,j}}\right) = \begin{pmatrix} \left[\min\limits_{1\le p\le k}\{\frac{E_{1,1}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{1,1}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{1,2}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{1,2}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{1,3}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{1,3}^{p}}{10}\}\right] \\ \left[\min\limits_{1\le p\le k}\{\frac{E_{2,1}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{2,1}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{2,2}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{2,2}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{2,3}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{2,3}^{p}}{10}\}\right] \\ \vdots & \vdots & \vdots \\ \left[\min\limits_{1\le p\le k}\{\frac{E_{n,1}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{n,1}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{n,2}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{n,2}^{p}}{10}\}\right] & \left[\min\limits_{1\le p\le k}\{\frac{E_{n,3}^{p}}{10}\}, \max\limits_{1\le p\le k}\{\frac{E_{n,3}^{p}}{10}\}\right] \end{pmatrix}, \tag{2}$$

where $RPN_{\mathrm{i,j}}$ refers to the interval-valued RPN of $FM_{\mathrm{i}}$, $i=\{1,2,\cdots,n\}$, when an autonomous ship operates in $OM_{\mathrm{j}}$, where $\mathrm{j}=1$ for MC, $\mathrm{j}=2$ for RC, and $\mathrm{j}=3$ for AC; $E_{\mathrm{i,j}}$=$\{O_{\mathrm{i,j}}, S_{\mathrm{i,j}}, D_{\mathrm{i,j}}\}$, $E_{\mathrm{i,j}}^{p}$ is the RPN parameter of the *i*-th FM for $OM_{\mathrm{j}}$, $p=\{1,2,\cdots,k\}$, evaluated by the *p*-th expert. For straightforward comparison in Step 3, the three RPN parameters were rescaled so as to fit a 0-1 scale. To this end, $E_{\mathrm{i,j}}^{p}$ was divided by 10. Thus, we obtained $E_{\mathrm{i,j}} \subseteq (0,1]$, $RPN_{\mathrm{i,j}} \subseteq (0,1]$.

Table 1. Ratings for the RPN parameters of a failure mode for an autonomous ship (adapted from [35]).

| Rank | Description of Failure Occurrence (O) | Description of Effect Severity (*S*) | Description of Chances for Detection (*D*) |
|---|---|---|---|
| 10 | Mean time between failures (MTBF) is lower than 2 h | Failure on- or off-ship is hazardous and occurs without warning. It involves suspension of the operation of the system and/or noncompliance with international or national regulations | The on- or off-ship subsystem or system does not detect a potential cause of failure or subsequent failure mode, or there is no system or subsystem in place for such detection |
| 9 | MTBF[h] $\in$ [2, 3) | Failure on- or off-ship involves hazardous outcomes and/or noncompliance with international or national regulations or standards | Very remote chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 8 | MTBF[h] $\in$ [3, 8) | The on- or off-ship system is inoperable, with loss of primary function. | Remote chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 7 | MTBF[h] $\in$ [8, 24) | Performance of the on- or off-ship system is severely affected, but still functioning. | Very low chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 6 | MTBF[h] $\in$ [24, 168) | Performance of the on- or off-ship system is degraded. Comfort or convince functions may not operate | Low chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 5 | MTBF[h] $\in$ [168, 720) | Moderate effect on performance of the on- or off-ship system. The on- or off-ship system requires repair | Moderate chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 4 | MTBF[h] $\in$ [720, 4320) | Small effect on the performance of the on- or off-ship system. The system does not require repair | Moderately high chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 3 | MTBF[h] $\in$ [4320, 8640) | Minor effect on the performance of the on- or off-ship subsystem or system | High chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 2 | MTBF[h] $\in$ [8640, 43200) | Very minor effect on the performance of the on- or off-ship subsystem or system | Very high chance that the on- or off-ship subsystem or system detects a potential cause of failure or subsequent failure mode |
| 1 | MTBF[h] $\in$ [43200, 86400) | No effect | The on- or off-ship subsystem or system almost certainly detects a potential cause of failure or subsequent failure mode |

***Assessment of the interval-valued RPN for an AS***

After assessing the risk of FMs for each given OM and presenting it in interval-valued RPNs, the navigational risk of an AS for autonomous ships was determined depending on the way of accidental path and the dependences among FMs, by adapting the logic of risk reasoning from [58].

For an AS with sequential FMs, the interval-valued RPN of an AS in $OM_{\mathrm{j}}$ was expressed as follows:

$$\begin{cases} RPN_{\mathrm{j}} \approx \max\limits_{\mathrm{i}}\left(RPN_{\mathrm{i,j}}\right), \text{high dependence} \\ RPN_{\mathrm{j}} = 1 - \prod_{\mathrm{i}=1}^{n}\left(1 - RPN_{\mathrm{i,j}}\right), \text{low dependence} \end{cases}, \tag{3}$$

where $\mathrm{j} = \{1, 2, 3\}$ denotes a given OM.

For an AS with FMs linked in parallel, the interval-valued RPN of an AS in $OM_{\mathrm{j}}$ was expressed as follows:

$$\begin{cases} RPN_{\mathrm{j}} \approx \min\limits_{\mathrm{i}}\left(RPN_{\mathrm{i,j}}\right), \text{high dependence} \\ RPN_{\mathrm{j}} = \prod_{\mathrm{i}=1}^{n} RPN_{\mathrm{i,j}}, \text{low dependence} \end{cases}. \tag{4}$$

For an AS with FMs linked in a mixed manner, the calculation was divided in two steps. Firstly, the interval-valued RPN of the *t*-th set of sequential FMs in $OM_{\mathrm{j}}$ was determined as follows:

$$\begin{cases} RPN\mathrm{t}_{\mathrm{j}} \approx \max\limits_{\mathrm{i}}\left(RPN_{\mathrm{i,j}}^{\mathrm{t}}\right), \text{high dependence} \\ RPN\mathrm{t}_{\mathrm{j}} = 1 - \prod_{\mathrm{i}=1}^{qt}\left(1 - RPN_{\mathrm{i,j}}^{\mathrm{t}}\right), \text{low dependence} \end{cases}, \tag{5}$$

where $RPN\mathrm{t}_{\mathrm{j}}$ denotes the interval-valued RPN of the *t*-th set of FM, $FM\mathrm{t}$, in $OM_{\mathrm{j}}$; and $RPN_{\mathrm{i,j}}^{\mathrm{t}}$ denotes the interval-valued RPN of the *i*-th FM in *t*-th set of FMs, i.e., $FM_{\mathrm{i}}^{\mathrm{t}}$, $\mathrm{i} = \{1, 2, \cdots, \mathrm{qt}\}$, in $OM_j$, which was calculated using Eq. (1), $RPN_{\mathrm{i,j}}^{\mathrm{t}} \subseteq (0, 1]$.

Secondly, the interval-valued RPN of an AS in $OM_{\mathrm{j}}$ was determined as follows:

$$\begin{cases} RPN_{\mathrm{j}} \approx \min\limits_{\mathrm{t}}\left(RPN\mathrm{t}_{\mathrm{j}}\right), \text{high dependence} \\ RPN_{\mathrm{j}} = \prod_{\mathrm{t}=1}^{s} RPN\mathrm{t}_{\mathrm{j}}, \text{low dependence} \end{cases}. \tag{6}$$

In these functions, the variables are expressed in term of interval numbers. To find the maximum or minimum in the reasoning process, ranking rules and arithmetic operations of interval numbers were adopted; they are illustrated in Section 2.2.

***Step 3: Risk comparison for the three OMs***

Given an AS, in Step 2 the navigational risks of an autonomous ship in the three OMs, i.e.,

$RPN_j$, were determined. In this step, the interval-valued RPNs of the three OMs for a given AS were compared. To this end, we ranked the interval-valued RPNs to obtain their ranking values, i.e., $Rank(RPN_j)$. The higher the ranking value $Rank(RPN_j)$, the larger the interval number $RPN_j$, thus the higher the navigational risk in $OM_j$ for a given AS.

### 2.2. Interval numbers

The basic concepts, arithmetic operations, and ranking rules of the interval numbers are illustrated in this sub-section.

**Definition 1** [59]. If $A = [a^l,\ a^u] = \{x|0 \leq a^l \leq x \leq a^u\}$ exists, then $A$ is called a non-negative interval number, with $a^l$ and $a^u$ as the lower and upper bound of $A$, respectively. If and only if $a^l = a^u$, $A$ is degraded to a crisp number. That is, $A = [a,\ a] = \{x|x = a\}$.

**Definition 2** [60]. If $A_1$ and $A_2$ are both non-negative interval numbers, then supposing that $A_1 = \left[a_1^l,\ a_1^u\right]$ and $A_2 = \left[a_2^l,\ a_2^u\right]$, and that $a_i^l$ and $a_i^u$ are the lower and upper bound of $A_i$, $i = \{1, 2\}$, respectively, then the subtraction and multiplication operations between them can be defined, respectively, as follows:

$$A_1 - A_2 = \left[a_1^l - a_2^u,\ a_1^u - a_2^l\right], \tag{7}$$

$$A_1 \times A_2 = \left[a_1^l \times a_2^l,\ a_1^u \times a_2^u\right]. \tag{8}$$

**Definition 3** [61]. If $A_1$ and $A_2$ are both interval numbers, then supposing $A_1 = \left[a_1^l,\ a_1^u\right]$ and $A_2 = \left[a_2^l,\ a_2^u\right]$, the probability that $A_1 \geq A_2$ can be defined as follows:

$$p(A_1 \geq A_2) = max\left\{1 - max\left\{\frac{a_2^u - a_1^l}{(a_1^u - a_1^l) + (a_2^u - a_2^l)}, 0\right\},\ 0\right\}. \tag{9}$$

**Definition 4** [62]. If $A_i = \left[a_i^l,\ a_i^u\right]$ is a set of interval numbers, then, based on Eq. (9), the preference matrix $P$ can be generated to rank $A_i$, as follows:

$$P = \begin{pmatrix} p(A_1 \geq A_1) & p(A_1 \geq A_2) & \cdots & p(A_1 \geq A_n) \\ p(A_2 \geq A_1) & p(A_2 \geq A_2) & \cdots & p(A_2 \geq A_n) \\ \vdots & \vdots & \vdots & \vdots \\ p(A_n \geq A_1) & p(A_n \geq A_2) & \cdots & p(A_n \geq A_n) \end{pmatrix}, \tag{10}$$

where $p(A_i \geq A_j)$ is the probability that $A_i \geq A_j$ (see Definition 3).

Based on Eqs. (9-10), the ranking value of $A_i$, $Rank(A_i)$ was calculated as follows:

$$Rank(A_i) = \frac{1}{n(n-1)}\left(\sum_{k=1}^{n} p(A_i \geq A_k) + \frac{n}{2} - 1\right), \tag{11}$$

where $1 \leq i \leq n$ and $\sum_{i=1}^{n} Rank(A_i) = 1$. The larger the ranking value $Rank(A_i)$, the greater the interval number $A_i$. Hence, based on Eqs. (9-11), the maximum or minimum of $A_i$ were determined.

### 2.3. Framework parameters

In the proposed framework, the inputs to evaluate navigational risk of an AS are FMs and their RPNs in the three OMs, which are the framework parameters. To identify FMs for the case study presented in Section 3, the 24Model was applied to analyse 65 grounding accident cases, developing AS as shown in Appendix A that in the supplementary materials associated with this article.

These accidents, recorded by the Shenzhen Maritime Safety Administration, took place in the west coast of the Shenzhen harbour between 2007 and 2013. Information on these accidents, including ship type, accident area, season, and time window, is presented in Appendix D that in the supplementary materials associated with this article. However, the detailed accident reports are not publicly available due to confidentiality agreements with the data owner. In accordance with Step 1, from these 65 groundings we identified 15 generic FMs. Following the procedure illustrated in Fig. 4, these 15 FMs were further analysed to answer two questions, i.e., what is the FM type in the context of MASS, and what is its immediate/direct cause in the three OMs. These two questions were answered based on the knowledge of MASS system structure [10, 18, 31, 32, 63-65], related factors [20, 29], and authors' experience in the maritime domain; the results are presented in Table 2. It was found that FMs that are due to human errors in MC may be considered as ship-related FMs in AC, i.e., $FM_2$, $FM_{11}$. Similarly, the error from crew onboard in MC may be that from an operator in RC or a software engineer in AC, i.e., $FM_4$. Interestingly, for some FMs, causes would exist in all three OMs, e.g., the organization-related causes of $FM_{11}$ and $FM_{12}$ and the environment-related causes of $FM_{15}$. In addition, for $FM_{13}$ ('Under-manning'), the causes are related to operator resource arrangements in both MC and

RC, and to maintenance resources in AC.

Obviously, the proposed framework is generic, even if it is based on specific data, leading to specific AS. In general, although these AS cannot be considered general, they can be deemed sufficient for the particular location and the particular system that they aim to describe. Moreover, the developed model can be considered valid as long and the boundary conditions of the analysed system remain stable. However, for any serious disruption in the system operational pattern, these AS need to be updated. The future operational pattern of the maritime transportation system with the presence of autonomous ships remains unknown; therefore, the proposed model features epistemic uncertainty that seems to be irreducible at the moment. This limitation does not apply to the overall generic idea of risk-based framework.

Table 2. Description of the FMs identified (H = human; Org = organization; S = ship; Env = environmental; T = technology-related FMs)

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| $FM_1$ | Improper assessment of ship position | H | Human error onboard | Over trust in data; poor situation awareness onboard or in the RCC; loss of contact; cyber-attack | Software engineer lacking design experience; cyber-attack |
| | | Org | No update in chart or electronic update | No update in chart or electronic update | No update in the electronic chart |
| | | S | Failure in the intra-system onboard | Failure in the intra-system onboard; loss of contact between ship and the RCC | Failure in the intra-system onboard |
| | | Env | Harsh weather | Harsh weather | Harsh weather |
| | | T | Software bug | Ship-RCC communication delay; software bug | Software bug |
| $FM_2$ | Inadequate lookout | H | Human error onboard | Over trust in data; ack of situation awareness onboard or in the RCC; human error in monitoring; cyber-attack | Cyber-attack |
| | | Org | Poor watching schedule without considering fatigue | No sufficient and accurate information; poor shift schedule | |
| | | S | Sensor failure | Loss of contact between ship and the RCC | Sensor failure; failure to communicate with surrounding ships or with third party |
| | | Env | Poor visibility | Poor visibility | Poor visibility |
| | | T | Software bug | Ship-RCC communication delay; software bug | Software bug |
| $FM_3$ | Inadequate training in personal quality or Sample for decision making | H | No update in navigation qualifications | No update in operation quality; software engineer lacking navigation experience; cyber-attack | Software engineer lacking navigation experience; cyber-attack |
| | | Org | Poor design in training plan | Poor design in training plan | Poor design in training sample |
| | | S | | Outdated training sample in the system from the ship or the RCC | Outdated training sample in the system onboard |

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| | | Env | | | |
| | | T | | Software bug | Software bug |
| $FM_4$ | Inappropriate stowage of cargo | H | Human error onboard | Human error onboard or in the RCC | Software engineer lacking experience of cargo management onboard |
| | | Org | Poor planning in cargo management; loss of control for cargo management | Poor planning in cargo management; loss of control for cargo management | Poor planning in cargo management; loss of control for cargo management |
| | | S | Failure of the securing device; failure in the sensor detecting cargo | Failure of the securing device; failure in the sensor detecting cargo | Failure of the securing device; failure in the sensor detecting cargo |
| | | Env | Heavy waves or wind | Heavy waves or wind | Heavy waves or wind |
| | | T | | Software bug | Software bug |
| $FM_5$ | Inappropriate/ineffective maintenance | H | | No awareness of prompt maintenance; cyber-attack | Inappropriate maintenance schedule designed by the software engineer; cyber-attack |
| | | Org | Poor management in the maintenance team onboard | Poor management in the maintenance team on- or off-ship | Poor management in the maintenance team off-ship |
| | | S | Lack of replacement parts | Lack of replacement parts or of maintenance engineers | Lack of replacement parts or of maintenance engineers |
| | | Env | Heavy waves or surge | Heavy waves or surge | Heavy waves or surge |
| | | T | | Software bug | Software bug |
| $FM_6$ | Ineffective use of technology | H | Low familiarity with technology; lack of knowledge; cyber-attack | Low familiarity with technology; lack of knowledge; lack of situation awareness; cyber-attack | Software engineer lacking knowledge or experience of using technology; cyber-attack |
| | | Org | Inappropriate coordination and cooperation onboard | Inappropriate coordination and cooperation between the ship and the RCC | |
| | | S | Failure to provide sufficient electricity or power; response delay | Failure to provide sufficient electricity or power; response delay | Failure to provide sufficient electricity or power; response delay |

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| | | Env | Harsh weather | Harsh weather | Harsh weather |
| | | T | Software bug | Software bug | Software bug |
| $FM_7$ | Insufficient anticipation of nautical conditions | H | Over trust in himself/herself | Over trust in himself/herself; cyber-attack | Software engineer lacking the latest information on nautical conditions; cyber-attack |
| | | Org | No update in chart or electronic update | No update in chart or electronic update; low cooperation among operation team members in the RCC | No update in the electronic chart |
| | | S | | Provision of insufficient or wrong information to the RCC | Provision of insufficient or wrong information to the decision-making system onboard |
| | | Env | Unknown change in the channel or traditional route | Unknown change in the channel or traditional route | Unknown change in the channel or traditional route |
| | | T | | Software bug | Software bug |
| $FM_8$ | Mishandling | H | Lack of attention; fatigue; lack of experience; lack of flexibility in applying regional or international rules; pirate or cyber-attack | Fatigue; boredom; lack of attention; lack of flexibility in using regional or international rules; pirate or cyber-attack | Software engineer lacking knowledge of ship manoeuvre; pirate or cyber-attack |
| | | Org | Poor cooperation onboard | Poor cooperation between the ship and the RCC | |
| | | S | Response delay | Response delay | Lack of flexibility in using regional or international rules; response delay |
| | | Env | Poor visibility; heavy waves or wind | Poor visibility; heavy waves or wind | Poor visibility; heavy waves or wind |
| | | T | | Communication delay between the ship and the RCC | |

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| $FM_9$ | Poor management of voyage plan | H | Human error onboard; pirate or cyber-attack | Human error onboard or in the RCC; pirate or cyber-attack | Software engineer lacking knowledge of voyage management; pirate or cyber-attack |
| | | Org | Poor coordination between the ship and the shipping company | Poor coordination between the ship and the shipping company | Poor coordination between the ship and the shipping company |
| | | S | Sensor failure in alert | Sensor failure in alert | Sensor failure in alert; provision of insufficient or wrong information to the decision-making system onboard |
| | | Env | Disastrous weather | Disastrous weather | Disastrous weather |
| | | T | Software bug | Software bug | Software bug |
| $FM_{10}$ | Rule violation | H | Result of risk balance (intention to grounding for the sake of collision avoidance); low familiarity with rules; pirate or cyber-attack | Result of risk balance (intention to grounding for the sake of collision avoidance); low familiarity with rules; pirate or cyber-attack | Software engineer lacking knowledge of the latest rules or potential traffic scenarios; pirate or cyber-attack |
| | | Org | Low coordination with other ships, the port authority, or maritime bureaus | Low coordination with other ships, the port authority, or maritime bureaus | Low coordination with other ships, the port authority, or maritime bureaus |
| | | S | Loss of control; providing insufficient or wrong information to OOW | Provision of insufficient or wrong information to the RCC; misunderstanding of other crewed merchant vessels' behaviour; loss of control | Provision of insufficient or wrong information to the decision-making system onboard; misunderstanding other crewed merchant vessels' behaviour; result of risk balance (intention to grounding for the sake of collision avoidance); loss of control |
| | | Env | Disastrous weather | Disastrous weather | Disastrous weather |
| | | T | | Software bug | Software bug |
| $FM_{11}$ | Overloading | H | Following wrong orders from the shipping company | Following wrong orders from the shipping company | |

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| | | Org | Shipping company driven by commercial interest | Shipping company driven by commercial interests | Shipping company driven by commercial interests |
| | | S | | | Following wrong orders from the shipping company |
| | | Env | | | |
| | | T | | Software bug | Software bug |
| $FM_{12}$ | Main engine failure | H | Lack of experience in using main engine; pirate or cyber-attack | Operation error; pirate or cyber-attack | Pirate or cyber-attack |
| | | Org | No maintenance plan conducted | No maintenance plan conducted | No maintenance plan conducted |
| | | S | Inappropriate orders to control the main engine from officer on duty | Inappropriate orders to control main engine from the decision-making system | Inappropriate orders to control the main engine from the decision-making system |
| | | Env | Heavy waves or surge | Heavy wave or surge | Heavy waves or surge |
| | | T | | Software bug | Software bug |
| $FM_{13}$ | Under-manning | H | Fatigue | Fatigue | |
| | | Org | Poor watch officer arrangement onboard | Poor operator arrangement in RCC | Poor maintenance by the team management |
| | | S | | | |
| | | Env | | | |
| | | T | | | |
| $FM_{14}$ | Failure in communication | H | Human error onboard; pirate or cyber-attack | Human error onboard or in the RCC; pirate or cyber-attack | Software engineer lacking knowledge of ship-RCC communication; pirate or cyber-attack |
| | | Org | Poor coordination scheme onboard; communication facility failure off-ship | Poor coordination scheme between the ship and the RCC; communication facility failure in the RCC | Poor coordination scheme between the ship and the shipping company; communication facility failure off-ship |

| No. | FM | Type | Unsafe acts or conditions in MC | Unsafe acts or conditions in RC | Unsafe acts or conditions in AC |
|---|---|---|---|---|---|
| | | S | Communication facility failure onboard | Communication facility failure onboard | Communication facility failure onboard |
| | | Env | Heavy rain or snow | Heavy rain or snow | Heavy rain or snow |
| | | T | No satellite signal; large signal noise | Software bug; no satellite signal; large signal noise | Software bug; no satellite signal; large signal noise |
| $FM_{15}$ | Weather/other environmental factors | H | | | |
| | | Org | | | |
| | | S | | | |
| | | Env | Change in natural conditions | Change in natural conditions | Change in natural conditions |
| | | T | | | |

To obtain the RPNs of the identified FMs, experts' knowledge elicitation sessions were organized to evaluate the three RPN parameters for the three OMs. These sessions were carried out through a questionnaire-based survey, as shown in Appendix B that in the supplementary materials associated with this article. The questionnaires were distributed among the participants in the international maritime conference "TransNav", held in the Gdynia Maritime University between the 12th and the 14th of June, 2019. To enhance the validity of the survey, three research assistants were dispatched to help respondents filling out the questionnaires. A total of 27 valid questionnaires were returned; the demographic data of the 27 respondents are presented in Fig. 6. The majority of respondents were males from Europe and Asia; over half of them had a PhD degree; and two thirds were professors. Among those, 15% of professors were representatives of maritime authorities with a maritime background, while 27% of researchers were active or former mariners.

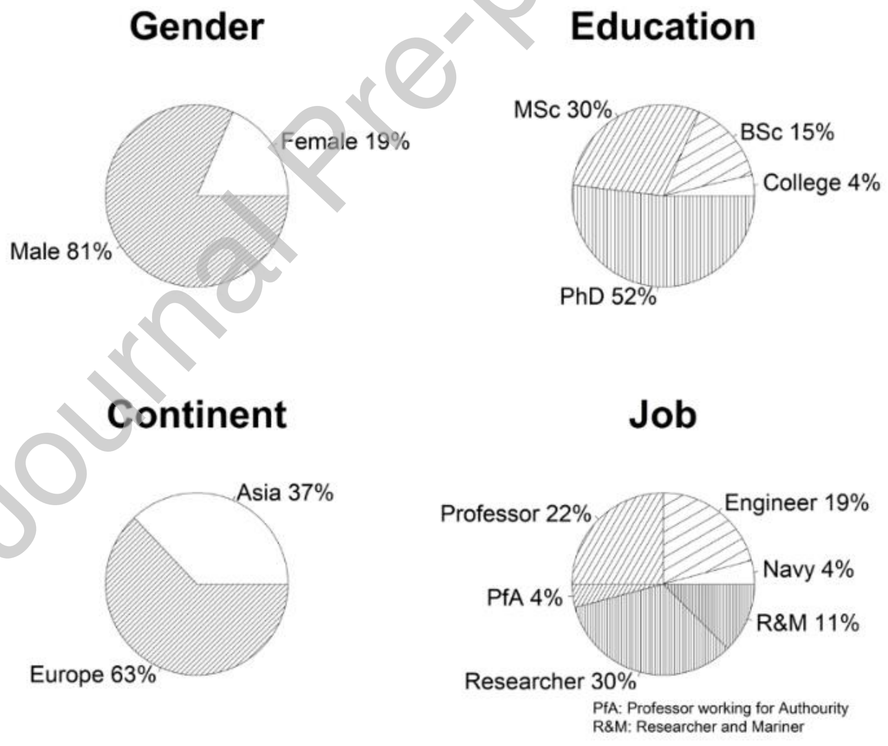



Fig. 6. Profiles of the respondents to the 27 valid questionnaires.

After the experts' estimation of the three RPN parameters for an FM in a given OM using crisp numbers (see Table 1), Eq. (2) was used to transform the crisp evaluation into interval numbers. Then, following Eq. (1), the interval-valued RPN of an FM in a given OM was generated.

Subsequently, the three RPN parameters and the interval-valued RPNs for the identified FMs in the three OMs were evaluated, as shown in Appendix C that in the supplementary materials associated with this article.

Taking $FM_7$ ('Insufficient anticipation of nautical conditions') as an example, three experts evaluated its three RPN parameters in $OM_1$ using the crisp numbers in Table 1. Based on Eq. (2), we obtained the interval-valued O, S, and D of $FM_7$ in $OM_1$, presented in Table 3. Then, based on Eq. (1), we obtained $RPN_{7,1} = [0.3, 0.8] \times [0.5, 1.0] \times [0.3, 0.8] = [0.045, 0.640]$.

Table 3. Evaluation by three experts of the three RPN parameters of $FM_7$ in $OM_1$.

| Parameter of RPN | O | S | D |
|---|---|---|---|
| $E_{7,1}^1$ | 5 | 8 | 3 |
| $E_{7,1}^2$ | 3 | 5 | 8 |
| $E_{7,1}^3$ | 8 | 10 | 7 |
| $\min_{1 \le p \le 3}\{\frac{E_{7,1}^p}{10}\}$ | 3E-01 | 5E-01 | 3E-01 |
| $\max_{1 \le p \le 3}\{\frac{E_{1,1}^7}{10}\}$ | 8E-01 | 10E-01 | 8E-01 |
| $E_{7,1}$ | [0.3, 0.8] | [0.5, 1.0] | [0.3, 0.8] |

## 3. Case study

This section describes the application of the proposed framework to compare navigational risks of potential grounding scenarios for an autonomous ship in three OMs. In Section 3.1, a grounding AS is analysed to present the logic of the framework. In Section 3.2, the validity of this framework is verified by analysing 65 grounding AS, drawing a risk profile for ships in the three discussed OMs in the sea area under investigation.

### 3.1. A grounding accident scenario

On 20 May 2007, two high-speed crafts, the *Universal Mk 2008* with 131 passengers and the *Universal Mk 2010* with 243 passengers, hit the breakwater at 34 and 19 knots, respectively. Both accidents were investigated as groundings by the local Marine Department. According to the accident report [66], these accidents were caused by the failure of both Masters to closely monitor the vessel's positions in squally weather conditions. Looking at the grounding of the *Universal Mk 2008*, we applied the proposed framework to generate potential AS and compare risks in the three OMs, i.e., MC, RC, and AC, as follows.

**[*Step 1*] *FMs identification and AS development***

***Identification of FMs based on the accident analysis model***

The analysis of the grounding of the *Universal Mk 2008* based on the accident report [66] and using the 24Model, did not allow us to identify neither the radical cause (safety management system) nor the root cause (safety culture), although it allowed to obtain immediate/direct causes, i.e., A1, B1, B2, and B3, indirect reasons, i.e., C1, C21, C22, and an external factor, i.e., F1, as shown in Fig. 7. The four immediate/direct causes correspond to the four FMs presented in Section 2.3, i.e., A1 for $FM_{15}$, B1 for $FM_2$, B2 for $FM_8$, and B3 for $FM_1$.

***Development of an AS based on the identified FMs***

Using the 24Model, the accident paths were also identified, as shown in Fig. 7. Following these paths, four identified FMs were linked to develop an AS (see Fig. 8). Fig. 8 shows that the AS was composed of two parallel sets of FMs, i.e., $FM1$ and $FM2$, defined separately. $FM1 =$

$\{FM_1^1, FM_2^1, FM_3^1\}$, where $FM_1^1$ was $FM_{15}$ ('Weather/other environmental factors'); $FM_2^1$ was $FM_2$ ('Inadequate lookout'); $FM_3^1$ was $FM_8$ ('Improper assessment of ship position'); and $FM2 = \{FM_1^2\}$, where $FM_1^2$ was $FM_1$ (Mishandling'). Moreover, from the accident paths in Fig. 7, the FMs in $FM1$ were found as consecutive, with strong mutual dependences, and were, thus, assessed as high. On the contrary, the dependence between $FM2$ and $FM1$ was identified as low, since $FM_2$ was parallel to the FMs in $FM1$.

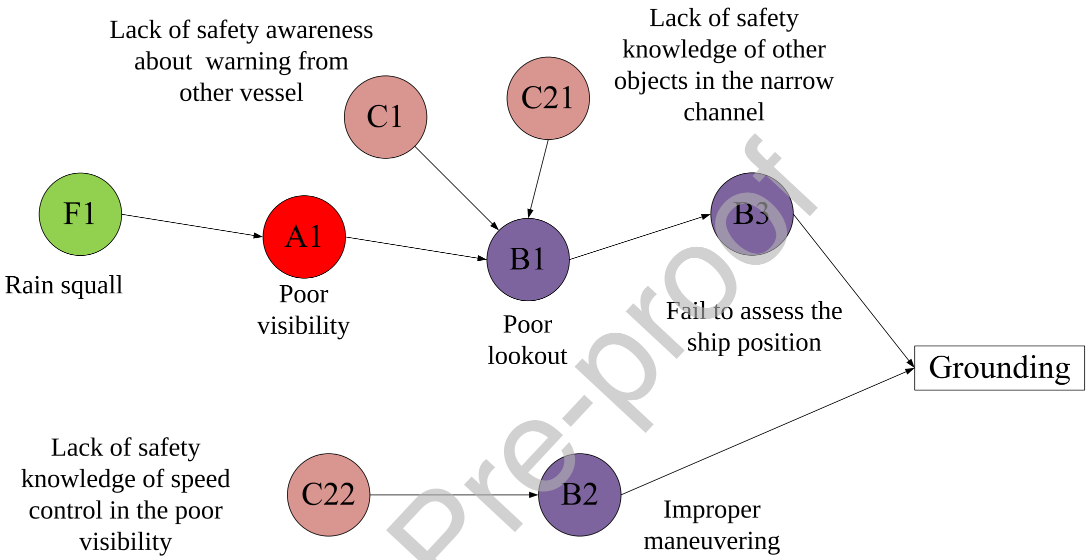



Fig. 7. The accident paths of the *Universal Mk 2008.*

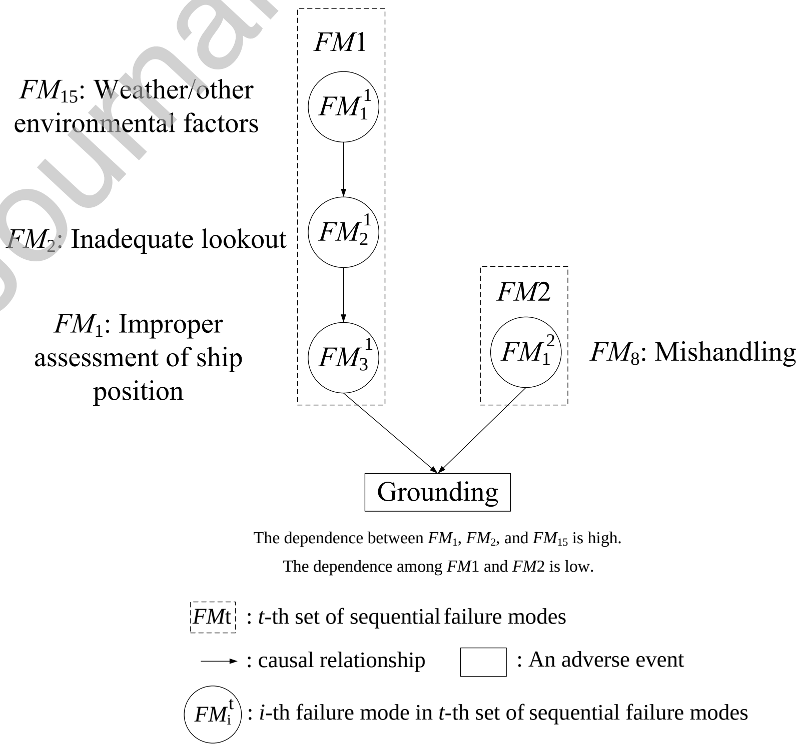



Fig. 8. The developed AS for the *Universal Mk 2008.*

**[*Step 2*] *Risk assessment of AS for the three OMs***

***Assessment of the interval-valued RPN for an FM***

The three RPN parameters of the four FMs identified in [*Step 1*] were evaluated by the experts for the three OMs (see Section 2.3). The evaluation results in terms of interval numbers are shown in Appendix C. Based on these, interval-valued RPNs of these four FMs in the three OMs were obtained using Eq. (1), which is also shown in Appendix C.

***Assessment of the interval-valued RPN for an AS***

The structure of the AS developed in [*Step 1*] was in the form of AS3. Therefore, Eq. (5) was used to calculate the interval-valued RPN of $FM1$ and $FM2$ on $OM_{\mathrm{j}}$, i.e., $RPN1_{\mathrm{j}}$ and $RPN2_{\mathrm{j}}$, respectively. In $FM1$, the dependences between the three FMs were evaluated as high in [*Step 1*]. Hence, $RPN\mathrm{t}_{\mathrm{j}} \approx \max\limits_{\mathrm{i}}\left(RPN_{\mathrm{i,j}}^{\mathrm{t}}\right)$ in Eq. (5) was used to calculate $RPN1_{\mathrm{j}}$, so as to rank the values of the *RPNs* of the involved FMs, i.e., $RPN_{1,\mathrm{j}}^{1}$, $RPN_{2,\mathrm{j}}^{1}$, and $RPN_{3,\mathrm{j}}^{1}$, and to identify the largest as $RPN1_{\mathrm{j}}$. Taking the calculation of $RPN1_{1}$ as an example, we ranked three interval numbers, i.e., $RPN_{1,1}^{1}$, $RPN_{2,1}^{1}$, and $RPN_{3,1}^{1}$, that were interval-valued RPN of $FM_{15}$, $FM_{2}$, and $FM_{1}$ on MC, respectively. Based on Eqs. (9-10), we obtained a preference matrix $P$ of these, as follows:

$$P = \begin{pmatrix} p\left(RPN_{1,1}^{1} \geq RPN_{1,1}^{1}\right) & p\left(RPN_{1,1}^{1} \geq RPN_{2,1}^{1}\right) & p\left(RPN_{1,1}^{1} \geq RPN_{3,1}^{1}\right) \\ p\left(RPN_{2,1}^{1} \geq RPN_{1,1}^{1}\right) & p\left(RPN_{2,1}^{1} \geq RPN_{2,1}^{1}\right) & p\left(RPN_{2,1}^{1} \geq RPN_{3,1}^{1}\right) \\ p\left(RPN_{3,1}^{1} \geq RPN_{1,1}^{1}\right) & p\left(RPN_{3,1}^{1} \geq RPN_{2,1}^{1}\right) & p\left(RPN_{3,1}^{1} \geq RPN_{3,1}^{1}\right) \end{pmatrix} = \begin{pmatrix} 0.5000 & 0.4525 & 0.6528 \\ 0.5475 & 0.5000 & 0.6754 \\ 0.3472 & 0.3246 & 0.5000 \end{pmatrix}.$$

Then, based on Eq. (11), the ranking values of $RPN_{1,1}^{1}$, $RPN_{2,1}^{1}$, and $RPN_{3,1}^{1}$ were obtained as equal to 0.3509, 0.3705, and 0.2786, respectively. Obviously, $RPN_{2,1}^{1}$ was the highest value; therefore, $RPN1_{1} = RPN_{2,1}^{1} = [0.027, 0.576]$. However, in $FM2$ with one FM involved, apparently, based on Eq. (5), $RPN2_{\mathrm{j}} = RPN_{1,\mathrm{j}}^{2}$. Given j = 1, $RPN2_{1} = RPN_{1,1}^{2} = [0.112, 0.810]$. Next, since the dependence between these two sets, $FM1$ and $FM2$, was evaluated as low in [*Step 1*], $RPN_{\mathrm{j}} = \prod_{\mathrm{t}=1}^{s} RPN\mathrm{t}_{\mathrm{j}}$ in Eq. (6) was used to calculate the interval-valued RPN of parallel sets of FMs. Hence, we obtained $RPN_{1} = RPN1_{1} \times RPN2_{1} =$

$[0.003, 0.467]$. Similarly, we obtained $RPN_2 = [0.002, 0.159]$ and $RPN_3 = [0.000, 0.026]$.

***[Step 3]* Risk comparison of the three OMs**

To rank $RPN_1$, $RPN_2$, and $RPN_3$ in [*Step 2*], based on Eqs. (9-10), we used a preference matrix $P$ of $RPN_j$ as follows:

$$P = \begin{pmatrix} p(RPN_1 \geq RPN_1) & p(RPN_1 \geq RPN_2) & p(RPN_1 \geq RPN_3) \\ p(RPN_2 \geq RPN_1) & p(RPN_2 \geq RPN_2) & p(RPN_2 \geq RPN_3) \\ p(RPN_3 \geq RPN_1) & p(RPN_3 \geq RPN_2) & p(RPN_3 \geq RPN_3) \end{pmatrix} = \begin{pmatrix} 0.5000 & 0.7488 & 0.9531 \\ 0.2512 & 0.5000 & 0.8689 \\ 0.0469 & 0.1311 & 0.5000 \end{pmatrix}.$$

Then, based on Eq. (11), the ranking values of $RPN_j$ were calculated as follows: $Rank(RPN_1) = 0.4503$, $Rank(RPN_2) = 0.3533$, and $Rank(RPN_3) = 0.1963$, as depicted in Fig. 9. Fig. 9 shows that the highest navigational risk for the analysed AS was associated with MC, followed by RC and AC.

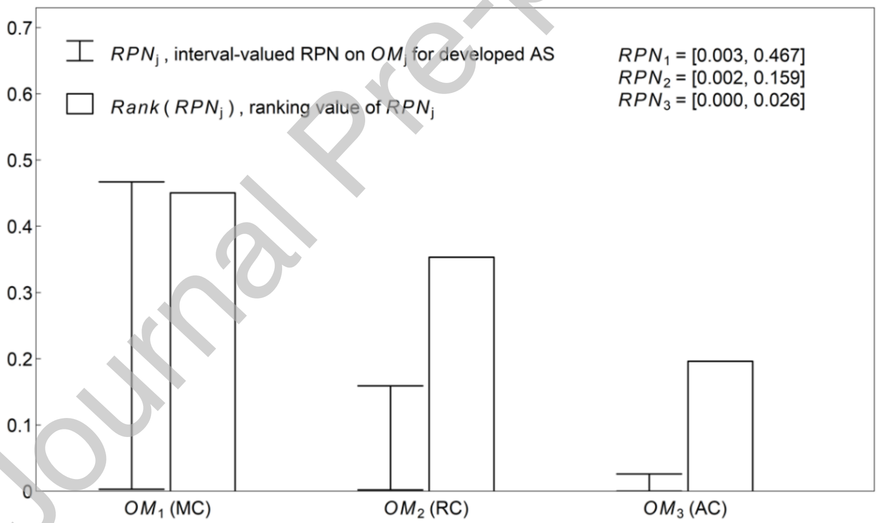



Fig. 9. Interval-valued RPNs in three OMs and corresponding ranking values.

### 3.2. Evaluation of the risk profile for a predefined sea area

In Section 2.3, data on 65 groundings occurred in the channels to and harbour or anchorage areas in the west of Port of Shenzhen were used to identify FMs and develop corresponding grounding scenarios, as shown in Appendix A. In this sub-section, the navigational risks of these 65 grounding scenarios for autonomous ships in three OMs were compared using the proposed framework. Due to limited space, the processes of calculation are omitted. The results are presented in Appendix D, as well as in Fig. 10 according to six ship types (i.e., container ship, supply vessel, bulk/general cargo ship, liquefied cargo ship, and passenger ship), and two areas (channels, and harbour or anchorage areas). The results are also presented in Fig. 11 according to four seasons and six time windows, in line with the shifts of the officers on bridge.

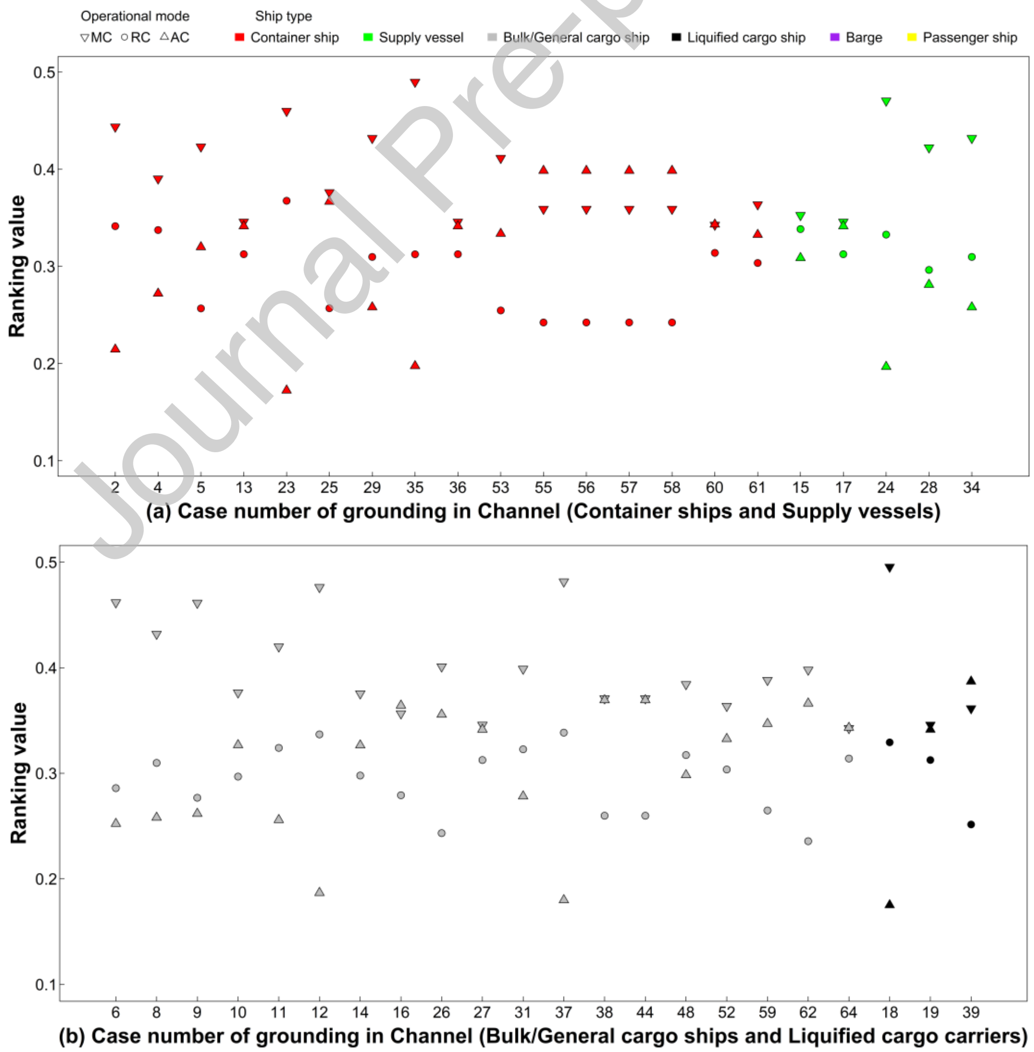
The majority of the cases shown in in Fig. 10 demonstrate that in channels, the risk of grounding for a ship operating in AC or RC is expected to be lower than for the ship operating in MC. This holds for all the analysed ship types, and is concurrent to the findings presented earlier in [54]. Additionally, more ship types are involved in the accident scenarios in the harbour or anchorage area (6) than in a channel (4). This may indicate the importance of geographical information in terms of waterways with complexity of traffic congestion as a grounding factor [67-71]. However for some scenarios (case 46, 49, and 51), reflecting harsh hydro-environmental conditions that caused the ships to run ground the risk level does not vary among operational modes. This means that changing OM may not be an effective measure to avoid grounding in case of very unfavourable weather conditions.

Moreover, the majority of cases shown in Fig. 11(a) yields the noticeably higher risk for MC than for AC or RC, regardless of the season and time window. However, there is an evident tendency for the accident occurrence time window for spring (16:00-20:00) and winter (04:00-08:00), while such relation is not observed for summer and autumn.

These conclusions, may assist in developing the operational procedures for the competent traffic management authorities.

In some cases the ranking values of two OMs is very close to each other, e.g., MC and RC in case 1 as well as MC and AC in case 27. The reason may be rooted in that the range of two RPN parameters, namely O and D, for the identified FM were the same in each OM (see Appendix C). In some cases the corresponding ranking values of the OMs were the same across the cases. This can be explained by the similarity of the developed accident scenarios based on accident records, e.g., cases 38, 40, 45, and cases 55, 58. Another reason is that, although the causes found in the accident reports were different, they were mapped to the same FMs that were used to develop their AS with the same structure, e.g., for cases 13, 17, 19, and 20. The FMs in the AS of these four cases were $FM_3$ ('Inadequate training/experience'), and $FM_7$ ('Insufficient anticipation of nautical conditions'). Nonetheless, the specific causes were not identical in their accident reports. Taking 'Inadequate training/experience' as an example, in case 13 and 19, the cause was the fact that the crew onboard did not estimate the proper tide window; in case 17, the cause was that the crew onboard did not navigate with caution; in case 20, by contrast, the cause is due to that the crew onboard did not use good seamanship.

Finally, the same FMs may lead to different ranking values. For example, case 13 and case 21 had the same FMs ($FM_3$ and $FM_7$) but different ranking values, which was due to the difference in the structures of the corresponding AS.



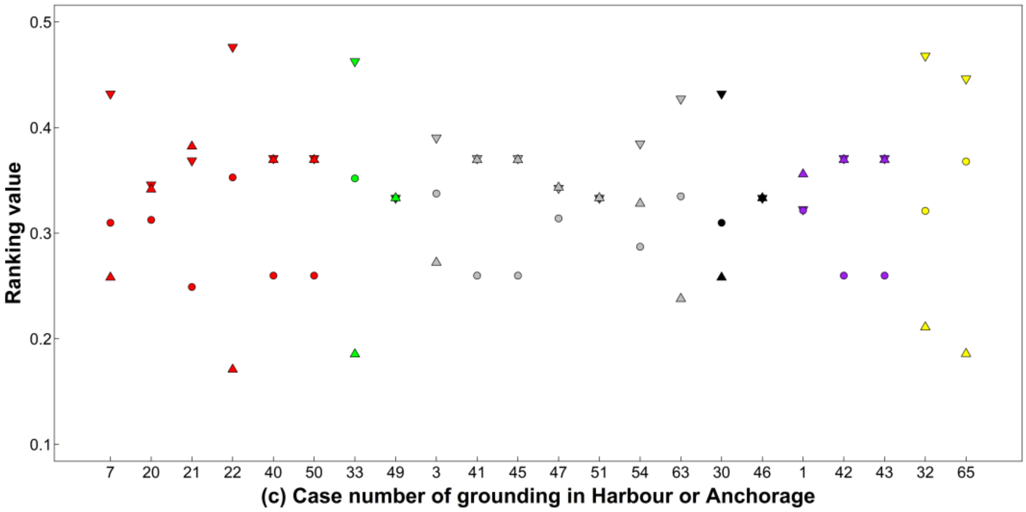



Fig. 10. Ranking values in three OMs for the 65 cases investigated, presented by ship type and accident area.

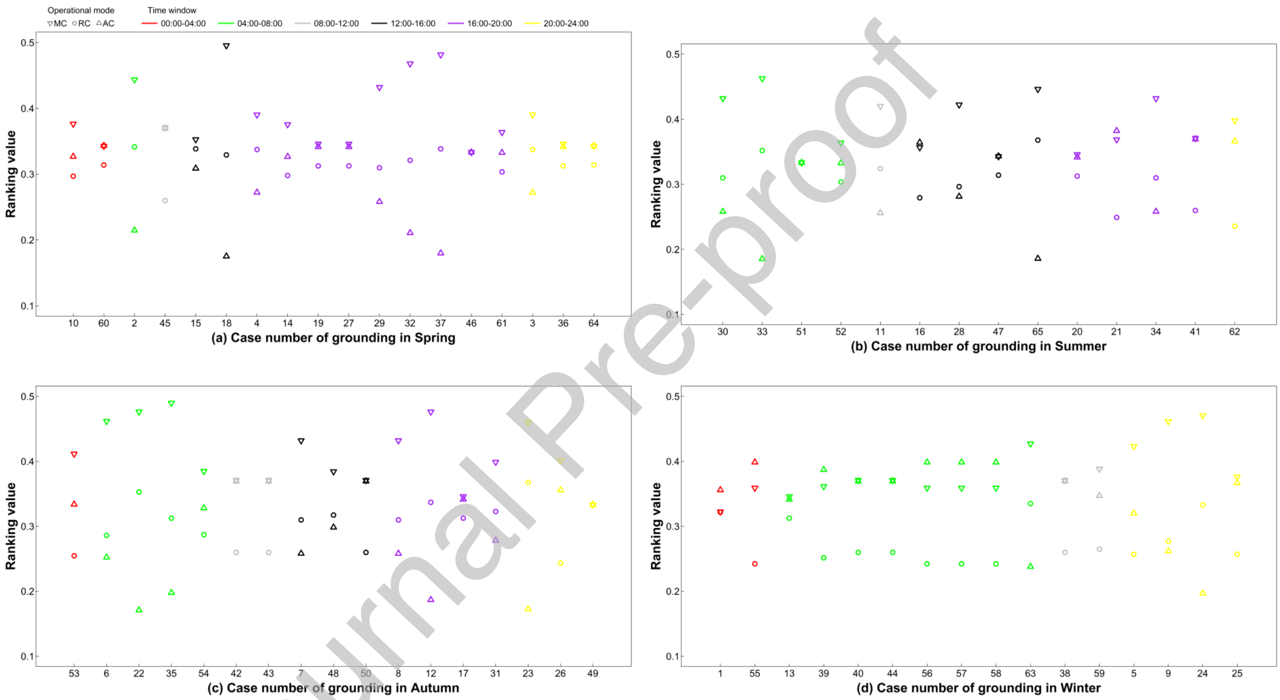



Fig. 11. Ranking values in three OMs for the 65 cases investigated, presented by season and time window.

## 4. Discussion

In the proposed framework, the structure of an AS was established based on accidental paths and FMs. In the case study, this structure was simplified considering immediate/direct causes and using generic FMs. This simplification resulted not only in the fact that the discussed AS ignored specific ship features such as ship type and size, but also in the minor effect of ship type on the results compared to geographical area and environmental factors, as shown in Fig. 10. However, ship type may be the key variable to determine human casualties or ships loss [40] and the results of risk assessment [72]. Although we have extended the scope of the causes to ships using the 24Model, in the future this neglect may be overcome with the release of data on accidents of autonomous ships. Furthermore, the logic of risk reasoning relies on the evaluation of dependence among FMs or sets of FMs, to improve the latter it is worth to refer to the existing guidance or standard processes [22, 73, 74]. Alternatively, it is suggested to analyse the impacts of the interactions and interdependencies between FMs [75, 76], i.e., common cause failures and cascading failures, on the risk of series-parallel structure of the scenario. Moreover, it is advisable to consider these dependences as time variant.

The immediate/direct causes of the FMs identified in the three OMs considered, are examined in Section 2.3. From Table 2, we found that an FM may belong to different types in relation to autonomous ships. For instance, $FM_2$ ('Inadequate lookout'), could be either human-related, e.g., caused by poor situation awareness, organization-related, e.g., caused by poor watching schedule, or ship-related, e.g., caused by sensor failure onboard. Moreover, we found that the immediate/direct causes for FMs belonging to the same type are not the same in different OMs; for example, novel causes related to human-machine interface interaction or Ship-RCC interaction appeared in RC, and only few of them appeared in MC or AC. In the accident count, we found that in several cases typhoons were the only cause leading to grounding, while in other cases, adverse sea condition contributed to grounding to a different extent. Therefore, we set 'Weather/other environmental factors' as $FM_{15}$. However, this FM could be an immediate/direct cause related to environment for other FMs, e.g., $FM_8$ ('Mishandling'), and

$FM_{10}$ ('Rule violation'). Hence, interconnectedness existed among some FMs identified. This intra-relationship on FM causes did not affect the results of our case study, since clarifying the dependences between FMs is also necessary for AS development. Although employing accident statistics on conventional ships is a way to solve the problem of lacking accidents of autonomous ships [40, 54], this is another limitation of the present study. On the one hand, the 15 generic FMs identified from the 65 groundings analysed in a specific area and for a limited period, do not cover all possible failures related to grounding. On the other hand, by only relying on conventional ships accident data it is hardly likely to uncover novel FMs that will arise in autonomous ships. Hence, future FMs needs to be identified from multiple sources, and the process of identification needs to satisfy the principle of Mutually Exclusive, Collectively Exhaustive. Even if we had autonomous ships accidents data, the identification of FMs and accident paths would still be an iterative process in the whole life of autonomous ships, since the concept of operation and the risk analysis are typically iterated until all relevant risks are managed [77]. The use of only historical data related to conventional ships to identify FMs for future operational patterns of maritime transportation systems accommodating autonomous ships does not seem not sufficient, especially when it comes to other modes than manual operations, [19, 41]. This is an evident limitation of this study, which could be addressed in the further research. This fact, however, does not undermine the overall idea of risk-informed framework presented here, which complements the ongoing research efforts in the direction of autonomous shipping risk and safety. In relation to the latter, risk assessment has been included in existing guidance for autonomous ships released by various maritime departments, shipping registries, and class societies [78-82]. For example the China Classification Society [80] suggests that emerging technologies not covered by the standing rules should be considered in the light of risk assessments procedure following FSA guidance, or related national and international rules. Specifically, in order to design autonomous navigational control and sensor functions or to select corresponding facilities, risk analysis methods such as FMEA are suggested to identify hazards in all navigational scenarios and quantify the associated risks. However, the approach taken by BV [81] and the Russian Maritime Register of Shipping [82] leads to the assessment of risk for autonomous ships simply by in the view of probability and consequence applying a predefined, classic risk matrix. As it seems sufficient for simple, technical systems, it may be inadequate for a complex and distributed system, with numerous aspects pertaining to risk and uncertainty remaining hidden. The framework proposed in this study not only addresses FMs occurrence and severity of consequence, but also accounts for the capability to detect FMs. The framework focuses on comparing the results of the risk assessment for a same scenario among three OMs, including inherent uncertainty. The assumption behind this comparison may be undermined by the argument that the potential accident mechanism of autonomous ships to generate accident scenarios may be different across OMs. However, the proposed framework is generic and open, therefore it can be expanded in the future to account for the new scenarios. Moreover, the results of navigational risk in each OM are required to be evaluated as either acceptable or not by using appropriate criteria, while a criterion to measure risk in terms of interval numbers is currently missing. Therefore, in the future this study could facilitate the development of rules stipulated by these class societies, and provide valuable risk-information to the stakeholders.

Despite the abovementioned challenges, the proposed framework can serve its purpose, which is the comparison of the RPNs associated with the operation of prospective MASS in different OMs. However, a limitation of this technique is that it cannot be applied in extreme cases, such as in the case of typhoons, as in cases 46, 49, and 51 presented in Section 4.2. This deficiency may be overcome through the formulation, by the port authority and the governmental maritime department, of policies on the OMs utilized in extreme weather that are stricter than those on OMs utilized in normal conditions. Therefore, this comprehensive framework may facilitate, although it may not determine, the selection of a specific OM. This selection is feasible based on risk assessment, but depends on the definition of acceptable criteria [35, 38, 83]. However, universally accepted criteria to measure the navigational risk for autonomous ships are still lacking. Moreover, the issue of how to select an appropriate OM for autonomous ships may be a multiple attribution problem, since this selection may consider not only the results of navigational risk comparison, but also other aspects, e.g., the availability of ship-RCC communication, and the accessibility of embarking. Moreover, in some cases, the OM to be adopted shall comply with compulsory rules of coast or port states, if any.

## 5. Conclusion

This paper proposes a framework to compare risks in scenarios where autonomous ships navigate in three possible modes, i.e., manual, remote, or autonomous control. To this end, we defined three generic AS comprising FMs connected sequentially or in parallel. The structure of the AS was built by linking FMs related to human, organization, ship, environment, or technology. The navigational risk of the scenarios with autonomous ship encounters was deduced following the logic of risk reasoning, that is by using the RPNs methodology to evaluate the risk of the FMs identified and considering the dependences among these FMs. This process employed experts' elicitation, due to the lack of data related to the operation of autonomous ships, which in turn draws uncertainty into risk assessment. To convey this uncertainty in risk quantification for the scenario and FMs, experts' evaluations using crisp numbers were transformed into interval numbers. Hence, when comparing navigational risks of the scenarios in the three OMs investigated, operational rules for interval numbers were applied. The comparison results could provide risk information for decision-making to select OMs as a risk management option. However, the question of how to choose the proper OM is still open, since this selection shall rely on solid criteria to measure the results of risk analysis directly, which are currently lacking, or it shall take into account other aspects such as the availability of ship-RCC interaction, the accessibility of embarking, and local rules.

In relation to the case study, the AS were derived from conventional ships' groundings in the Pearl River Estuary, a coastal area in China. With the assumption that autonomous ships navigate in a given AS, the identified FMs were analysed in the three OMs considered, while the framework parameters were determined by domain experts. The results revealed significant variation of risk levels for the three analysed OMs for an average operational conditions.

However, in case of extreme hydro-meteorological conditions the ranking values of navigational risks remain the same across the three OMs considered.

Although the risk reasoning logic in the proposed framework, which takes into account the way to link FMs and their dependences, compromises the easiness and transparency of the method, its advantages in ranking navigational risks are verified by the results of 66 cases in total. To enable a constant improvement of the obtained results, the accident mechanism of autonomous ships needs to be revealed, as such accidents will happen in the future, with a better description of the associated FMs and developed scenarios.

The findings may facilitate the process of operational rule development for the relevant traffic management authorities.

# cRedit

Cunlong Fan: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing- Original draft, Writing-review & editing
Jakub Montewka: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing- Original draft, Writing-Reviewing and Editing
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# Declaration of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, 'A risk comparison framework for autonomous ships navigation.'

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The views expressed remain solely those of the authors.

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