Gil, M, Poczęta, K, Wróbel, K, Yang, Z and Chen, P

Toward Using Fuzzy Grey Cognitive Maps in Manned and Autonomous Collision Avoidance at Sea

Article

Gil, M, Poczęta, K, Wróbel, K, Yang, Z and Chen, P (2025) Toward Using Fuzzy Grey Cognitive Maps in Manned and Autonomous Collision Avoidance at Sea. IEEE Journal of Oceanic Engineering. pp. 1-21. ISSN 0364-9059

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Toward Using Fuzzy Grey Cognitive Maps in Manned and Autonomous Collision Avoidance at Sea

Mateusz Gil, Katarzyna Poczęta, Krzysztof Wróbel, Zaili Yang, and Pengfei Chen

***Abstract*—With Maritime Autonomous Surface Ships (MASS) slowly but steadily nearing full-scale implementation, the question of their safety persists. Regardless of being a disruptive technology, they will likely be subject to the same factors shaping their safety performance as manned ships nowadays are. Yet, the impact of these factors may be different in each case. The current study presents an application of Fuzzy Grey Cognitive Maps (FGCMs) to the comparative evaluation of factors affecting collision avoidance at sea. To this end, subject matter experts have been elicited, and the data obtained from them have been analyzed, concerning how changes in the intensity of given factors would affect safety performance. The obtained results showed that with the use of FGCM, it was possible to model the relative impact of selected factors both on a specific phase of the maritime collision avoidance process as well as on its entirety. The conducted analysis shows noticeable variability of the influence of some factors, depending on the timing of their activation during the process (time dependence), and using FGCM, it was possible to assess its quantification. Furthermore, the results indicate that greater differences can be found between the factors' impact on phases of an encounter than between manned and autonomous ships. The outcome of this study may be found interesting for all parties involved in maritime safety modeling as well as working on the forthcoming introduction of autonomous ships.**

***Index Terms*—Collision avoidance, Fuzzy Grey Cognitive Maps (FGCMs), Maritime Autonomous Surface Ships (MASS), maritime safety, safety modeling.**

I. Introduction

INTERNATIONAL shipping is responsible for carrying over 80% of global trade volume [1]. Although it is vital to the sustainable development of the global economy, shipping is also facing two primary challenges, including the need for decarbonization [2] and shortages in the workforce [3]. A frequently suggested solution to both challenges, and especially the latter one, is the introduction of autonomous merchant vessels, also referred to as Maritime Autonomous Surface Ships (MASS). With reduced crews and various innovative technologies installed, they offer the potential to solve numerous problems existing within maritime transportation. Among these is a declining but still high number of marine casualties and incidents involving ships [4]. However, the potential positive impact of MASS on maritime safety is still being discussed [5], [6], [7]. With different methods and models applied [8], [9], neither appears to have delivered a conclusive result. This can be attributed to the lack of data on operations due to MASS being in a prototype phase as of late 2024. This issue has in most cases been addressed by an application of fuzzy Bayesian Belief Networks [10], [11] to help estimate and understand related uncertainties. In our present study, we suggest that Fuzzy Grey Cognitive Maps (FGCMs) can also be applied to quantify, assess, and inform about these uncertainties.

One of the aspects that is most studied with respect to MASS is collision avoidance at sea [12]. It has been raised on several occasions that interactions of fully crewed ships with those to a varied extent operating in an autonomous mode can present a major challenge to maintaining the safety of maritime traffic [13], [14], [15], [16]. This can be attributed to potentially differing ways of understanding the navigational situation by both humans and computers [17], [18], but can also be the effect of different factors affecting the performance of both types of ships [19], such as density of traffic, crew performance, or weather conditions. However, these factors may affect the overall safety performance of either manned or autonomous ships in a different manner and with different intensities, thus influencing the collision avoidance process dissimilarly.

To identify the impact of these factors, an expert study has been performed with an application of FGCM to model the relative impact of factors affecting successful collision avoidance in two cases: 1) of a fully-crewed ship and 2) a fully autonomous one.

FGCM is a soft computing technique combining the advantages of Fuzzy Cognitive Maps (FCMs) [20] and Grey System Theory [21]. FGCM has made some improvements over classical FCMs and can be applied in numerous multiple-meaning problems and grey environments. The biggest advantage of using FGCM is its ability to handle the uncertainty of the experts' assessments for causal relations between concepts and within the initial concepts' states [22]. The output of the FGCM analysis presents the degree of uncertainty of the output concepts

Received 23 May 2024; revised 8 November 2024; accepted 23 November 2024. This work was supported in part by the European Research Council through TRUST project under Grant CoG 2019 864724 and in part by Gdynia Maritime University under Grant WN/2024/PZ/12. *(Corresponding author: Mateusz Gil.)*

Associate Editor: Y. Tang.

Mateusz Gil and Krzysztof Wróbel are with the Research Group on Maritime Transportation Risk and Safety, Faculty of Navigation, Gdynia Maritime University, 81-345 Gdynia, Poland (e-mail: m.gil@wn.umg.edu.pl).

Katarzyna Poczęta is with the Faculty of Electrical Engineering, Automatics Control and Computer Science, Kielce University of Technology, 25-314 Kielce, Poland.

Zaili Yang is with the Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF Liverpool, U.K.

Pengfei Chen is with the School of Navigation, Wuhan University of Technology, Wuhan 430063, China, and also with the Hubei Key Laboratory of Inland Shipping Technology, Wuhan 430063, China.

Digital Object Identifier 10.1109/JOE.2024.3516095

expressed by the greyness metric. The inference process in a FGCM may converge to a fixed point, a limit cycle, or exhibit chaotic behavior. Convergence is an important topic in recent studies on the behavior of FGCMs. The conditions for the existence and uniqueness of fixed points of FGCMs have been analyzed in [23], [24], and [25].

FGCMs have been successfully applied to model an industrial electrical transformer [22], a chemical process control system [26], radiotherapy treatment planning [27], and an intelligent security system controlling surveillance assets [28]. In [29], FGCMs have been used to model the causal relationships between personal beliefs and types of intelligence. The uncertainty propagation in FGCM dynamics on the example of a chemical control problem has been analyzed in [30]. In addition, to increase the efficiency of the model, Hebbian-based algorithms were used in the learning process. In [31], FGCM was used to build an Intelligent Security System model that controls surveillance assets and enables the selection of the best surveillance assets to detect an intruder. The results presented in the research literature confirm that FGCM is an effective method for approximating the human decision-making process. This study, in turn, aimed to investigate the feasibility of using this type of model for a detailed analysis of the collision avoidance process for manned and autonomous vessels.

Till now, cognitive maps have been applied in the maritime domain to analyze past accidents [32] as well as safety factors in inland navigation [33]. Notably, FCMs have been applied to model human factors in maritime collision avoidance [34]. However, to the best of the authors' knowledge, no attempt has been undertaken to apply FGCM to the safety of MASS, although some studies using mere fuzzy numbers in this field have been published previously [35], [36]. However, looking a bit wider at the use of fuzzy set theory in maritime collision avoidance, these were engaged to determine the size and shape of various ship domains [37], [38], [39] as well as to properly model the ship's behavior [40], [41], allow for collision avoidance decision-making [42] and prediction of a safe path as a solution for a close-quarters situation [43], [44], [45].

It should be noted that using FGCM, it is possible to analyze the relative impact of certain predefined factors (these are often referred to as "*concepts*" in FGCM-based studies) on the process, in this case in the scope of ship collision avoidance. This ability arises due to a lack of knowledge about the initial magnitude of its activation in the current moment of a dangerous ship encounter. Therefore, using the proposed approach, it is possible to analyze the relative impact of the concept(s) on the process, while bearing in mind that during a real close-quarters situation, the initial state of the concept's activation remains unknown to a decision-maker. Thus, the change in the safety level of a ship during an encounter caused by the simulation of activation of one or multiple concepts should be understood as relative rather than absolute.

The objective of this study was to develop and analyze a model of the collision avoidance process for both manned and autonomous ships with the application of FGCM and to identify the most significant differences between these two types of vessels. The secondary objective was to test the applicability of FGCM to investigate features of maritime autonomous systems distinguishing them from traditional manned ones.

To this end, the following Research Questions (RQs) have been formulated:

1) RQ1: How does the intensity of predefined concepts affect the likelihood of avoiding collision?
2) RQ2: What are the differences in the relative impact of given concepts on the collision avoidance process of manned and autonomous ships?
3) RQ3: How does such a related impact change with the development of a ship encounter?

This article presents three main contributions to the contemporary scientific literature in the field of maritime transportation research, none of which have been investigated before as per the authors' best knowledge.

1) Application of FGCM to analyze factors (concepts) affecting the safety performance of merchant vessels, both manned and autonomous, during the collision avoidance process.
2) Analysis of various simulation scenarios, in which different concepts are activated at different magnitudes, to depict their significance and interaction in the maritime collision avoidance process.
3) A comparison of the safety performance and vulnerability of two types of vessels, i.e., manned ships being currently in operation as well as just emerging autonomous ones, during the four phases of a dangerous ship encounter.

The rest of this article is organized as follows. First, Section II outlines the methods applied and materials used. Then, Section III presents the results of the study, which are then discussed in Section IV. Finally, Section V concludes this article.

II. Materials and Methods

The following section presents the framework applied within the current study. First, a simplified, time-dependent approach to collision avoidance is presented along with an overview of the impact factors considered. Then, the expert elicitation process is described, followed by an overview of FGCM itself. Finally, research scenarios are introduced.

A. Generalized and Time-Dependent Collision Avoidance Process Model

In the research literature, many different models of maritime collision avoidance process have been proposed to date using various methods and approaches [46], [47], [48]. Nonetheless, most of these solutions focus either on certain phases of a dangerous encounter [49], such as conflict detection [50], [51] and safe trajectory planning [44], [52], or on factors affecting the (probability of) collision, such as traffic complexity [53], [54], situational awareness [55], and weather conditions [56], [57]. Seldom are these two aspects jointly taken into consideration. Moreover, only to a lesser extent are they evaluated through a comparison of their performance and applicability to both manned and autonomous ships.

Even when advanced and mature solutions are proposed, these rarely provide a practical and time-dependent viewpoint on the entire collision avoidance process, as well as the variability of its outcome throughout the development of an encounter situation. Typically, three or four stages of the collision avoidance process are distinguished [58], [59], [60], [61], which derive from International Regulations for Preventing Collisions at Sea (COLREGs) and practical interpretation of these rules [62], [63]. However, even if the model takes into account a time-varying approach [10], [64], this usually involves different actors and actions in each stage of the process, which leads to the complex structure of the model [10], [65], [66], which may cause its demanding practical application. Furthermore, some of the actions or factors affecting one phase of collision avoidance are often omitted in the remaining ones, even when these are present but with limited impact on the overall process.

Therefore, the following research assumptions were set to propose and achieve a reasonable model that could be applied to the evaluation of the collision avoidance process regardless of the presence of the crew on board or even the ship's current degree of autonomy (DoA) as understood in [67].

1) The model should be focused on the operational phase of ship collision avoidance as watchkeeping officers, crew, or prospective remote operators of MASS have virtually no impact on the design stage.
2) The structure of the model should reflect the entire collision avoidance process, i.e., from detection of a potentially threatening object through effective resolution of a close-quarters situation. Thus, this should account for time dependence.
3) The model should be provided at a high level of generalization to be easily applied to each ship at each DoA and allow for future development of the model.
4) The blocks (nodes) of the model should consider factors concerning a set of specific actions, rather than considering every single action separately. This maintains the overarching level of the model and will reduce the number of its final nodes.

After assumptions were made, possible factors contributing to the collision avoidance process (sets of actions gathered under the common name) were listed based on the existing literature on the subject. In Fig. 1, the generalized, time-dependent process model of collision avoidance is presented with respect to subsequent phases of a dangerous encounter (marked with different colors). As can be observed, all determined factors that exhaust (at least at a high level) the process of maritime collision avoidance exist in each DoA, while only the contributing actor differs (e.g., a human operator is replaced by an algorithm or actuator). However, actions underlying the factors are still present regardless of the type of ship or the phase of an encounter.

The color code used in Fig. 1 to distinguish the phase of an encounter will also be maintained in further sections of this article for the sake of easy recognition of the results. Similarly, in the subsequent figures shown, the outcomes obtained for a fully manned ship are always presented in blue while for a fully autonomous vessel in red.

When it comes to the relations and dependencies between the factors, due to the generalized structure of the model, all

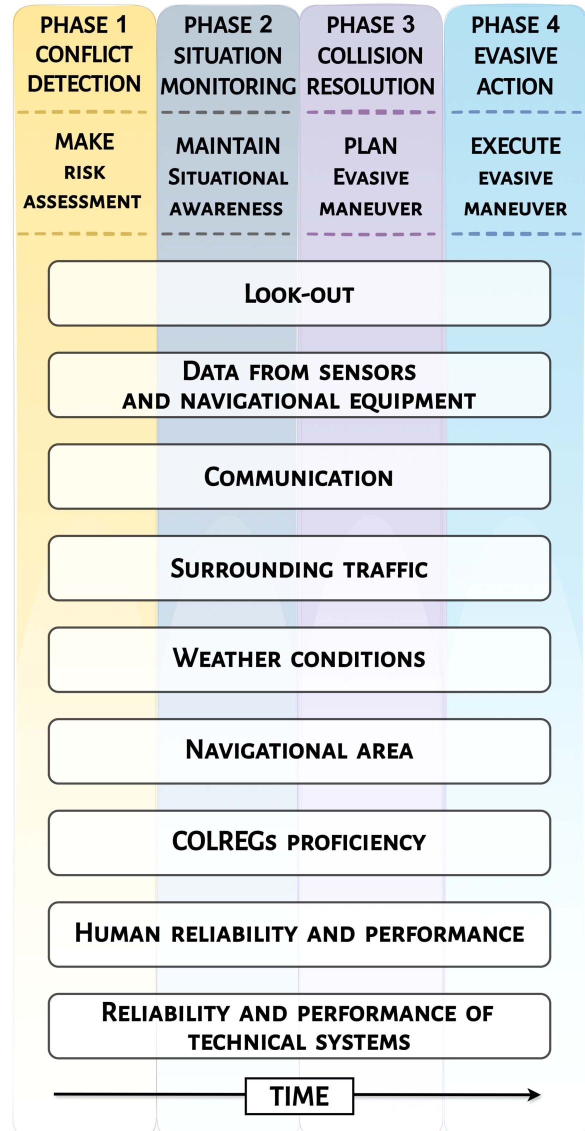


Fig. 1. Generalized and time-dependent collision avoidance process model.

nodes are somehow linked to the others. Therefore, it seems to be unreasonable to simply assess the impact of, for instance, *look-out* on *communication* (especially, when one bears in mind that behind them there are many different predefined actions, such as, e.g., *internal communication*, *VTS communication*, *ship-ship communication*, etc.). Such an influence exists, but its importance (weight) significantly differs within the process (time dependence) and should be analyzed in this respect. For example, the *look-out* at the beginning of the process (ship encounter) allows for detecting a target in an ample time, establishing *communication*, confirming the target's intentions, and finally taking effective countermeasures. If an operator detects the target when ships are already in a close-quarters situation (thus at the late stage of the encounter), the ship will not be able to avoid a collision or a near-miss, while communication at this stage of encounter and agreeing on evasive maneuvers may lead to misunderstanding and an accident. Thus, this exemplary impact of *look-out* on *communication* will be present at each stage of the process but will be time-dependent with different impacts on the entire process depending on its phase.

Therefore, in this study, the collision avoidance process has been split into four phases, which is quite a common approach. In the research literature, there are many collision avoidance tools rooted in the conflict detection and resolution concept also used in nonmaritime transportation modes [68], [69], [70]. By following this approach, the process has been developed and expanded by adding a phase of situation monitoring (when the target is detected but is still too far to take any evasive action) and splitting the *conflict resolution* part into planning an evasive action (when an operator knows, it will be necessary to act but the question is how to do it), and execution of an evasive maneuver (that is a physical execution of the maneuver). Thus, the generalized collision avoidance process presented in Fig. 1 concerning the timeline looks as follows:

> Conflict detection (make risk assessment) → Situation monitoring (maintain situational awareness) → Collision resolution (plan evasive maneuver) → Evasive action (execute evasive maneuver).

This generalized, high-level collision avoidance process allowed for considering the same list of factors in each of the proposed phases. The same actions would be present in each DoA of an autonomous ship and during each phase of the process (regardless of the manned ship or MASS). However, their impact on each phase and thus on the entire collision avoidance process will significantly differ.

B. Predefined Factors

As a foundation for an expert elicitation, a set of nine factors affecting the safety performance of a ship in an encounter situation, as well as their descriptions, has been refined based on a literature review on collision avoidance of both manned and autonomous ships. In particular, factors in [12], [65], [71], [72], [73], and [74] have been addressed. The set of factors along with their descriptions and symbols used in further parts of this research is presented in Table I; note that the underlined keywords provided there are afterward used as a reference in further sections of this article. These factors have then been distributed among the SMEs, using proprietary web-based software with a request for their evaluation.

C. Expert Elicitation

Expert elicitation has been carried out using an online survey, which allowed for determining SMEs' opinions on the impact of a particular factor on the overall safety of the collision avoidance process, using an interval scale described with linguistic variables. Proprietary web-based software was used, and afterward, the results obtained were then transformed into numerical fuzzy data. Since the survey applied to both manned vessels and future autonomous vessels, invitations to complete the questionnaire were sent out to both seafarers with practical experience in ship collision avoidance as well as to researchers working in the field of maritime safety and MASS. For this reason, the established eligibility criteria included two types of respondents: 1) holders of at least an operational license in the deck department under the International Convention on Standards of Training, Certification and Watchkeeping (STCW), i.e., the Officers of the Watch (OOW) diploma or higher, regardless of the declared level of formal education; 2) holders of a doctoral degree, regardless of maritime license status.

First, the experts were familiarized with research assumptions as well as instructions on how to fill out the questionnaire, including handling interactive slider-type questions and interpretation of the interval scale. Second, both the list of predetermined factors, along with their descriptions and definitions of manned and autonomous ships used in this study, were presented to them. Finally, SMEs were asked to assess the impact of each of the predetermined factors in increasing or decreasing the likelihood of success in collision avoidance separately for manned and autonomous ships. This was achieved by indicating an interval between the fully negative (growth of likelihood) and fully positive (reduction of likelihood) impact on ship collision. The assessment of each factor's impact on the collision process was made for each of the proposed phases as well as on the entire process for a fully manned and then repeated for a fully autonomous ship.

To avoid biasing the respondents by suggesting any values, the interval-type slider was used in the questionnaire, with numerical values hidden from the participants of the study, leaving only linguistic descriptions of the scale. In addition, at the beginning of the study, both sliders' tips were set to the neutral position to enforce their movement by the respondent. SMEs were aware that the survey was anonymous, and only some statistical data used to depict the profile of the respondents were collected. A total of 43 respondents filled out the questionnaire. Among the answers collected, 14 did not meet the eligibility criteria or were deemed unreliable during the preliminary stage of data processing and cleaning. The unreliable responses were verified by assessing their share of a given SME's total answers before admitting them to further calculations. A significant number of responses in which neither of the two slider tips was moved (i.e., the beginning or end of the interval was set to zero) were considered unreliable. While a few such responses may have been intentional, their significant share of a respondent's total responses suggested that the SME was bored and seeking to complete the survey as quickly as possible without providing thoughtful answers. Accordingly, for the sake of the credibility of further FGCM results, the SMEs whose responses contained more than 30% of such zero-type intervals were thus considered unreliable and excluded from the dataset.

Therefore, $n = 29$ responses were eventually used in the further steps of the study. To make these even more meaningful and realistic, the authors decided to additionally consider onboard experience affecting respondents' professional knowledge. This was achieved by introducing arbitrarily set weights that have been assigned to each of the SMEs, based on the maritime license held. Therefore, the responses of participants who did not declare the STCW license in the deck department were considered with weight $w_i = 0.4$. OOWs were analyzed with $w_i = 0.75$, Chief Officers with $w_i = 0.85$, and Master Mariners with $w_i = 1$ as the most experienced experts, thus providing (most likely) the

TABLE I
FACTORS AFFECTING THE COLLISION AVOIDANCE PROCESS

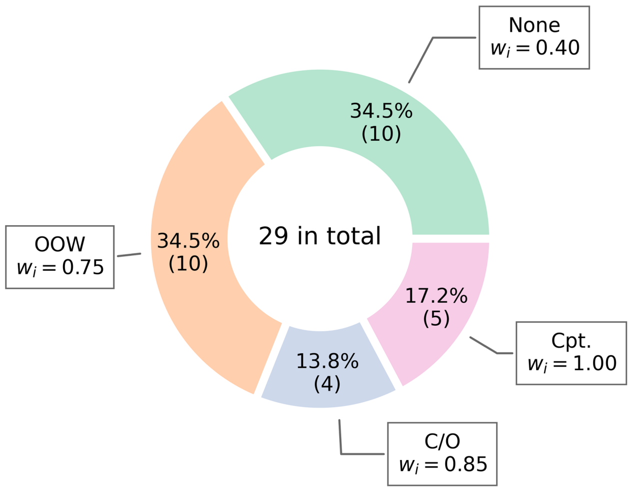
Factor	Reference	Symbol	Description
Navigational area	[71], [74], [75]	X_1	All issues related to (natural and artificial) characteristics of the navigational area in the vicinity of a ship, affecting her safety and performance. For instance, the sufficiency of water depth, distance to the shoreline or other No-Go Areas, nature of the coastline, shoals and shallows, presence of wind farms and other offshore installations, etc.
Human reliability and performance	[73], [76]	X_2	All issues related to good reliability and performance of humans present in the control loop (conning officer, bridge team, operator in the Remote Operation Centre - ROC, etc.). For instance, a lack of fatigue, good mental and physical conditions, sobriety, good health, good situation awareness, etc.
COLREGs proficiency	[12], [77]	X_3	A proper understanding, interpretation, and use of COLREGs (International Regulations for Preventing Collisions at Sea) by the watchkeepers, including, but not limited to identification of lights, shapes, and fog signals; giving way according to the Rules; etc.
Look-out	[72], [77]	X_4	Proper performance of all kinds of look out by a watchkeeper (human or machine) including, but not limited to visual, auditory, RADAR, etc.
Data from sensors and navigational equipment	[78], [79]	X_5	A proper tuning, receiving, and use of navigational equipment, as well as the correct interpretation of data collected by sensors and devices (RADAR, AIS, etc.).
Surrounding traffic	[19], [71], [80]	X_6	All issues related to the density of maritime traffic in the vicinity of a ship, affecting her safety and performance. For instance, the number of ships nearby, presence of privileged vessels (ships with right of way), presence of fishing or sailing vessels, traffic (un)regulated by the VTS, etc.
Weather conditions	[74], [81], [82]	X_7	All issues related to weather conditions in the vicinity of a ship affecting her safety and performance. For instance, visibility conditions, wind speed, sea state, presence of sea ice, etc.
Reliability and performance of technical systems	[65], [73], [83]	X_8	All issues related to the good fitness of technical systems required to maintain the safe operation of the vessel. For instance, a lack of defects and malfunctions within safety-critical systems; a proper operation of navigational equipment, steering gear, engine, etc.; correct maintenance, reliability of the systems, etc.
Communication	[12], [84]	X_9	A proper establishing and conducting of all kinds of external and internal, two-way communication by a watchkeeper including, but not limited to ship-ship, ship-VTS, ship-ROC, within bridge team, bridge-ECR, etc.

most valuable knowledge to the study. The basic demographic information about the SMEs is presented in Fig. 2.

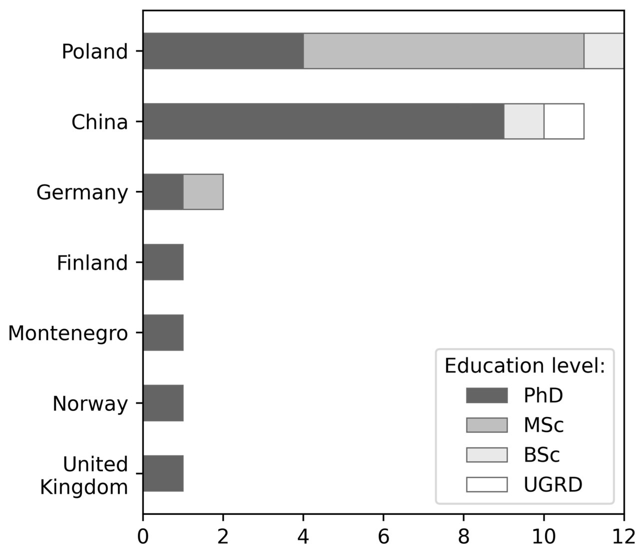
D. Fuzzy Grey Cognitive Maps

The FCM model consists of concepts important for the analyzed problem. Concepts influence each other with the strength described by the relationships between them [20]. FCMs can be initialized with the use of machine learning algorithms or based on expert knowledge [85]. In the FGCM, each relationship is described by its grey intensity $\otimes w_{i,j}$ [21]

$$\otimes w_{i,j} \in \left[\underline{w}_{i,j}, \bar{w}_{i,j}\right] \tag{1}$$



(a)



(b)

Fig. 2. Experts' breakdown by maritime license held [(a) upper part] as well as country of origin and declared level of education [(b) lower part].

where

$i, j = 1, \ldots, n$;
n is the number of concepts;
$\underline{w}_{i,j}$ and $\bar{w}_{i,j}$ are the lower and upper limits of the relationship;
$\otimes w_{i,j}$ is the grey intensity of the relationship between the *i*th concept and the *j*th concept
$\underline{w}_{i,j} \leq \bar{w}_{i,j}$
$\{\underline{w}_{i,j}, \bar{w}_{i,j}\} \in [-1, 1]$.

The FGCM allows for *what-if* analysis to describe possible grey scenarios. The analysis begins with a determination of the initial grey vector state $\otimes\vec{C}(0)$ described as follows [21]:

$$\begin{aligned} \otimes\vec{C}\,(0) &= \left(\otimes C_1\,(0)\,, \otimes C_2\,(0)\,, \ldots, \otimes C_n\,(0)\right) \\ &= \left(\left[\underline{C}_1\,(0)\,, \bar{C}_1\,(0)\right], \left[\underline{C}_2\,(0)\,, \bar{C}_2\,(0)\right], \right. \\ &\quad \left. \ldots, \left[\underline{C}_n\,(0)\,, \bar{C}_n\,(0)\right]\right). \end{aligned} \tag{2}$$

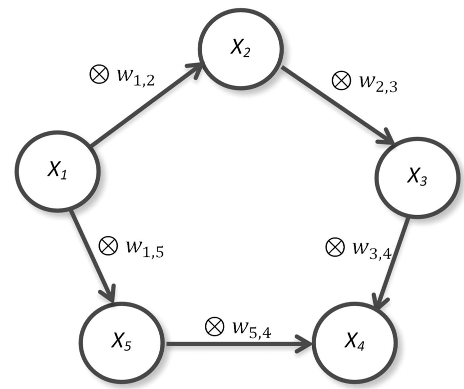


Fig. 3. FGCM example.

Then, the concepts influence each other, and the new grey vector state is calculated based on the selected dynamics model. Each concept can be updated based on the following formula:

$$\begin{aligned} \otimes C_j\,(t+1) &= f\left(\otimes C_j\,(t) + \sum_{i=1,\, i\neq j}^{n} \underline{w}_{i,j} \cdot \otimes C_i\,(t)\right) \\ &= \left[\underline{C}_j\,(t+1)\,, \bar{C}_j\,(t+1)\right] \end{aligned} \tag{3}$$

where

$\underline{C}_j(t)$ and $\bar{C}_j(t)$ are the lower and upper limits of the *j*th concept at the *t* iteration;
$f(x)$ is the activation function, which normalizes the values.

The most frequently used activation functions in FCMs are the sigmoid activation function and the hyperbolic tangent [86]. Thus, the FGCM designers must select the activation function and determine the value of its parameter λ. The choice of activation function and λ value depends on the FGCM designers' preferences and the analyzed problem [86]. The experiments presented in this article have been undertaken using the hyperbolic tangent as an activation function with $\lambda = 0.5$.

The process ends when stability is achieved. Fig. 3 depicts the FGCM model example. In addition, the adjacency grey matrix A($\otimes$) is shown in the following:

$$A\,(\otimes) = \begin{pmatrix} 0 & \otimes w_{1,2} & 0 & 0amp; & \otimes w_{1,5} \\ 0 & 0 & \otimes w_{2,3} & 0 & 0 \\ 0 & 0 & 0 & \otimes w_{3,4} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \otimes w_{5,4} & 0 \end{pmatrix}. \tag{4}$$

The grey values of the concepts and the relationships can be transformed into white numbers with the use of whitenization [87]. The whitenization values can be calculated as follows:

$$\hat{\otimes}\; w_{i,j} = \delta \underline{w}_{i,j} + (1-\delta)\,\bar{w}_{i,j} \tag{5}$$

$$\hat{\otimes}\; C_i = \delta \underline{C}_i + (1-\delta)\,\bar{C}_i \tag{6}$$

where $\delta \in [0, 1]$.

For $\delta = 0.5$, the calculated value is called equal weight mean whitenization.

TABLE II
DESCRIPTION OF THE CONDUCTED RESEARCH SCENARIOS

Research scenario	**Activated concepts (X_i)**	**The magnitude of the concept activation**	**Scope of analysis**
A	*Human* (X_2)	$\{0.1 \cdot X_2 \vert X_2 \in [-10..10]\}$	Impact of a single concept on the overall collision avoidance process
B	*COLREG* (X_3)	$\{0.1 \cdot X_3 \vert X_3 \in [-10..10]\}$	Impact of a single concept on the collision avoidance process for its four time-dependent phases
C	*Communication* (X_9)	$\{0.1 \cdot X_9 \vert X_9 \in [-10..10]\}$	Impact of a single concept on the collision avoidance process for its four time-dependent phases
D	*Look-out* (X_4) *Sensors* (X_5) *Traffic* (X_6)	$\{0.1 \cdot X_6 \vert X_6 \in [-10..10]\}$ $X_5 \in \{-0.75, 0.75\}$ $X_4 \in \{-0.25, 0.25\}$	Impact of combined concepts on the collision avoidance process for manned ships broken down into its four time-dependent phases
E	*Sensors* (X_5) *Traffic* (X_6) *Weather* (X_7)	$\{0.1 \cdot X_7 \vert X_7 \in [-10..10]\}$ $X_5 \in \{-0.75, 0.75\}$ $X_6 \in \{-0.25, 0.25\}$	Impact of combined concepts on the collision avoidance process for MASS broken down into its four time-dependent phases
F	*Look-out* (X_4) *Sensors* (X_5) *Traffic* (X_6) *Weather* (X_7)	$\{0.1 \cdot X_5 \vert X_5 \in [-10..10]\}$ $X_4, X_6, X_7 = 0.5$	Impact of combined concepts on the collision avoidance process for its four time-dependent phases

Greyness metric for grey values in the FGCM can be also calculated. Higher values of greyness mean a higher uncertainty degree. Greyness metric for relationships and concepts is described as follows [22]:

$$\phi\left(\otimes w_{i,j}\right) = \frac{\left|l\left(\otimes w_{i,j}\right)\right|}{l\left(\otimes \psi\right)} \tag{7}$$

$$\phi\left(\otimes C_i\right) = \frac{\left|l\left(\otimes C_i\right)\right|}{l\left(\otimes \psi\right)} \tag{8}$$

where

$|l(\otimes w_{i,j})|$ is the absolute value of the length of the relationship $\otimes w_{i,j}$;
$|l(\otimes C_i)|$ is the absolute value of the length of the concept $\otimes C_i$;
$l(\otimes\psi)$ is the absolute value of the range in the information space

$$l\left(\otimes \psi\right) = \begin{cases} 1, & \text{if } \{\otimes C_i, \otimes w_{i,j}\} \subseteq [0,1] \\ 2, & \text{if } \{\otimes C_i, \otimes w_{i,j}\} \subseteq [-1,1]. \end{cases} \tag{9}$$

The advantage of using FGCM is that experts can introduce both white numbers and grey numbers with varying degrees of uncertainty to describe the causal relationships between concepts, as well as to initialize the initial states of the concepts.

E. Research Scenarios

FGCM allows for *what-if* analysis, using different initial vectors of the activated concepts. Therefore, six exemplary research scenarios (A–F) have been determined to analyze the collision avoidance process of manned and autonomous ships using FGCM (see Table II). The sample sets of the concepts used under the considered research scenarios were selected based on two main reasons: 1) due to their common occurrence as contributing factors to maritime accidents [4], as well as their direct relation to challenges of the safe operation of both manned and autonomous ships [73], [81], [82], and 2) because of their largest influence on the established FGCM model. The latter was investigated and verified through a variance-based sensitivity analysis using Sobol S_{Ti} [88], and the results of which are presented in the last subsection of Section III-A.

In the first three conducted scenarios (A–C), the impact of a single concept, namely, *Human* (X_2), *COLREG* (X_3), and *Communication* (X_9). To this end, the considered concept was

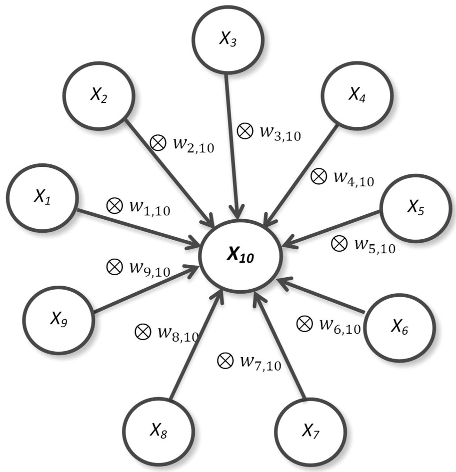


Fig. 4. Proposed FGCM.

activated using a discrete 0.1 step of the white values incrementation while the remaining concepts were inactive. Scenario A considered the entire collision avoidance process, while Scenarios B and C consisted of investigating the impact of a given concept on the individual phases of the process.

The research scenarios D and E consider the simultaneous activation of several factors for either manned ships (D) or autonomous ones (E). In these complex cases, the outcome was always presented as a function of the activation of the concept to which the model was the most sensitive.

The final scenario F investigated the impact of four concepts, selected based on their prevailing impact on the outcome of the model.

Higher order research scenarios have not been pursued due to the large number of possible combinations and the observed dilution of the concepts' impact. Similarly, in future research, other single- and multiconcept scenarios could be investigated, also using various magnitudes of their initial activation values.

III. Results and Analysis

To analyze the FGCM results, it was necessary to convert the responses collected from the experts into grey numbers. Then, the obtained results were investigated twofold: 1) by checking the impact of the individual concept on the entire collision avoidance process for manned and autonomous ships, respectively, and 2) using predefined research scenarios, in which both single and combined concepts were activated at different magnitudes.

A. Overview of the FGCM Results

After collecting, the results of expert elicitation were processed using a weighted geometric mean to reflect SMEs' professional experience in their joint opinion. The weighted results were then transformed into fuzzy numbers and applied to the proposed FGCM model. The model itself is depicted in Fig. 4. As presented, it contains ten concepts (nine factors as listed in Table I and the resulting concept of an overall collision avoidance process X_{10}) and nine relationships. Although one may expect that some factors can be affected by others (i.e., *Look-out* X_4 on *Communication* X_9, see Section II-A), these impacts have not been pursued here for the sake of simplification of the expert elicitation process, and the fact that it could potentially create infinite loops of mutual impacts, thus rendering the network unresolvable.

1) Results Concerning the Entire Collision Avoidance Process: The numerical FGCM results obtained with respect to the relative impact of a given concept on the entire collision avoidance process are collated in Table III and depicted in Fig. 5. This overview allows for some basic analysis and preliminary drawing of conclusions about the influence of a given factor on ship collision avoidance, as well as on the FGCM usability in maritime safety assessment.

As can be seen, the experts were not usually in agreement, and the level of uncertainty in their answers (expressed by greyness) was significant. The X_9 *Communication* was identified as the concept affecting the worst ship safety in avoiding collisions by manned vessels. This was reflected through the largest negative grey and the smallest whitened value. The opposite relationship applies to the X_9 concept for MASS, where this was considered potentially (but not very) beneficial. In the case of the lowest rated factor for an autonomous ship, one can point to *Human reliability and performance* (X_2), among other concepts.

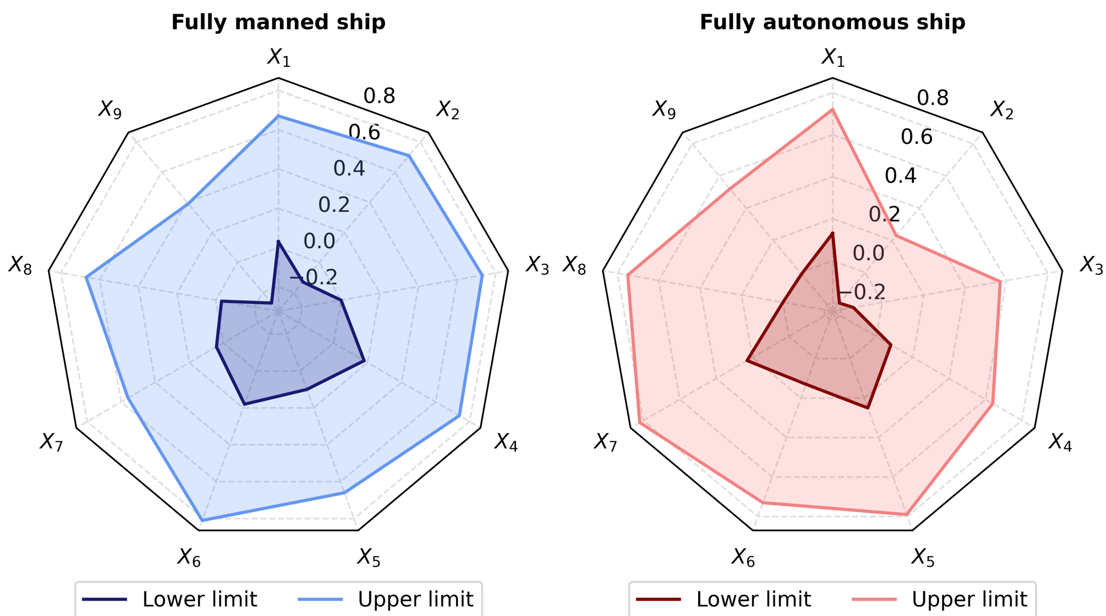
Somewhat surprisingly, in the case of another reliability, i.e., this considered in *technical systems* X_8, the SMEs assessed the impact of this concept on the outcome of the collision avoidance process very similarly (quite significant and mostly positive) in both cases of the manned and autonomous vessel.

It is noteworthy that in the case of concepts that imply the involvement of humans (*Look-out*, *COLREGs proficiency*, *Human reliability and performance*, *Communication*), SMEs evaluated these concepts with a high degree of uncertainty expressed by a significant range of greyness. This may indicate difficulties in quantifying the impact of humans on maritime operations.

The impact of the *Navigational area* (X_1) and *Surrounding traffic* (X_6) concepts was also assessed quite similarly for both vessels. Interestingly, in this case, MASS was considered to perform slightly better than a manned ship in congested waters. It is of note that, in the case of the *Weather conditions* factor (X_7), respondents rated the impact as significantly greater for autonomous vessels with a large spread of the results, indicating the uncertainty of the answers as well as the fact that the impact of weather on MASS can be both extremely favorable and unfavorable during collision avoidance.

2) Results Concerning Time-Dependent Phases: As for the grey results concerning a specific phase of the collision avoidance process, the numerical results are summarized in Table IV and depicted in Fig. 6. It can be noted that despite the similar shape of the fuzzified SMEs' results in each phase, the assessment regarding some specific concepts significantly differs depending on the stage of the process. For instance, the beneficial impact of the *Navigational area* factor was assessed in both types of ships much larger in phases regarding planning and execution of evasive maneuvers (Phases 3 and 4) than in the former ones, where target detection and monitoring are conducted. This time

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.



(a) (b)

Fig. 5. Breakdown of the grey numbers obtained from the SMEs' answers regarding the impact of a given factor on the entire collision avoidance process of fully manned [(a) blue] and fully autonomous [(b) red] ships.

TABLE III
GREY WEIGHTS OBTAINED FOR THE FGCM MODEL IN THE EVALUATION OF THE ENTIRE COLLISION AVOIDANCE PROCESS

$\otimes w_{i,j}$	Fully manned ship				Fully autonomous ship			
	$\underline{w}_{i,j}$	$\overline{w}_{i,j}$	$\widehat{\otimes w_{i,j}}$	$\phi(\otimes w_{i,j})$	$\underline{w}_{i,j}$	$\overline{w}_{i,j}$	$\widehat{\otimes w_{i,j}}$	$\phi(\otimes w_{i,j})$
$\otimes w_{1,10}$	0.03	0.67	0.35	0.32	0.13	0.72	0.42	0.30
$\otimes w_{2,10}$	−0.13	0.71	0.29	0.42	−0.19	0.23	0.02	0.21
$\otimes w_{3,10}$	0.0	0.73	0.36	0.37	−0.14	0.57	0.21	0.36
$\otimes w_{4,10}$	0.18	0.74	0.46	0.28	0.08	0.64	0.36	0.28
$\otimes w_{5,10}$	0.1	0.66	0.38	0.28	0.25	0.79	0.52	0.27
$\otimes w_{6,10}$	0.18	0.81	0.49	0.32	0.13	0.73	0.43	0.30
$\otimes w_{7,10}$	0.04	0.56	0.3	0.26	0.23	0.82	0.53	0.30
$\otimes w_{8,10}$	−0.03	0.67	0.32	0.35	0.00	0.75	0.38	0.38
$\otimes w_{9,10}$	−0.27	0.39	0.06	0.33	−0.01	0.52	0.26	0.27

dependence is also clearly visible, especially in the case of the X_9 factor, i.e., *Communication*. First, the concept was rated from neutral to slightly positive until the commencement of collision resolution, when its impact was assessed as unfavorable in the case of a manned ship while beneficial for an autonomous one. Similar tendencies regarding the different evaluation of the factors in time may be also observed in the cases of the *COLREGs proficiency* (X_3), *Data from sensors and navigational equipment* (X_5), and *Surrounding traffic* (X_6) concepts. It is also noteworthy that the assessed impact of factors, such as X_7 *Weather*, X_8 *Technical*, and X_9 *Communication,* also varies between ship types (manned/autonomous), but these differences appear to be phase-dependent.

3) *Sensitivity Analysis of the Model:* To adequately design the simulation scenarios for the case studies (see Section II-E), a variance-based sensitivity analysis of the established FGCM

TABLE IV
GREY WEIGHTS OBTAINED FOR THE FGCM MODEL IN THE EVALUATION OF FOUR CONSIDERED PHASES OF THE COLLISION AVOIDANCE PROCESS

Phase	$\otimes w_{i,j}$	Fully manned ship				Fully autonomous ship			
		$\underline{w}_{i,j}$	$\overline{w}_{i,j}$	$\widehat{\otimes} w_{i,j}$	$\phi(\otimes w_{i,j})$	$\underline{w}_{i,j}$	$\overline{w}_{i,j}$	$\widehat{\otimes} w_{i,j}$	$\phi(\otimes w_{i,j})$
1	$\otimes w_{1,10}$	–0.03	0.41	0.19	0.22	0.10	0.56	0.33	0.23
	$\otimes w_{2,10}$	–0.13	0.72	0.29	0.43	–0.13	0.21	0.04	0.17
	$\otimes w_{3,10}$	–0.15	0.62	0.23	0.39	–0.18	0.48	0.15	0.33
	$\otimes w_{4,10}$	0.13	0.79	0.46	0.33	0.01	0.68	0.35	0.34
	$\otimes w_{5,10}$	0.18	0.67	0.43	0.25	0.12	0.82	0.47	0.35
	$\otimes w_{6,10}$	0.11	0.73	0.42	0.31	0.08	0.63	0.35	0.28
	$\otimes w_{7,10}$	0.04	0.64	0.34	0.30	0.27	0.88	0.57	0.31
	$\otimes w_{8,10}$	0.11	0.61	0.36	0.25	–0.10	0.72	0.31	0.41
	$\otimes w_{9,10}$	–0.12	0.43	0.15	0.28	–0.22	0.51	0.15	0.37
2	$\otimes w_{1,10}$	–0.02	0.40	0.19	0.21	0.10	0.50	0.30	0.20
	$\otimes w_{2,10}$	–0.16	0.72	0.28	0.44	–0.14	0.22	0.04	0.18
	$\otimes w_{3,10}$	0.00	0.63	0.32	0.32	–0.18	0.48	0.15	0.33
	$\otimes w_{4,10}$	0.18	0.76	0.47	0.29	0.12	0.69	0.40	0.29
	$\otimes w_{5,10}$	0.22	0.70	0.46	0.24	0.31	0.83	0.57	0.26
	$\otimes w_{6,10}$	0.13	0.71	0.42	0.29	0.07	0.58	0.32	0.26
	$\otimes w_{7,10}$	0.03	0.56	0.3	0.27	0.26	0.84	0.55	0.29
	$\otimes w_{8,10}$	0.07	0.59	0.33	0.26	–0.1	0.72	0.31	0.41
	$\otimes w_{9,10}$	–0.02	0.46	0.22	0.24	–0.15	0.51	0.18	0.33
3	$\otimes w_{1,10}$	0.09	0.64	0.36	0.28	0.17	0.68	0.43	0.26
	$\otimes w_{2,10}$	–0.03	0.69	0.33	0.36	–0.16	0.29	0.06	0.23
	$\otimes w_{3,10}$	0.07	0.74	0.41	0.34	–0.13	0.63	0.25	0.38
	$\otimes w_{4,10}$	0.12	0.55	0.34	0.22	–0.06	0.55	0.25	0.31
	$\otimes w_{5,10}$	0.05	0.58	0.32	0.27	0.28	0.76	0.52	0.24
	$\otimes w_{6,10}$	0.20	0.80	0.50	0.30	0.19	0.79	0.49	0.30
	$\otimes w_{7,10}$	0.04	0.46	0.25	0.21	0.19	0.74	0.46	0.28
	$\otimes w_{8,10}$	0.00	0.49	0.24	0.25	0.01	0.69	0.35	0.34
	$\otimes w_{9,10}$	–0.34	0.31	–0.02	0.33	0.02	0.54	0.28	0.26
4	$\otimes w_{1,10}$	0.20	0.77	0.48	0.29	0.20	0.76	0.48	0.28
	$\otimes w_{2,10}$	–0.14	0.60	0.23	0.37	–0.17	0.26	0.04	0.22
	$\otimes w_{3,10}$	–0.05	0.61	0.28	0.33	–0.18	0.46	0.14	0.32
	$\otimes w_{4,10}$	0.09	0.46	0.28	0.19	0.01	0.41	0.21	0.20
	$\otimes w_{5,10}$	0.05	0.44	0.24	0.20	0.17	0.63	0.40	0.23
	$\otimes w_{6,10}$	0.21	0.81	0.51	0.30	0.15	0.77	0.46	0.31
	$\otimes w_{7,10}$	0.10	0.54	0.32	0.22	0.22	0.79	0.51	0.29
	$\otimes w_{8,10}$	0.07	0.70	0.39	0.32	0.06	0.75	0.41	0.35
	$\otimes w_{9,10}$	–0.26	0.26	0.00	0.26	–0.07	0.44	0.18	0.26

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

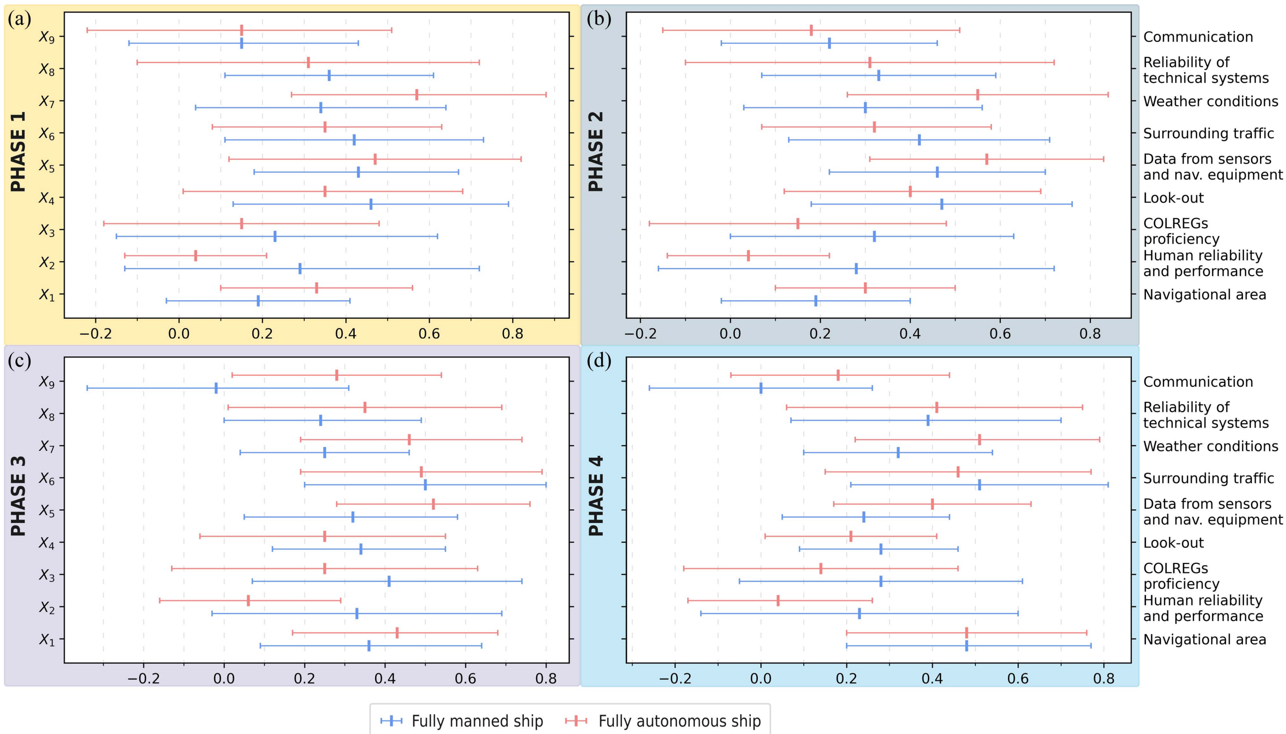


Fig. 6. Grey results obtained from SMEs' answers regarding the impact of a given factor on a specific phase of the collision avoidance process.

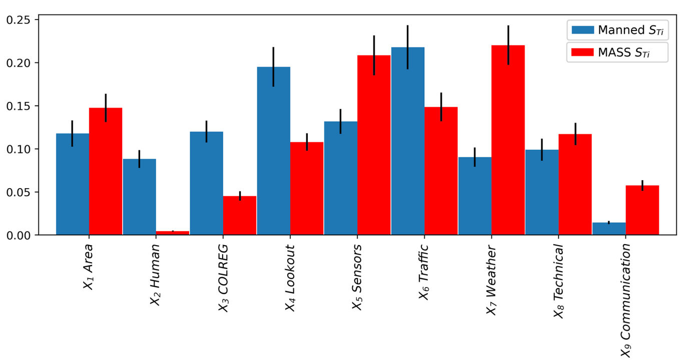


Fig. 7. Total-effect Sobol indices obtained for manned and autonomous ships with respect to the entire collision avoidance process.

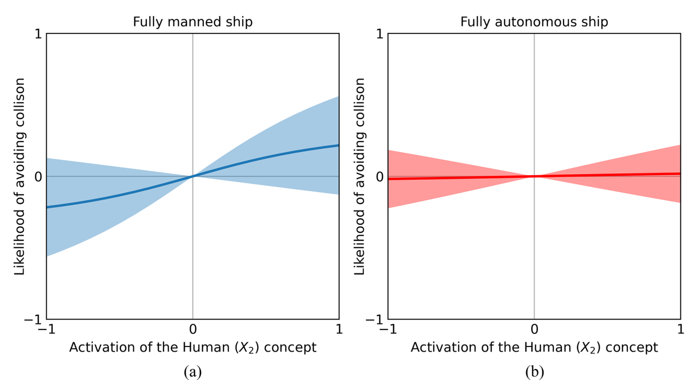


Fig. 8. Impact of the *Human reliability and performance* (X_2) concept on the likelihood of avoiding a ship collision.

model was first performed using the SALib library [89], [90]. This was to find the concepts to which the model is most sensitive, that is, those that have the greatest impact on the results it yields. The analysis was made with regard to the total-effect Sobol S_{Ti} [88], in which the top three results depicting the most influential concepts are presented in Table V for a given phase of the collision avoidance model as well as for the entire FGCM model.

Because the obtained values of S_{Ti} vary depending on the process phase, the sensitivity analysis was also conducted for the entire collision avoidance process. Consequently, the most influential concepts having the highest S_{Ti} determined for the entire process model were selected to be activated in the simulation scenarios introduced in Section II-E. These are presented in detail in Fig. 7, where a comparison between all total-effect indices determined for manned and autonomous ships is depicted.

B. Simulation Scenarios

The results of the conducted FGCM modeling are presented in the following paragraphs according to the research scenarios described in Section II-E. In each of the figures presented (see Figs. 8–13), the neutral value indicates that a given factor does not affect the process (in this case, the likelihood of ship collision). The horizontal axis represents the changing intensity of a given factor, while the vertical axis indicates its effect on the process. Due to the questionnaire setup during expert

TABLE V
RESULTS OF THE TOP THREE TOTAL-EFFECT SOBOL INDICES $S_{\mathrm{T}i}$ OBTAINED FOR EACH PHASE OF THE COLLISION AVOIDANCE PROCESS

Phase	Top results	Manned		MASS	
		Top 3 S_{Ti} concepts	S_{Ti} value	Top 3 S_{Ti} concepts	S_{Ti} value
1	*#1*	*X_4 Lookout*	0.2083	*X_7 Weather*	0.3142
	#2	*X_5 Sensors*	0.1796	*X_5 Sensors*	0.2062
	#3	*X_6 Traffic*	0.1764	*X_6 Traffic*	0.1299
2	*#1*	*X_4 Lookout*	0.2095	*X_5 Sensors*	0.2821
	#2	*X_5 Sensors*	0.1976	*X_7 Weather*	0.2674
	#3	*X_6 Traffic*	0.1682	*X_4 Lookout*	0.1495
3	*#1*	*X_6 Traffic*	0.2497	*X_5 Sensors*	0.2177
	#2	*X_3 COLREG*	0.1636	*X_6 Traffic*	0.1946
	#3	*X_1 Area*	0.1435	*X_7 Weather*	0.1830
4	*#1*	*X_6 Traffic*	0.2531	*X_7 Weather*	0.2331
	#2	*X_1 Area*	0.2349	*X_1 Area*	0.2098
	#3	*X_8 Technical*	0.1506	*X_6 Traffic*	0.1904

elicitation, the vertical axis should be understood as the likelihood of *successfully avoiding* collision (not: the likelihood of collision).

Unless otherwise indicated, the columns separating the subplots in a figure marked with lowercase letters *a* and *b* denote the results obtained for a fully manned ship (*a*) and a fully autonomous ship (*b*). For the sake of meaningful and legible presentation, the results obtained for a given phase of encounter or type of a ship are color-coded as introduced before in Section II-A.

1) Scenario A: Fig. 8 represents the influence of *Human reliability and performance* (X_2) on the overall safety of the collision avoidance process and is interpreted as follows. Zero (neutral value) indicates that in default conditions, the *Human reliability and performance* concept has a certain effect on the collision avoidance process. If the conditions change from default to negative (that is, humans have a lesser impact on the process in given circumstances), the safety of the process is affected negatively in the case of manned ships (left-hand part of Fig. 8), and *vice versa*, increased intensity of X_2 (positive values on the horizontal axis) affects safety (that is, the likelihood of avoiding collision) positively. The greater the impact of the *Human reliability and performance* concept on collision avoidance, the greater the safety (on average) is and the greater the chance of successfully avoiding a collision. However, since some of the experts evaluated that impact differently, this introduced a level of uncertainty into the overall assessment of the impacts. This is represented by a range with its center in whitened values (bold blue curve). The latter follows the general notion that the more intensive impact of the X_2 concept in manned ships, the greater the likelihood of avoiding a collision, thus the greater the level of ship safety.

On the other hand, the right-hand side of Fig. 8 indicates that the impact of the *Human reliability and performance* concept on the overall safety performance of a fully autonomous ship is rather vague. Regardless of how intensive X_2 is in this case, safety depicted by whitened values is not affected significantly. This is understandable as fully autonomous ships would by definition be less affected by human performance, at least on the sharp end of the system. Interestingly, lesser greyness indicates a greater certainty among the SMEs than in the case of manned vessels.

2) Scenario B: Fig. 9 depicts results for the (X_3) concept, i.e., *COLREG proficiency*. In this and following scenarios, the analyzed process has been broken down into four, time-dependent phases, as described in Fig. 1 and Table I.

As can be noted, the changing intensity of the *COLREG* concept has a comparable effect on both manned and autonomous ships' ability to avoid collisions at sea with rather small levels of uncertainty. However, good adherence to COLREG affects MASS performance less positively than that of manned ships. Lesser upward deflection of the whitenization curve for MASS compared to manned ships indicates that a fully autonomous vessel is likely to be slightly more susceptible and vulnerable to the risk of collision in COLREG-intensive situations. This is depicted by a correspondingly lower or higher likelihood, depending on the direction of the concept activation on the right-hand side of Fig. 9. In the present legal setup, one can hardly imagine a ship encounter that does not involve COLREG.

3) Scenario C: Fig. 10 depicts the impact of the X_9 concept: *Communication* on the collision avoidance performance of both manned and autonomous ships. The *Communication* concept seems to have benefits for avoiding a collision for two considered

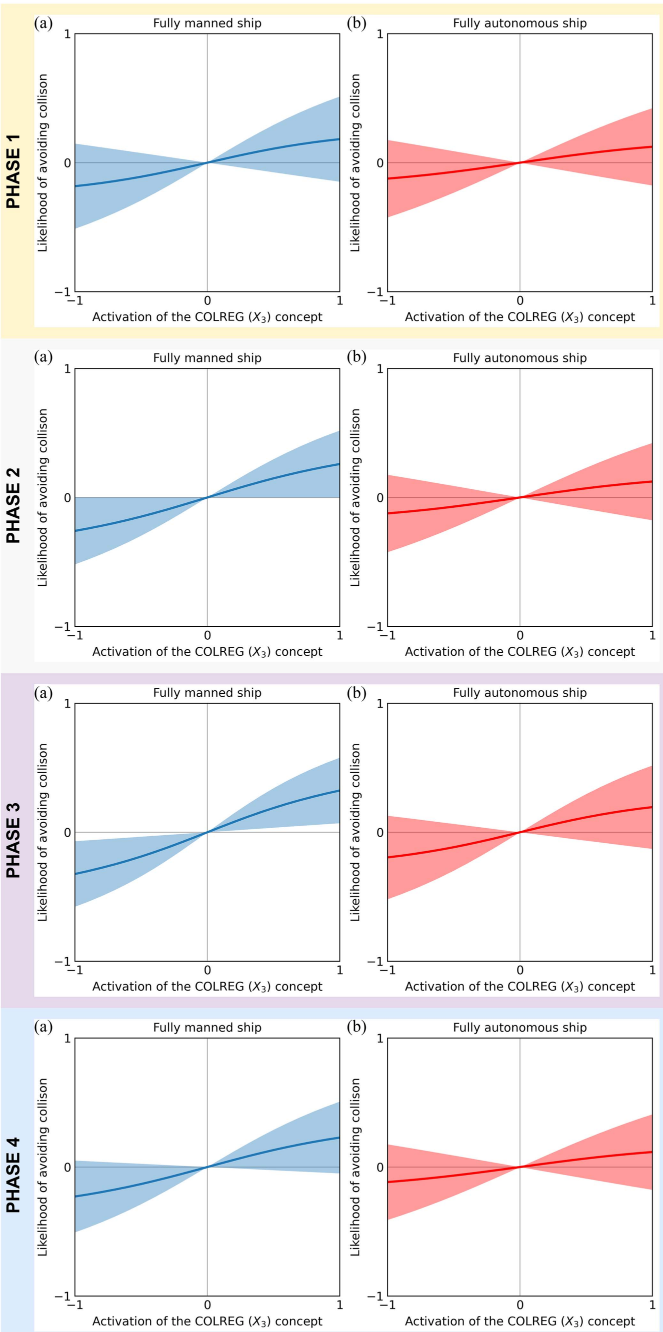


Fig. 9. Impact of the *COLREG* (X_3) concept on the likelihood of avoiding ship collision.

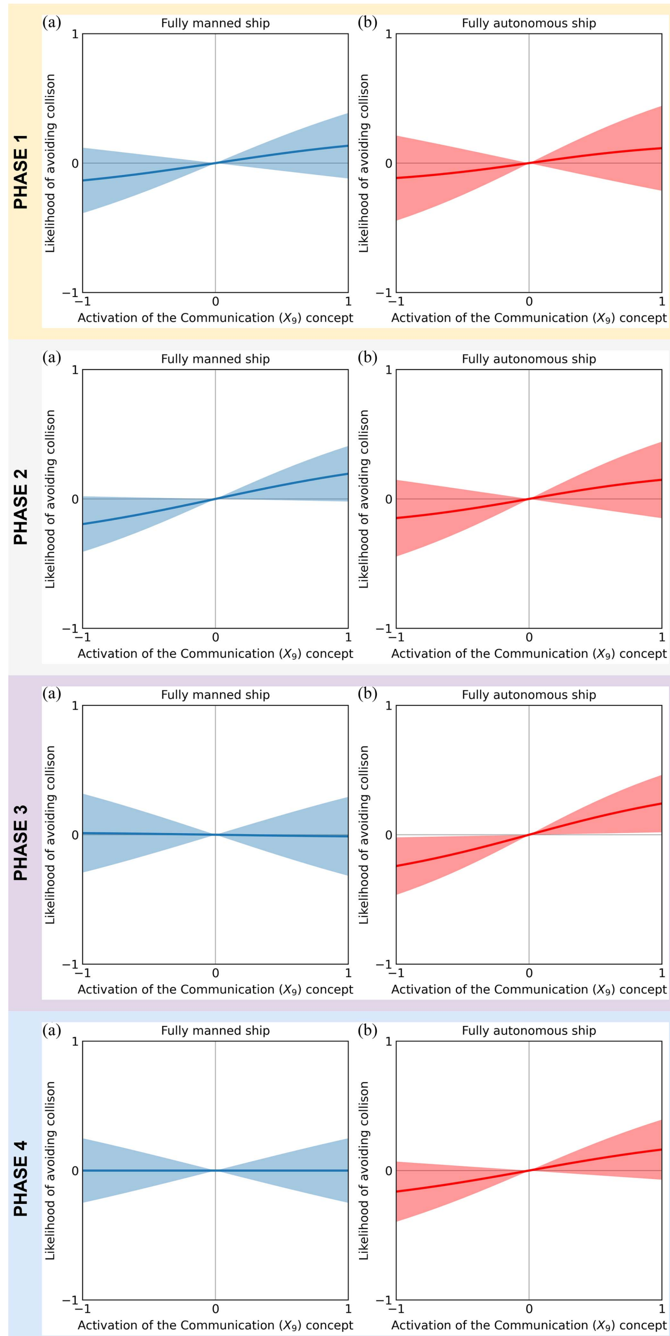


Fig. 10. Impact of the *Communication* (X_9) concept on the likelihood of avoiding ship collision broken into four phases of an encounter (presented in rows).

types of vessels, especially at the beginning of the process, that is, when the conflict between the parties must be detected and then the situation constantly monitored. This may arise from seagoing experience that SMEs have gained during their service onboard conventional ships, as it is usually claimed to be useful and beneficial [91], [92] for ship safety to get an idea of other ship's intentions during a dangerous encounter, to increase situational awareness and act accordingly.

Nevertheless, a sudden shift can be noted in the performance of a manned ship in Phases 3 and 4; thus, the *Communication* negatively affects his or her performance during the *Collision resolution* and *Evasive action* phases. This is in line with generally recognized difficulties in human-to-human coordination of collision avoidance actions [93], including so-called very high frequency (VHF)-assisted collisions [94]. On the other hand, for autonomous ships, the opposite effect can be observed, especially in Phase 3, which may imply that SMEs firmly believe that MASS may more effectively communicate their intentions or even negotiate and coordinate their evasive maneuvers with other MASS, in particular [79], [91].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

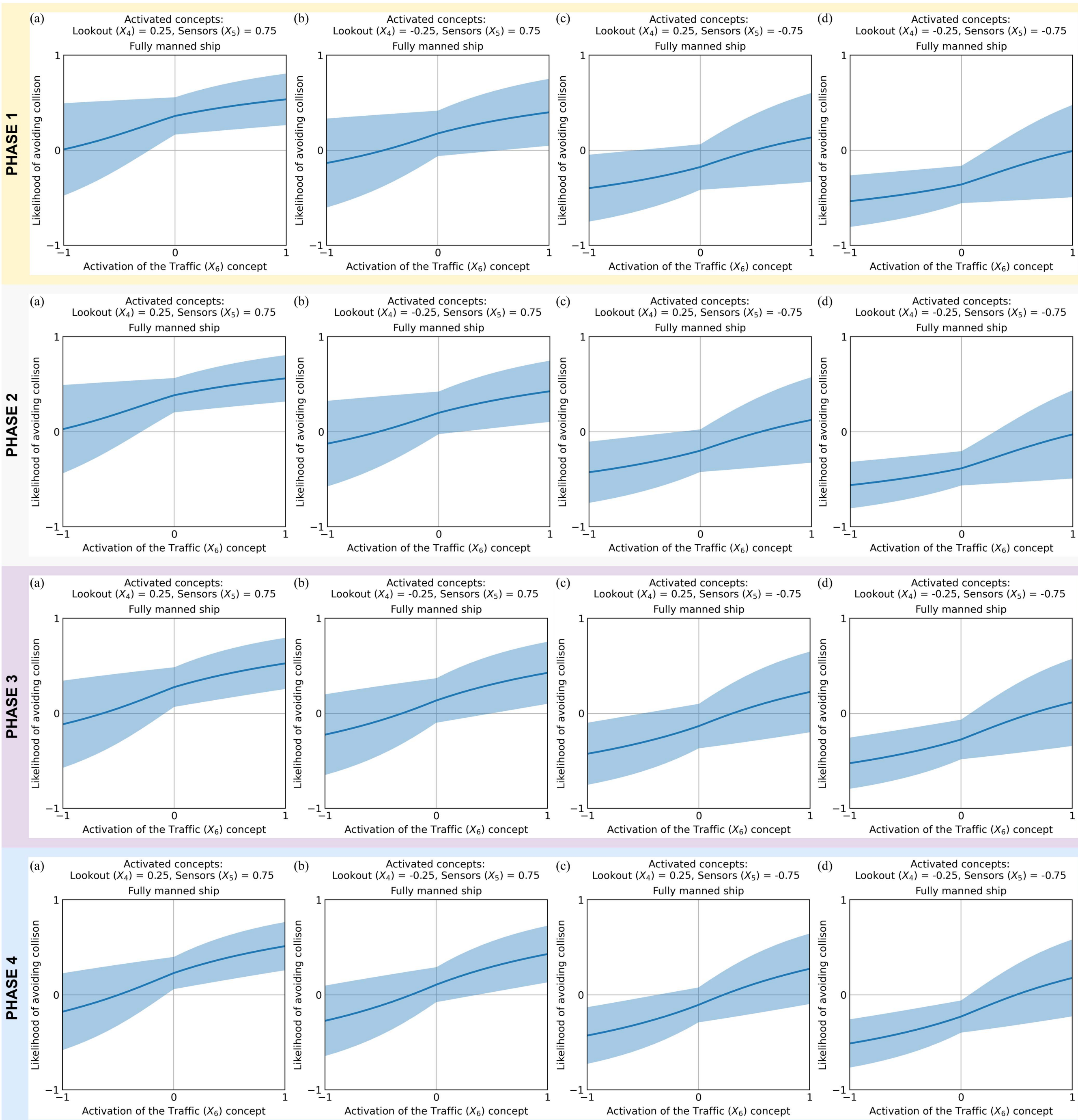


Fig. 11. Impact of the *Lookout* (X_4), *Sensors* (X_5), and *Traffic* (X_6) concepts on the likelihood of avoiding collision by a fully manned ship with different magnitudes of their activation (presented in columns) and concerning four phases of an encounter (presented in rows).

4) Scenario D: Another aspect of the investigation of the FGCM collision avoidance process is the mutual interactions between activated concepts. To this end, Fig. 11 depicts the influence of three concepts, namely, *Look-out* (X_4), *Sensors* (X_5), and *Traffic* (X_6) at different phases and magnitudes of their activation for fully manned and autonomous ships, respectively. The magnitudes of the concepts' activation have been set as a combination of -0.75 and $+0.75$ for X_5 and -0.25 and $+0.25$ for X_4, and are presented in the subsequent columns marked from a) of the figures, given as follows:

1) *Sensors* (X_5) = +0.75, *Look-out* (X_4) = +0.25;
2) *Sensors* (X_5) = +0.75, *Look-out* (X_4) = -0.25;
3) *Sensors* (X_5) = -0.75, *Look-out* (X_4) = +0.25;
4) *Sensors* (X_5) = -0.75, *Look-out* (X_4) = -0.25.

The activation set has been chosen to depict how the changes in the activation magnitude of a very influential concept of *Sensors* and a fairly influential concept of *Look-out* affect the entire collision avoidance process. The X_6 has been modeled like in previous scenarios; thus, the whole process has been simulated as a function of the *Traffic* concept.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

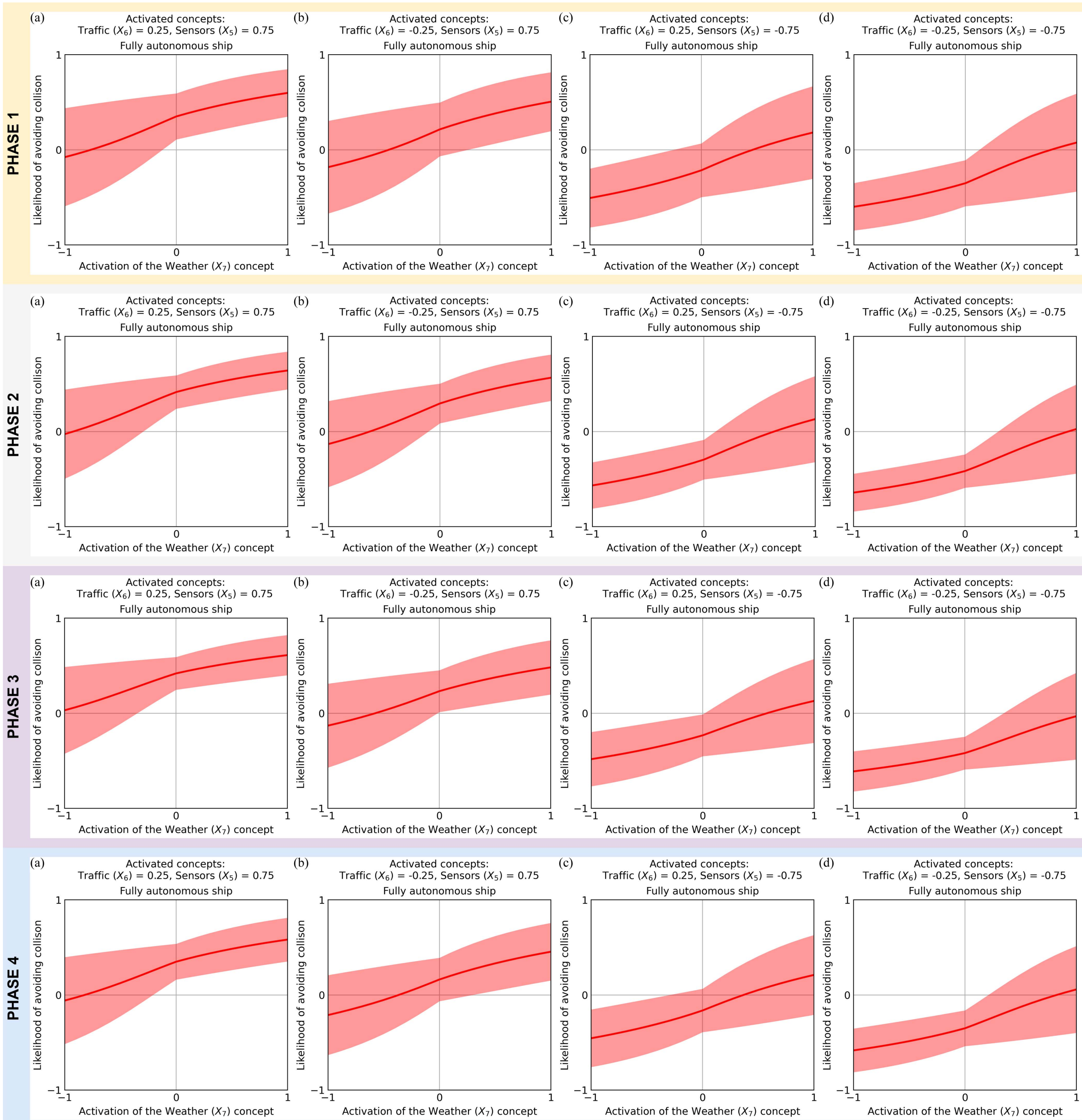


Fig. 12. Impact of the *Sensors* (X_5), *Traffic* (X_6), and *Weather* (X_7) concepts on the likelihood of avoiding collision by a fully autonomous ship with different magnitudes of their activation (presented in columns) in the four phases of an encounter (presented in rows).

It can be noted that reversing the value of *Sensors* (X_5) activation from (+0.75) to (−0.75) has a more prominent effect on the outcome of the process than reversing the value of *Lookout* (X_4), as can be seen by comparing the second and third column with the first. In neither of the cases (phases or activation magnitudes) does the reversing of the values change the overall trend in which the more *Traffic*-dependent the process, the better its outcome. It must be highlighted that this does not imply that the traffic itself is intensive in each situation, but that its outcome heavily *depends on* factors related to its intensity and organization. Furthermore, it can be noted that the likelihood of avoiding a collision does not depend on the outcome of a particular phase of an encounter as much as it does on the intensity of concepts considered.

5) Scenario E: Like scenario D, scenario E investigated the top three concepts to which the model of MASS performance is the most sensitive. These included *Sensors* (X_5), *Traffic* (X_6), and *Weather* (X_7) with various magnitudes of activation, as depicted

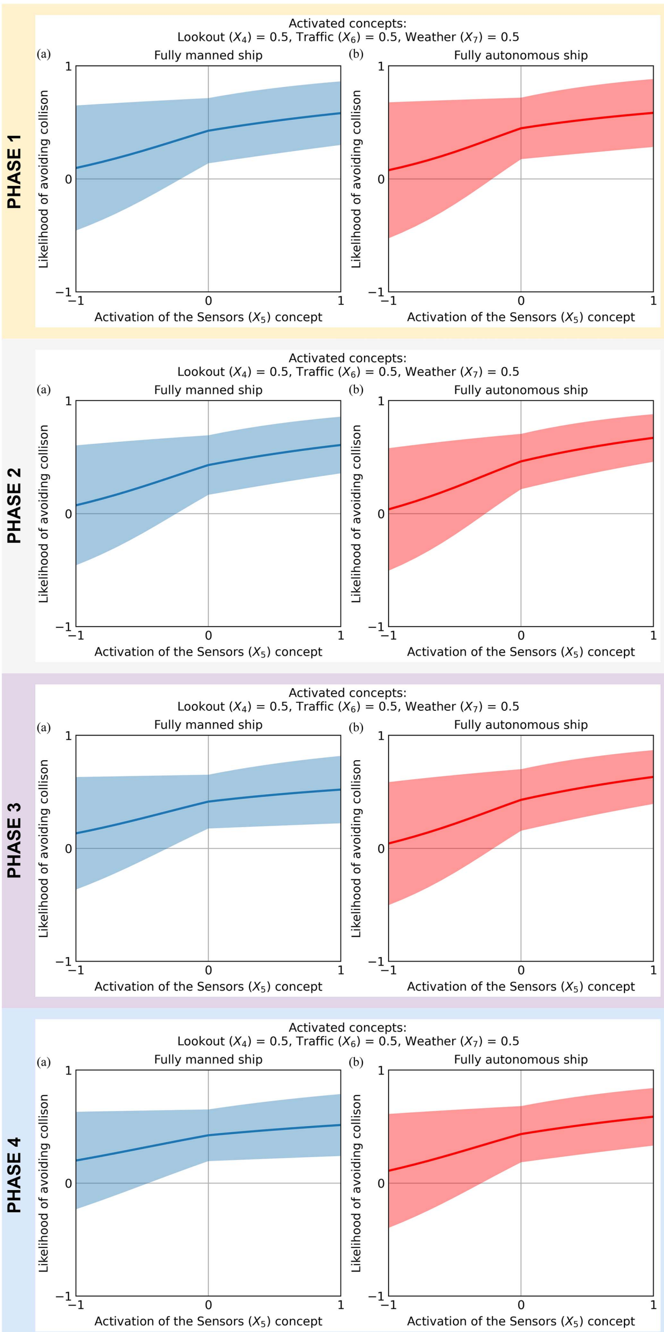


Fig. 13. Impact of the *Sensors* (X_5), *Lookout* (X_4), *Traffic* (X_6), and *Weather* (X_7) concepts on the likelihood of avoiding ship collision broken into four phases.

in Fig. 12. The results are comparable with those of scenario D in the sense that they do not depend on the phase of an encounter as much as on the magnitude of analyzed concepts.

6) Scenario F: In the final scenario, the *Lookout/Sensors/Traffic/Weather* (X_4, X_5, X_6, X_7) quadruplet has been analyzed, as depicted in Fig. 13. As presented, the quadruplet has a predominantly positive impact on the safety of collision avoidance operations, regardless of how influential these factors are in each situation. Noteworthy differences between respective phases and types of ships are minimal, which strengthens the argument that none of the concepts has a dominant impact on the outcome of the entire collision avoidance process, even though their individual assessments vary significantly. It is of note that the greyness of combined impact is smaller on the positive side of the X_5 spectrum as if SMEs were more certain of the positive impact of the investigated factors than the negative one. Just as if they could imagine what positive effect more sensors-intensive ships would have on safety, but had difficulty assessing what would happen if sensors were of lesser relevance for collision avoidance. This effect is less apparent for manned ships in their Phases 3 and 4.

IV. Discussion and Implications

In this section, the findings of the study as well as their significance are discussed. This is followed by an analysis of the identified limitations of the conducted study. Finally, the potential for further developments is outlined.

A. Findings

The results suggest that in several cases, the SMEs were generally not convinced of their judgments, which may be exemplified in Figs. 5 and 6. This is not surprising and may result from the very narrow spectrum of specialization that was sought because of the topic raised in the study. Here, the question arises: is there anyone around the world who knows enough about how both manned and prospective autonomous ships would operate to provide precise and certain answers related to safety-critical aspects of their operation? Arguably so; however, the number of such experts is tiny, due to their unique knowledge and professional experience, and access to them is extremely limited. Therefore, the participants engaged in the study most likely have greater expertise in the operation of one of the two examined ships, and due to their similarity, *per analogiam*, they tried to assess the remaining one. In some decision-making methods, it is argued that additional fuzzification of the experts' answers does not lead to better outcomes [95]. However, in this case, where it is challenging to find experts in the still novel area, the use of intervals to collect judgments seems to be a promising approach. First, it allows us to deal with uncertainties of the SMEs' responses, and second, it allows us to determine the values of impacts crucial in safety-critical systems.

Surprisingly, when it comes to the interpretation of the FGCM results, similar and sometimes wider ranges of grey values were attributed by the SMEs to manned than to autonomous ships. One of the possible reasons for such an outcome may be that contemporary manned ships are more familiar to maritime experts than prospective autonomous ones. It may have been easier for SMEs to conceive and evaluate the impact of given concepts on the former. Paradoxically, it is MASS that can be characterized by greater uncertainty due to their largely unknown design and performance, but this ambiguity appears difficult to grasp. Just as if SMEs had a clearer *vision* of MASS than the *understanding* of manned ships; the novelty of MASS and related uncertainties were compensated by SMEs *knowing* how chaotic manned shipping can be.

When it comes to discussion on the results obtained, it is of note that some of the factors revealed interesting differences between their impact on manned and autonomous ships (RQ2). One such example that may be pointed out is, for instance, X_9 – *Communication*, where the differences in the values determined depending on the type of ship considered are quite significant (see Figs. 6 and 10). Interestingly, the SMEs indicated that communication during collision avoidance of a manned ship can be both beneficial and detrimental in ensuring its safety. This can arise from the practical and routine use of VHF radio onboard ships operating nowadays. The watchkeeping officers should not coordinate an evasive maneuver, as this can lead to numerous misunderstandings [96] and eventually, to an accident [97]. Yet, direct ship–ship communication may still be beneficial to determine the intentions [98] of the other vessel at a long range. For this reason, the SMEs perhaps responded, showing a high degree of uncertainty (this is indicated by a large interval, thus greyness, of the X_9 *Communication* results), as this factor can impact the entire collision avoidance process of the manned vessel twofold. On the contrary, the results obtained for autonomous ships indicated that the *Communication* factor influences the collision avoidance process mainly in a positive way by decreasing the likelihood of a collision. Furthermore, the experts in this case were more certain of their opinion. This may result from a reduction of the human factor involved in MASS–MASS automatic communication (when the fully autonomous ship is considered). Therefore, the probability of misunderstanding between two machines in the experts' opinion is much smaller, and communication may be beneficial in ensuring collision avoidance. That is also why some researchers recommend using, for instance, negotiation algorithms [79], [99] or other forms of ship cooperation [91], [100] during a dangerous encounter of two MASS to coordinate and finally agree on the details of evasive maneuvers [44].

Another noteworthy observation concerns the factor denoted as X_2, i.e., *Human reliability and performance*. As expected, for the autonomous ship, the SMEs assessed the influence of this factor considerably less than in the case of the manned ship. It is quite natural at first glance since in MASS (especially the fully autonomous one), the presence of humans and their performance is almost totally reduced, which is highly misleading, as their presence will be in fact clearly visible [9], [76], [101]. However, it is of note that the respondents do not account for human operators in the case of, for instance, supervisory control [65], [102] of MASS (even in the case of monitoring) or as an important and indispensable element to be considered during their design phase [71], [103]. The whitenization of the results indicated that the SMEs assessed the human reliability and performance in MASS as almost neutral with limited greyness. On the other hand, in the case of the manned ship, the X_2 factor plays an essential role in the ship–ship collision avoidance process in the SMEs' opinion, which is confirmed by existing research literature [104], as well as ordinary seamanship practice. In the case of the manned vessel, the greyness was considerably greater, which suggests that respondents were not confident about the impact of this factor, and that human reliability may lead to both a reduction and growth of the likelihood of collision depending on human action, which is also in line with the scientific and professional literature. Even if there is no consensus among researchers on how large the contribution of human factors in maritime accidents is, it is definitely present among the most common causes of ship collisions [105].

Upon inspection of the multiple concepts being activated (scenarios D through F), it can be noted that the outcome of the process generally improves with their higher magnitude (RQ1), and that the positive trend exists for both manned and autonomous ships (RQ2). However, the resultant impact of the analyzed concepts on the outcomes of given phases of the process may have proven negative in certain combinations of activation values. This indicates that, especially in cases where the negative magnitude of some concepts was analyzed (scenarios D and E), factors of positive magnitude could not prevail and help achieve a positive impact. From a practical point of view, even presumably insignificant factors can derail the entire process if not properly taken care of.

Finally, it must be noted that in reality, ship encounters are dynamic processes and as such can undergo rapid change. For instance, some concepts generally positively affect safety but can in some cases induce a negative impact (and reduce safety) when in high intensity (RQ1). Such an effect is visible especially when whitened numbers are considered. A clue for the reason behind such an outcome can be found in Fig. 10, particularly on its left-hand side. Therein, X_9 *Communication* suddenly changes its impact in Phase 3, thus leading to an overall reduction of safety (RQ3). The more the intensive *Communication*, the more it reduces safety—slightly but notably. It is of note that the discussed effects are more apparent for manned ships.

B. Limitations

Expert studies are always burdened with some typical limitations related to the process of gathering and processing the participants' knowledge. This is mainly due to the subjectivity of their opinions, which may cause some biases. Moreover, in safety-related studies concerning high-risk transportation sectors, such as maritime or aviation, the experts may try to present themselves in a better light than in reality by proving themselves as responsible and safety-focused individuals. Therefore, the survey was designed in a way allowing, to some extent, a reduction of the negative impact of these issues. That is why, among others, the study was anonymized, and all numerical or default values were hidden to SMEs to not suggest any values and responses. Moreover, numerous factors affecting the process of collision avoidance were categorized into nine concept categories, as specified in Section II-B, to allow for their easier evaluation by SMEs. This may have caused some level of oversimplification, which, on the other hand, would allow SMEs to assess more generalized factors affecting somewhat uncharted operations of MASS.

FCMs are also prone to errors in expert knowledge. If the relationships determined by experts contain any errors, this may lead to incorrect results. Therefore, grey numbers were used to handle the uncertainty of the experts' assessments. This study focused only on analyzing the direct relationships between nine input factors and the likelihood of avoiding a ship collision. There may also be hidden connections between these input factors that may indirectly impact safety. However, such influences will not be as significant as direct relationships.

Another limitation associated with the expert elicitation is the relatively small sample of respondents ($n = 29$). Furthermore, the scope of the survey was, at least to some extent, unfamiliar to the experts, as the modeling collision avoidance process of autonomous ships remains in the realm of conjecture and predictions. Despite MASS being far from full operation, assessments regarding their safety are being made on strong foundations by transferring SMEs' knowledge and expertise from well-known manned ships. This is possible because presumably autonomous ships will largely face the same problems regarding collision avoidance, but they will use slightly different methods and means to solve them.

C. Future Work

An interesting direction for future work seems to be the determination of the initial (current) magnitude of the concept's activation during a given phase of the collision avoidance process. This would allow for a determination of not only the relative impact of a given factor on the process or its phase but also for analyzing the change in the entire state of the model's safety, including its time dependence.

Moreover, mixed-traffic conditions were not considered in the current study, where certain levels of global shipping saturation with MASS may affect how ships interact with each other. Should autonomous ships push manned ones out of the shipping lanes, the significance of certain factors may change.

Finally, FGCM applications in the risk and safety domain have been mostly limited to reliability analysis [22], [106]. The herein application of FGCM to more abstract phenomena than previously pursued failure probabilities opens up the possibility of seeking their use in novel safety analysis models, including those from the Safety-II and Safety-III realms. One such application may consist of prioritization of tasks, functions, control actions, and other items used in respective approaches.

V. Conclusion

The goal of the performed study was to investigate differences between collision avoidance processes for manned and fully autonomous ships. This was achieved through an application of the FGCM technique, coupled with the development of a generalized time-dependent model of a process in question as well as expert elicitation. Such an approach allowed for the analysis of nine factors affecting the performance of respective kinds of ships (manned and autonomous) in four phases of an encounter, which answered the research questions raised in Section I. It also allowed for depicting uncertainties related to experts' aggregated opinions.

Several interesting outcomes can be drawn from the performed study. First, there are significant differences in the relative impact of certain factors on the overall performance of the collision avoidance process. These do not only differ between manned and autonomous ships but also change significantly across phases of an encounter, and their impact can even turn from positive to negative in some cases.

Interestingly, aggregated responses of the experts as depicted by grey numbers appear to illustrate a greater level of confidence toward the performance of autonomous ships than their manned counterparts. The reasons for this remain unclear but may be a demonstration of a more mindful and conservative approach of experts toward the more familiar notion of manned ships than more imaginary autonomous ones.

These results can be found relevant by scholars and practitioners of a growing field of autonomous shipping but also for modeling the safety of the collision avoidance process in its generic form. The successful application of FGCM in dynamic transportation processes opens up possibilities for its further development toward use in conjunction with novel safety modeling approaches.

References

[1] UNCTAD, *Review of Maritime Transport 2022: Navigating stormy Waters*. New York, NY, USA: United Nations Publications, 2022.

[2] P. Kołakowski, M. Gil, K. Wróbel, and Y.-S. Ho, "State of play in technology and legal framework of alternative marine fuels and renewable energy systems: A bibliometric analysis," *Maritime Policy Manage.*, vol. 49, no. 2, pp. 236–260, Feb. 2022.

[3] L. Tang and S. Bhattacharya, "Revisiting the shortage of seafarer officers: A new approach to analysing statistical data," *WMU J Marit Affairs*, vol. 20, no. 4, pp. 483–496, Dec. 2021.

[4] EMSA, *Annual Overview of Marine Casualties and Incidents 2023*. Lisboa, Portugal: EMSA, Jun. 2023.

[5] C.-H. Chang, C. Kontovas, Q. Yu, and Z. Yang, "Risk assessment of the operations of Maritime Autonomous Surface Ships," *Rel. Eng. Syst. Saf.*, vol. 207, Mar. 2021, Art. no. 107324.

[6] T. Porathe, Å. Hoem, Ø. Rødseth, K. Fjørtoft, and S. O. Johnsen, "At least as safe as manned shipping? Autonomous shipping, safety and 'human error'," in *Safety and Reliability – Safe Societies in a Changing World*, 1st ed. London, U.K.: CRC Press, 2018, pp. 417–425.

[7] K. Wróbel, J. Montewka, and P. Kujala, "Towards the assessment of potential impact of unmanned vessels on maritime transportation safety," *Rel. Eng. Syst. Saf.*, vol. 165, pp. 155–169, Sep. 2017.

[8] C. A. Thieme, I. B. Utne, and S. Haugen, "Assessing ship risk model applicability to Marine Autonomous Surface Ships," *Ocean Eng.*, vol. 165, pp. 140–154, Oct. 2018.

[9] E. Veitch and O. Andreas Alsos, "A systematic review of human-AI interaction in autonomous ship systems," *Saf. Sci.*, vol. 152, Aug. 2022, Art. no. 105778.

[10] J. Zhang, M. Jin, C. Wan, Z. Dong, and X. Wu, "A Bayesian network-based model for risk modeling and scenario deduction of collision accidents of inland intelligent ships," *Rel. Eng. Syst. Saf.*, vol. 243, Mar. 2024, Art. no. 109816.

[11] P. Li, Y. Wang, and Z. Yang, "Risk assessment of Maritime Autonomous Surface Ships collisions using an FTA-FBN model," *Ocean Eng.*, vol. 309, Oct. 2024, Art. no. 118444.

[12] X. Zhang, C. Wang, L. Jiang, L. An, and R. Yang, "Collision-avoidance navigation systems for Maritime Autonomous Surface Ships: A state of the art survey," *Ocean Eng.*, vol. 235, Sep. 2021, Art. no. 109380.

[13] J. C. Chong, "Impact of maritime autonomous surface ships (MASS) on VTS operations," Master's thesis, World Maritime Univ., Malmö, Sweden, 2018.

[14] K. E. Fjørtoft and Ø. J. Rødseth, "Using the operational envelope to make autonomous ships safer," in *Proc. 30th Eur. Saf. Rel. Conf. 15th Probabilistic Saf. Assessment Manage. Conf.*, 2020, pp. 76–83.

[15] E. Hannaford, P. Maes, and E. Van Hassel, "Autonomous ships and the collision avoidance regulations: A licensed deck officer survey," *WMU J. Maritime Affairs*, vol. 21, no. 2, pp. 233–266, Jun. 2022.
[16] T. Kim, L. P. Perera, M.-P. Sollid, B.-M. Batalden, and A. K. Sydnes, "Safety challenges related to autonomous ships in mixed navigational environments," *WMU J. Maritime Affairs*, vol. 21, no. 2, pp. 141–159, Jun. 2022.
[17] Ø. J. Rødseth, L. A. L. Wennersberg, and H. Nordahl, "Improving safety of interactions between conventional and autonomous ships," *Ocean Eng.*, vol. 284, Sep. 2023, Art. no. 115206.
[18] K. Wróbel, M. Gil, Y. Huang, and R. Wawruch, "The vagueness of COLREG versus collision avoidance techniques—A discussion on the current State and future challenges concerning the operation of autonomous ships," *Sustainability*, vol. 14, no. 24, Dec. 2022, Art. no. 16516.
[19] M. Chaal et al., "Research on risk, safety, and reliability of autonomous ships: A bibliometric review," *Saf. Sci.*, vol. 167, Nov. 2023, Art. no. 106256.
[20] B. Kosko, "Fuzzy cognitive maps," *Int. J. Man-Mach. Stud.*, vol. 24, no. 1, pp. 65–75, Jan. 1986.
[21] J. L. Salmeron, "Modelling grey uncertainty with fuzzy Grey cognitive maps," *Expert Syst. Appl.*, vol. 37, no. 12, pp. 7581–7588, Dec. 2010.
[22] J. L. Salmeron and E. Gutierrez, "Fuzzy grey cognitive maps in reliability engineering," *Appl. Soft Comput.*, vol. 12, no. 12, pp. 3818–3824, Dec. 2012.
[23] I. Á. Harmati and L. T. Kóczy, "On the convergence of fuzzy grey cognitive maps," in *Information Technology, Systems Research, and Computational Physics*. Cham, Switzerland: Springer, 2020, pp. 74–84.
[24] L. Concepción, G. Nápoles, R. Bello, and K. Vanhoof, "On the behavior of fuzzy grey cognitive maps," in *Rough Sets*. Cham, Switzerland: Springer, 2020, pp. 462–476.
[25] I. Á. Harmati and L. T. Kóczy, "On the convergence of sigmoidal fuzzy grey cognitive maps," *Int. J. Appl. Math. Comput. Sci.*, vol. 29, no. 3, pp. 453–466, Sep. 2019.
[26] J. L. Salmeron and E. I. Papageorgiou, "Using fuzzy grey cognitive maps for industrial processes control," in *Fuzzy Cognitive Maps For Applied Sciences and Engineering*, vol. 54, E. I. Papageorgiou, Ed. Berlin, Germany: Springer, 2014, pp. 237–252.
[27] J. L. Salmeron and E. I. Papageorgiou, "A fuzzy Grey cognitive maps-based decision support system for radiotherapy treatment planning," *Knowl.-Based Syst.*, vol. 30, pp. 151–160, Jun. 2012.
[28] J. L. Salmeron, "A fuzzy grey cognitive maps-based intelligent security system," in *Proc. IEEE Int. Conf. Grey Syst. Intell. Serv.*, Leicester, U.K., 2015, pp. 29–32.
[29] S. Arokiamary and M. Mary Mejrullo Merlin, "A study on human intelligence using fuzzy grey relational maps (FGRMs)," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1012, no. 1, Jan. 2021, Art. no. 012067.
[30] J. L. Salmeron and P. R. Palos-Sanchez, "Uncertainty propagation in fuzzy grey cognitive maps with Hebbian-like learning algorithms," *IEEE Trans. Cybern.*, vol. 49, no. 1, pp. 211–220, Jan. 2019.
[31] J. L. Salmeron, "An autonomous FGCM-based system for surveillance assets coordination," *J. Grey Syst.*, vol. 28, no. 1, pp. 27–35, 2016.
[32] E. Akyuz and M. Celik, "Utilisation of cognitive map in modelling human error in marine accident analysis and prevention," *Saf. Sci.*, vol. 70, pp. 19–28, Dec. 2014.
[33] L. Wang, Q. Liu, S. Dong, and C. G. Soares, "Effectiveness assessment of ship navigation safety countermeasures using fuzzy cognitive maps," *Saf. Sci.*, vol. 117, pp. 352–364, Aug. 2019.
[34] L. Ma, X. Ma, H. Lan, Y. Liu, and W. Deng, "A data-driven method for modeling human factors in maritime accidents by integrating DEMATEL and FCM based on HFACS: A case of ship collisions," *Ocean Eng.*, vol. 266, Dec. 2022, Art. no. 112699.
[35] M. Poornikoo and K. I. Øvergård, "Levels of automation in Maritime Autonomous Surface Ships (MASS): A fuzzy logic approach," *Maritime Econ. Logistics*, vol. 24, no. 2, pp. 278–301, Jun. 2022.
[36] J. Xue, P. H. A. J. M. Van Gelder, G. Reniers, E. Papadimitriou, and C. Wu, "Multi-attribute decision-making method for prioritizing maritime traffic safety influencing factors of autonomous ships' maneuvering decisions using grey and fuzzy theories," *Saf. Sci.*, vol. 120, pp. 323–340, Dec. 2019.
[37] R. Fiskin, O. Atik, H. Kisi, E. Nasibov, and T. A. Johansen, "Fuzzy domain and meta-heuristic algorithm-based collision avoidance control for ships: Experimental validation in virtual and real environment," *Ocean Eng.*, vol. 220, Jan. 2021, Art. no. 108502.
[38] Z. Pietrzykowski, "Ship's fuzzy domain–A criterion for navigational safety in narrow fairways," *J. Navigation*, vol. 61, no. 3, pp. 499–514, Jul. 2008.
[39] R. Szlapczynski and J. Szlapczynska, "Review of ship safety domains: Models and applications," *Ocean Eng.*, vol. 145, pp. 277–289, Nov. 2017.
[40] M. Mohamed-Seghir, "The fuzzy properties of the ship control in collision situations," in *Proc. IEEE Int. Conf. INnovations Intell. Syst. Appl.*, Gdynia, Poland, 2017, pp. 107–112.
[41] B. Wu, T. L. Yip, X. Yan, and C. G. Soares, "Fuzzy logic based approach for ship-bridge collision alert system," *Ocean Eng.*, vol. 187, Sep. 2019, Art. no. 106152.
[42] L. P. Perera, J. P. Carvalho, and C. G. Soares, "Intelligent ocean navigation and fuzzy-Bayesian decision/action formulation," *IEEE J. Ocean. Eng.*, vol. 37, no. 2, pp. 204–219, Apr. 2012.
[43] Y. Hu, X. Meng, Q. Zhang, and G.-K. Park, "A real-time collision avoidance system for autonomous surface vessel using fuzzy logic," *IEEE Access*, vol. 8, pp. 108835–108846, 2020.
[44] Z. Xiao, X. Lu, J. Ning, and D. Liu, "COLREGs-compliant unmanned surface vehicles collision avoidance based on improved differential evolution algorithm," *Expert Syst. with Appl.*, vol. 237, Mar. 2024, Art. no. 121499.
[45] L. P. Perera, V. Ferrari, F. P. Santos, M. A. Hinostroza, and C. G. Soares, "Experimental evaluations on ship autonomous navigation and collision avoidance by intelligent guidance," *IEEE J. Ocean. Eng.*, vol. 40, no. 2, pp. 374–387, Apr. 2015.
[46] P. Chen, Y. Huang, J. Mou, and P. H. A. J. M. van Gelder, "Probabilistic risk analysis for ship-ship collision: State-of-the-art," *Saf. Sci.*, vol. 117, pp. 108–122, Aug. 2019.
[47] T. Statheros, G. Howells, and K. M. Maier, "Autonomous ship collision avoidance navigation concepts, technologies and techniques," *J. Navigation*, vol. 61, no. 1, pp. 129–142, Jan. 2008.
[48] C. Tam, R. Bucknall, and A. Greig, "Review of collision avoidance and path planning methods for ships in close range encounters," *J. Navigation*, vol. 62, no. 3, pp. 455–476, 2009.
[49] Y. Huang, L. Chen, P. Chen, R. R. Negenborn, and P. H. A. J. M. van Gelder, "Ship collision avoidance methods: State-of-the-art," *Saf. Sci.*, vol. 121, pp. 451–473, Jan. 2020.
[50] P. Chen, Y. Huang, J. Mou, and P. H. A. J. M. van Gelder, "Ship collision candidate detection method: A velocity obstacle approach," *Ocean Eng.*, vol. 170, pp. 186–198, Dec. 2018.
[51] J. Park and J. Kim, "Predictive evaluation of ship collision risk using the concept of probability flow," *IEEE J. Ocean. Eng.*, vol. 42, no. 4, pp. 836–845, Oct. 2017.
[52] A. Vagale, R. T. Bye, R. Oucheikh, O. L. Osen, and T. I. Fossen, "Path planning and collision avoidance for autonomous surface vehicles II: A comparative study of algorithms," *J Mar Sci Technol*, vol. 26, no. 4, pp. 1307–1323, Dec. 2021.
[53] J. Montewka, T. Manderbacka, P. Ruponen, M. Tompuri, M. Gil, and S. Hirdaris, "Accident susceptibility index for a passenger ship-a framework and case study," *Rel. Eng. Syst. Saf.*, vol. 218, Feb. 2022, Art. no. 108145.
[54] X. Xin, Z. Yang, K. Liu, J. Zhang, and X. Wu, "Multi-stage and multi-topology analysis of ship traffic complexity for probabilistic collision detection," *Expert Syst. Appl.*, vol. 213, Mar. 2023, Art. no. 118890.
[55] L. Du, F. Goerlandt, O. A. Valdez Banda, Y. Huang, Y. Wen, and P. Kujala, "Improving stand-on ship's situational awareness by estimating the intention of the give-way ship," *Ocean Eng.*, vol. 201, Apr. 2020, Art. no. 107110.
[56] R. Szlapczynski and P. Krata, "Determining and visualizing safe motion parameters of a ship navigating in severe weather conditions," *Ocean Eng.*, vol. 158, pp. 263–274, Jun. 2018.
[57] M. Zhang, J. Montewka, T. Manderbacka, P. Kujala, and S. Hirdaris, "A big data analytics method for the evaluation of ship - ship collision risk reflecting hydrometeorological conditions," *Rel. Eng. Syst. Saf.*, vol. 213, Sep. 2021, Art. no. 107674.
[58] I. B. Hagen, O. Vassbotn, M. Skogvold, T. A. Johansen, and E. F. Brekke, "Safety and COLREG evaluation for marine collision avoidance algorithms," *Ocean Eng.*, vol. 288, Nov. 2023, Art. no. 115991.
[59] H. Yoshioka, H. Hashimoto, and H. Makino, "Decision-making algorithm for ship collision avoidance with collision risk map," *Ocean Eng.*, vol. 286, Oct. 2023, Art. no. 115705.
[60] X. Yuan, D. Zhang, J. Zhang, M. Zhang, and C. G. Soares, "A novel real-time collision risk awareness method based on velocity obstacle considering uncertainties in ship dynamics," *Ocean Eng.*, vol. 220, Jan. 2021, Art. no. 108436.

[61] K. Zhang et al., "A real-time multi-ship collision avoidance decision-making system for autonomous ships considering ship motion uncertainty," *Ocean Eng.*, vol. 278, Jun. 2023, Art. no. 114205.

[62] A. N. Cockcroft and J. N. F. Lameijer, *Guide to the Collision Avoidance Rules - International Regulations for Preventing Collisions at Sea*, 7th Ed. Oxford, U.K.: Elsevier, 2012.

[63] M. Gil, J. Montewka, P. Krata, T. Hinz, and S. Hirdaris, "Determination of the dynamic critical maneuvering area in an encounter between two vessels: Operation with negligible environmental disruption," *Ocean Eng.*, vol. 213, Oct. 2020, Art. no. 107709.

[64] M. Li, J. Mou, P. Chen, H. Rong, L. Chen, and P. H. A. J. M. Van Gelder, "Towards real-time ship collision risk analysis: An improved R-TCR model considering target ship motion uncertainty," *Rel. Eng. Syst. Saf.*, vol. 226, Oct. 2022, Art. no. 108650.

[65] T. Johansen and I. B. Utne, "Supervisory risk control of autonomous surface ships," *Ocean Eng.*, vol. 251, May 2022, Art. no. 111045.

[66] S. V. Rothmund, T. Tengesdal, E. F. Brekke, and T. A. Johansen, "Intention modeling and inference for autonomous collision avoidance at sea," *Ocean Eng.*, vol. 266, Dec. 2022, Art. no. 113080.

[67] IMO, *MSC 100/5 - Regulatory Scoping Exercise for the use of Maritime Autonomous Surface Ships (MASS)*. London, U.K.: IMO, Sep. 2018.

[68] W. Dai, Z. H. Quek, and K. H. Low, "Probabilistic modeling and reasoning of conflict detection effectiveness by tracking systems towards safe urban air mobility operations," *Rel. Eng. Syst. Saf.*, vol. 244, Apr. 2024, Art. no. 109908.

[69] A. Li, M. Hansen, and B. Zou, "Traffic management and resource allocation for UAV-based parcel delivery in low-altitude urban space," *Transp. Res. Part C: Emerg. Technol.*, vol. 143, Oct. 2022, Art. no. 103808.

[70] J. K. Kuchar and L. C. Yang, "A review of conflict detection and resolution modeling methods," *IEEE Trans. Intell. Transport. Syst.*, vol. 1, no. 4, pp. 179–189, Dec. 2000.

[71] M. A. Ramos, I. B. Utne, and A. Mosleh, "Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events," *Saf. Sci.*, vol. 116, pp. 33–44, Jul. 2019.

[72] C. Fan, K. Wróbel, J. Montewka, M. Gil, C. Wan, and D. Zhang, "A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships," *Ocean Eng.*, vol. 202, Apr. 2020, Art. no. 107188.

[73] C. Fan, J. Montewka, and D. Zhang, "A risk comparison framework for autonomous ships navigation," *Rel. Eng. Syst. Saf.*, vol. 226, Oct. 2022, Art. no. 108709.

[74] H. Lyu et al., "Ship autonomous collision-avoidance strategies—A comprehensive review," *JMSE*, vol. 11, no. 4, Apr. 2023, Art. no. 830.

[75] Y. Cho, J. Park, J. Kim, and J. Kim, "Autonomous ship collision avoidance in restricted waterways considering maritime navigation rules," *IEEE J. Ocean. Eng.*, vol. 48, no. 4, pp. 1009–1018, 2023.

[76] K. Wróbel, M. Gil, and C.-J. Chae, "On the influence of Human factors on safety of remotely-controlled merchant vessels," *Appl. Sci.*, vol. 11, no. 3, Jan. 2021, Art. no. 1145.

[77] X.-Y. Zhou, J.-J. Huang, F.-W. Wang, Z.-L. Wu, and Z.-J. Liu, "A study of the application barriers to the use of autonomous ships posed by the good seamanship requirement of COLREGs," *J. Navigation*, vol. 73, no. 3, pp. 710–725, May 2020.

[78] M. Gil, K. Wróbel, and J. Montewka, "Toward a method evaluating control actions in STPA-based model of ship-ship collision avoidance process," *J. Offshore Mechan. Arctic Eng.*, vol. 141, no. 5, Feb. 2019, Art. no. 051105.

[79] Z. Pietrzykowski et al., "The autonomous navigation system of a sea-going vessel," *Ocean Eng.*, vol. 261, Oct. 2022, Art. no. 112104.

[80] H. Li et al., "Unsupervised hierarchical methodology of maritime traffic pattern extraction for knowledge discovery," *Transp. Res. Part C: Emerg. Technol.*, vol. 143, Oct. 2022, Art. no. 103856.

[81] H.-C. Burmeister, W. Bruhn, and L. Walther, "Interaction of harsh weather operation and collision avoidance in autonomous navigation," *TransNav*, vol. 9, no. 1, pp. 31–40, 2015.

[82] Y. Zhou, W. Daamen, T. Vellinga, and S. Hoogendoorn, "Review of maritime traffic models from vessel behavior modeling perspective," *Transp. Res. Part C: Emerg. Technol.*, vol. 105, pp. 323–345, Aug. 2019.

[83] A. BahooToroody, M. M. Abaei, O. V. Banda, P. Kujala, F. De Carlo, and R. Abbassi, "Prognostic health management of repairable ship systems through different autonomy degree; from current condition to fully autonomous ship," *Rel. Eng. Syst. Saf.*, vol. 221, May 2022, Art. no. 108355.

[84] K. Wrobel, P. Krata, J. Montewka, and T. Hinz, "Towards the development of a risk model for unmanned vessels design and operations," *TransNav*, vol. 10, no. 2, pp. 267–274, 2016.

[85] Ł. Kubuś, K. Poczęta, and A. Yastrebov, "A new learning approach for fuzzy cognitive maps based on system performance indicators," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, Vancouver, BC, Canada, 2016, pp. 1398–1404.

[86] S. Bueno and J. L. Salmeron, "Benchmarking main activation functions in fuzzy cognitive maps," *Expert Syst. Appl.*, vol. 36, no. 3, pp. 5221–5229, Apr. 2009.

[87] S. Liu and Y. Lin, *Grey Information: Theory and Practical Applications*. London, U.K.: Springer, 2006.

[88] A. Saltelli et al., *Global Sensitivity Analysis: The Primer*. Chichester, U.K.: Wiley, 2008.

[89] J. Herman and W. Usher, "SALib: An open-source Python library for Sensitivity Analysis," *JOSS*, vol. 2, no. 9, Jan. 2017, Art. no. 97.

[90] T. Iwanaga, W. Usher, and J. Herman, "Toward SALib 2.0: Advancing the accessibility and interpretability of global sensitivity analyses," *SESMO*, vol. 4, May 2022, Art. no. 18155.

[91] M. Akdağ, P. Solnør, and T. A. Johansen, "Collaborative collision avoidance for Maritime Autonomous Surface Ships: A review," *Ocean Eng.*, vol. 250, Apr. 2022, Art. no. 110920.

[92] F. Goerlandt, J. Montewka, V. Kuzmin, and P. Kujala, "A risk-informed ship collision alert system: Framework and application," *Saf. Sci.*, vol. 77, pp. 182–204, Aug. 2015.

[93] C. Chauvin, J. P. Clostermann, and J.-M. Hoc, "Situation awareness and the decision-making process in a dynamic situation: Avoiding collisions at sea," *J. Cogn. Eng. Decis. Mak.*, vol. 2, no. 1, pp. 1–23, Mar. 2008.

[94] M. P. A. Singapore, "Port Marine Circular no 18 of 2005: Caution on the use of VHF radio in collision avoidance," Maritime and Port Authority of Singapore, Singapore, 2005. [Online]. Available: https://maritimesafetyinnovationlab.org/wp-content/uploads/2016/02/pc 05-18.pdf

[95] T. L. Saaty and L. T. Tran, "On the invalidity of fuzzifying numerical judgments in the analytic hierarchy process," *Math. Comput. Model.*, vol. 46, no. 7–8, pp. 962–975, Oct. 2007.

[96] M. Boström, "Mind the gap! A quantitative comparison between ship-to-ship communication and intended communication protocol," *Saf. Sci.*, vol. 123, Mar. 2020, Art. no. 104567.

[97] R. P. Argüelles, J. A. García Maza, F. M. Martín, and M. Bartolomé, "Ship-to-ship dialogues and agreements for collision risk reduction," *J. Navigation*, vol. 74, no. 5, pp. 1039–1056, Sep. 2021.

[98] T. Porathe, M. Lützhöft, and G. Praetorius, "What is your intention? Communicating routes in electronic nautical charts," *Procedia - Social Behav. Sci.*, vol. 48, pp. 3266–3273, 2012.

[99] L. Chen, H. Hopman, and R. R. Negenborn, "Distributed model predictive control for vessel train formations of cooperative multi-vessel systems," *Transp. Res. Part C: Emerg. Technol.*, vol. 92, pp. 101–118, Jul. 2018.

[100] M. Gil, "A concept of critical safety area applicable for an obstacle-avoidance process for manned and autonomous ships," *Rel. Eng. Syst. Saf.*, vol. 214, Oct. 2021, Art. no. 107806.

[101] E. Veitch, O. A. Alsos, T. Cheng, K. Senderud, and I. B. Utne, "Human factor influences on supervisory control of remotely operated and autonomous vessels," *Ocean Eng.*, vol. 299, May 2024, Art. no. 117257.

[102] I. B. Utne, B. Rokseth, A. J. Sørensen, and J. E. Vinnem, "Towards supervisory risk control of autonomous ships," *Rel. Eng. Syst. Saf.*, vol. 196, Apr. 2020, Art. no. 106757.

[103] O. A. Valdez Banda, S. Kannos, F. Goerlandt, P. H. A. J. M. Van Gelder, M. Bergström, and P. Kujala, "A systemic hazard analysis and management process for the concept design phase of an autonomous vessel," *Rel. Eng. Syst. Saf.*, vol. 191, Nov. 2019, Art. no. 106584.

[104] C. Chauvin, S. Lardjane, G. Morel, J.-P. Clostermann, and B. Langard, "Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS," *Accident Anal. Prevention*, vol. 59, pp. 26–37, Oct. 2013.

[105] K. Wróbel, "Searching for the origins of the myth: 80% human error impact on maritime safety," *Rel. Eng. Syst. Saf.*, vol. 216, Dec. 2021, Art. no. 107942.

[106] Q. Ma, X. Zhu, Q. Pu, J. Liu, G. Fu, and R. Zhang, "A method based on q-rung orthopair fuzzy cognitive map and TOPSIS method for failure mode and effect analysis considering risk causal relationships," *Eng. Failure Anal.*, vol. 158, Apr. 2024, Art. no. 107970.

Mateusz Gil received the B.Eng. and M.Sc. degrees in navigation, majoring in maritime transportation and offshore technologies, and the Ph.D. degree (cum laude) in civil engineering, geodesy, and transport from the Gdynia Maritime University, Gdynia, Poland, in 2015, 2017, and 2023, respectively.

Before starting his academic career, he worked in the deck department on board merchant ships. He is currently an Assistant Professor with the Department of Navigation, Gdynia Maritime University, where he carries out his teaching, scientific, and research activities. His research interests include issues related to maritime transportation risk and safety, autonomous shipping as well as maritime education and training.

Katarzyna Poczęta received the Ph.D. degree in computer science from the Lodz University of Technology, Łódź, Poland, in 2015.

She is currently an Assistant Professor with the Department of Information Systems, Kielce University of Technology, Kielce, Poland. She has been working as a Researcher in three research projects: TARGET—a multifunctional system for transport fleets, EMOTICA AI—Intelligent Contact Center System, and TRAFFIC—Autonomous coordinator of eco-diverse transport resources. She is the author and co-author of 56 publications in journals, conference papers and book chapters. Her research interests include decision support systems, fuzzy cognitive maps, artificial neural networks, evolutionary computation, natural language processing, time series prediction, machine learning, and data mining.

She is a Reviewer in many international journals, e.g., IEEE TRANSACTIONS ON FUZZY SYSTEMS, *Applied Soft Computing*, IEEE TRANSACTIONS ON BIG DATA, NEURAL COMPUTING AND APPLICATIONS, and *Neurocomputing*.

Krzysztof Wróbel received the M.Sc. degree in ocean engineering from the Gdańsk University of Technology, Gdańsk, Poland, in 2013, and the Ph.D. degree in civil engineering and transport from Gdynia Maritime University, Gdynia, Poland, in 2019.

He has been working as a seafarer on board several types of merchant vessels, including gas carriers, as a Deck Officer and Training Supervisor. His academic carrier started in 2013 at Gdynia Maritime University, where he is currently an Assistant Professor. His research interests include various aspects of autonomous shipping, including its safety and social impacts. He has co-authored several research papers related to this field as well as participated in R&D projects including AAWA initiative.

Dr. Wróbel is also an active member of several national and international bodies working on legal aspects of Maritime Autonomous Surface Ships, including International Maritime Organization working groups.

Zaili Yang received the B.Eng. degree in maritime transportation from Dalian Maritime University, Dalian, China, in 2001, the M.Sc. degree in international transport from Cardiff University, Cardiff, U.K., in 2003, and the Ph.D. degree in maritime safety from Liverpool John Moores University (LJMU), Liverpool, U.K., in 2006.

He is currently a Professor of Maritime Transport and the Co-Director of Liverpool, Logistics, Offshore and Marine Research Institute, LJMU. His research interests include analysis and modeling of safety, resilience, and sustainability of transport networks, particularly maritime systems. He has authored or coauthored more than 400 refereed papers in risk and transport areas, including more than 250 long journal papers.

Pengfei Chen received the M.Sc. degree in traffic information engineering and control from the Wuhan University of Technology, Wuhan, China, in 2017, and the Ph.D. degree in maritime transportation safety from the Delft University of Technology, Delft, The Netherlands, in 2020.

He is a currently Professor with the School of Navigation, Wuhan University of Technology. His research interests include safety-driven decision-making support for autonomous ships and intelligent maritime transportation systems.