A methodology to define risk matrices – Application to inland water ways autonomous ships

V Bolbot[1,2*], G Theotokatos[1], J McCloskey[3], D Vassalos[1], E Boulougouris[1], Bernard Twomey[4]

[1]Maritime Safety Research Centre, Department of Naval Architecture and Marine Engineering, University of Strathclyde, Glasgow, United Kingdom

[2]Marine Technology, Department of Mechanical Engineering, School of Engineering, Aalto University, 00340 Espoo, Finland

[3]Maritime & Coastguard Agency, Southampton, United Kingdom

[4]Department of Naval Architecture and Marine Engineering, University of Strathclyde, Glasgow, United Kingdom

* victor.bolbot@aalto.fi

ABSTRACT

The autonomous ships' introduction is associated with a number of challenges including the lack of suitable risk acceptance criteria to support the risk assessment process during the initial design phases. The aim of this research is to develop a rational methodology for selecting appropriate risk matrix ratings, which are required to perform the risk assessment of autonomous and conventional ships at an early design stage. This methodology consists of four phases and employs the individual and societal risk acceptance criteria to determine the risk matrix ratings for the groups of people exposed to risks. During the first and second phase, input for the risk matrix ratings based on the individual risk and societal risk are calculated respectively. During the third phase, the risk matrix ratings are defined using input from the first and second phases. During the fourth phase, the equivalence between the different types of consequences is specified. The methodology is applied to a crewless inland waterways ship to assess her typical operation within north-European mainland. The results demonstrate that the inclusion of societal risk resulted in more stringent risk matrix ratings compared to the ones employed in previous studies. Moreover, the adequacy of the proposed methodology and its effectiveness to provide risk acceptance criteria aligned with societal and individual risk acceptance criteria as well as its applicability to conventional ships are discussed.

Keywords: Risk matrix; Risk matrix ratings; Autonomous ships; Inland Waterway ship; individual and societal criteria.

1 INTRODUCTION

The continuous research and advancement of technology results in the development of novel systems such as autonomous and crewless ships. The introduction of autonomous and crewless ships is expected to bring substantial benefits, such as enhanced safety level, increased energy efficiency, reduced operational and lifecycle costs, reduced environmental footprint and enhanced equity (Abaei et al., 2021a; de Vos et al., 2021; Kim et al., 2019; Rødseth and Burmeister, 2015a; Wróbel et al., 2017); yet, these claims need to be verified. The autonomous ships are a subject of intense research, with a number of systems being developed supporting their operations, such as specialised fire suppression systems (Lee et al., 2020), collision avoidance systems (Hu and Park, 2020; Zhou et al., 2021), path planning systems (Yang et al., 2015), and remote inspections (Poggi et al., 2020).

However, the introduction of autonomous and crewless ships is associated with several challenges. One of these challenges is related to the design of adequately safe autonomous ships. The lack of a detailed regulatory framework renders the use of utilitarian approaches and tools, such as probabilistic risk assessment (Rozell, 2018), necessary for carrying out the safety assurance of next generation autonomous ships (Nzengu et al., 2021), whereas the use of risk assessment for novel systems is considered a requirement in the maritime community (IMO, 2013). This is connected to a set of other challenges, such as the lack of statistical data, pertinent to the ranking of hazardous scenarios and the risk estimation for autonomous ships, the lack of standardised approaches to perform the risk assessment methodology, and the ambiguity on the acceptable risk levels for the autonomous and crewless ships functional failures (Bolbot et al., 2021b; Chang et al., 2021; Hiroko Itoh et al., 2021; Hoem, 2019; Montewka et al., 2018).

The existing maritime regulations provide examples of individual risk criteria (IMO, 2018) and guidance for the estimation of the societal risk criteria (IMO, 2000). Yet, these guidelines are provided for crewed ships and not in the context of autonomous ships. These guidelines typically refer to the aggregated ship risk and therefore, they cannot be used for the assessment of individual functional failures and hazardous scenarios. However, it is important that both individual and societal risk criteria are considered as early as possible during the design phase to determine the safety and integrity requirements for the investigated system during the design as it is followed by some marine equipment manufacturers.

The assessment of functional failures and hazardous scenarios can be effectively achieved by using risk matrixes as demonstrated in a number of studies (EMSA, 2020; Rødseth and Burmeister, 2015b). Whilst the use of risk matrices is associated with a number limitations (Anthony Cox Jr, 2008; Duijm, 2015; Thomas et al., 2014), risk matrices can be required during the initial design stages of systems generally (DoD, 2012) and autonomous ships specifically (BV, 2019). Risk matrices still constitute a popular tool for decision-making in several industries (Duijm, 2015; Thomas et al., 2014) and is strongly recommended for use according to the Formal Safety Assessment procedures (Kontovas and Psaraftis, 2009). Typical examples of risk matrices used in the maritime industry can be found in the class societies guidance for the assessment of novel technology (ABS, 2017; DNV GL, 2011) and the IMO Formal Safety Assessment (FSA) guidelines (IMO, 2018).

However, the current regulations and guidance do not provide any direction on how to determine the risk matrix, risk ratings and contextualise them for the investigated problem. The ambiguity in connection to the risk matrix design can be of high importance, as an arbitrary defined risk matrix and risk ratings can directly influence the crewless ship or other maritime system design process and mislead the decision-making process (Anthony Cox Jr, 2008; Duijm, 2015; Thomas et al., 2014). The maritime industry, in this respect, has been lagging behind the aviation industry, where acceptable probabilities of failure that depend on the consequences of failures are already defined and employed in the design process (EASA, 2010; FAA, 2011; GOVINFO, 2002; IEC, 2010; Lawrence, 2011; SAE, 1996a).

A number of research studies focused on the definition of risk matrixes and rating schemes. Guidance and rationale for specified acceptable probability of failure for aircrafts can be found in (transportation, 2011). Anthony Cox Jr (2008) examined the main limitations of risk matrixes and reported ways to address them. Garvey (2008), and Meyer and Reniers (2016) investigated the ways to consider decision-makers risk attitude (consequence- or likeliness averseness) during the risk ranking. Ni et al. (2010) reported the extensions of the risk matrix approach by considering additional operators. Levine (2012) proposed the use of risk matrices with logarithmic scales demonstrating their applicability to information system. Iverson et al. (2012) developed a risk matrix tailored to the needs of climate change problem. Ruan et al. (2015) connected the risk matrix development with the utility theory. Hsu et al. (2016) recommended the use of a revised risk matrix integrated with the analytical hierarchical process for the risk assessment of aviation systems. Goerlandt and Reniers (2016) have reviewed the use of uncertainty in risk matrixes and risk diagrams and proposed ways to improve the uncertainty consideration when risk matrixes and diagrams are employed. Li et al. (2018) proposed a sequential approach for altering the rating schemes based on a set of assumptions. Oliveira et al. (2018) developed an approach for designing the risk matrix by using multiple acceptance criteria. Jensen et al. (2022) provided recommendations based on questionnaires' results for updating the characterisation of likelihood and severity used in risk matrix-based risk assessments.

Other pertinent studies focused on the identification and calculation of risk levels in autonomous systems. Blom et al. (2021) proposed an approach to estimate the third party risk in autonomous drones based on simulation results. de Vos et al. (2021) examined the potential impact of autonomy on safety on various ship types. Wróbel et al. (2017) investigated the impact of autonomy in terms of safety from the perspectives of prevention and mitigation. Vinnem (2021) investigated the applicability of current risk acceptance criteria in the context of autonomous offshore installations. A number of studies implemented risk and reliability assessments for the autonomous ships (Abaei et al., 2021a; Abaei et al., 2021b; Bolbot et al., 2021a; Bolbot et al., 2019; Bolbot et al., 2020; Chang et al., 2021; Tam and Jones, 2018; Utne et al., 2020), however, without specifying specific risk acceptance criteria.

The pertinent literature demonstrates that (a) very few studies focused on development of risk matrices; (b) the majority of studies did not interconnect the matrix ratings with individual and societal risk acceptance criteria; (c) there is a lack of guidance to support the development of the risk matrix and risk matrix ratings required for the risk assessment of maritime systems, which can lead to a number of challenges.

The purpose of this study is therefore to develop a methodology for defining a risk matrix and rating schemes. This study focuses on the safety related consequences, whilst including the financial, environmental and reputational consequences, ignoring other aspects, such as, the one related to the risk perception, accountability, liability, social benefits other than revenue, political costs, and trust, which can influence the decision-making. Aspects related to uncertainty are considered outside the scope of this study, as they have been addressed and discussed in detail in Goerlandt and Reniers (2016). The novelty of the present study stems from the developed methodology and demonstration of its applicability through a case study.

The remaining of this article is organised as follows. The developed methodology for determining the risk matrix and risk matrix rating schemes is presented in Section 2. Section 3 provides the parameters of the investigated case study ship. Section 4 presents the results derived by implementing the developed methodology followed by the discussion of the findings and limitations. Section 5 summarises the main findings of this study.

2 DEVELOPED METHODOLOGY DESCRIPTION

2.1 Methodology assumptions and overview

The developed methodology is based on a number of overarching assumptions, which influence the risk matrix development. They are provided below:

- Assumption 1: All the developments focus on the risk matrix and regulations used in the international maritime framework, namely the FSA risk matrix and guidance (IMO, 2018), since this has been already employed by the maritime community as reported in (Bolbot et al., 2021b; EMSA, 2020; Rødseth and Burmeister, 2015b; Wang et al., 2020). The FSA risk matrix has logarithmic scales, which is a useful property as demonstrated by previous studies (Duijm, 2015; Levine, 2012). As a consequence of this assumption, this study considers that one fatality is equivalent to ten severe injuries, whereas one severe injury is equivalent to ten minor injuries (IMO, 2018).
- Assumption 2: Aversion against accidents resulting in more than 10 fatalities is not considered. Instead, neutrality is assumed with respect to the risk taking when studying the accidents size and frequency. In other words, several small accidents are considered equal to a big one with the same risk. This is in line with the advice provided in (IMO, 2000), as well as several guidelines in other industries (Ball and Floyd, 1998; EMSA, 2015). However, it should be noted that some national authorities might require risk aversion for societal risks (EMSA, 2015).
- Assumption 3: The autonomous ships designs should exhibit at least an equivalent level of safety compared with the conventional ships or equivalent safety requirements. This assumption is prescribed in the international guidelines for approval of alternative designs (IMO, 2013) and other previous studies (van Lieshout et al., 2021).
- Assumption 4: The risks are classified in the following three categories considering the As Low As Reasonably Practicable (ALARP) limit: (Intolerable, tolerable or ALARP and negligible). This is in line with existing guidelines for FSA (IMO, 2018), several class societies (ABS, 2017; DNV GL, 2011) and other industries (Ball and Floyd, 1998; Duijm, 2015; EMSA, 2015).
- Assumption 5: All risks types (e.g., environmental, safety, reputational) are considered as equally important. Therefore, the aversion of different risks types, as employed for instance in the nuclear industry (Ball and Floyd, 1998), is not considered herein.

- Assumption 6: It is assumed that the overall risk can be attributed to maximum 10 functional failures with severe consequences (leading to single fatality). This is implemented in line with (transportation, 2011). The application of this assumption is further elaborated in section 2.4 and the results section.
- Assumption 7: Aspects, such as, the one related to the risk perception, accountability, liability, general social benefits, political costs, and trust are excluded from consideration in this study.

The developed methodology overview is provided in the flowchart shown of Figure 1. The methodology consists of four major phases. The first phase deal with the estimation of the intolerable ($F_{int}^{N_F=1}$) and negligible ($F_{neg}^{N_F=1}$) fatality rates for a single person based on the individual risk (N_F is used to denote the number of the occupational fatalities per annum). The second phase includes the steps related to the estimation of the intolerable ($F_{int}^{N_F=1}$) and negligible ($F_{neg}^{N_F=1}$) fatality rates for a single person from the societal risk criteria. The third phase focuses on the development of the risk matrix and the selection of the risk matrix ratings based on the previous phases results. The final phase deals with the expansion of the risk matrix with respect to other consequence types based on the assumption of equivalence between the risks.

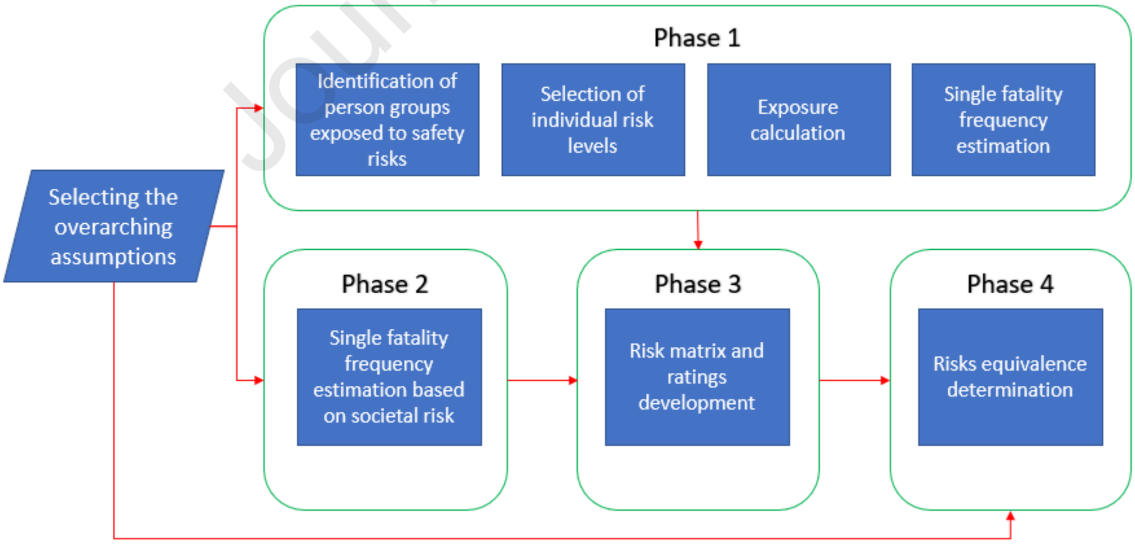

Figure 1 Methodology overview.

2.2 Phase 1: Estimation of single fatality frequency based on individual risk

This phase involves the following steps: (a) identification and grouping of the persons who are exposed to the risks from the investigated ship; (b) selection of tolerable and negligible risk levels for individuals in each group; (c) estimation of exposure for individuals in each group; (d) estimation of the tolerable and negligible levels of the single fatality frequency ($F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$) for the most exposed individual in each group.

2.2.1 Identification of person group's exposed to safety risks

In this step, the persons who are exposed to risks from the investigated ship are identified with the assistance of a questionnaire filled by ship operators and pertinent literature review. The relevant persons are then classified as primary parties, third parties or passengers. The primary parties are those who reap direct financial benefits from the specific activity (army, 2002). The third parties are those who are involuntarily exposed to the safety risks stemming from ship operation (Skjong, 2002). The notion of the second parties could be also employed in line with (army, 2002), to denote those people who indirectly benefit from the related activities e.g., cargo operators at ports. However, in line with the FSA guidelines (IMO, 2018) (following assumption 1) and because these parties can be classified as primary parties or passengers, the notion of second parties is not employed herein.

2.2.2 Selection of tolerable and negligible individual risk

The individual risk can be measured in terms of the single fatality frequency due to specific activities during a specific time period (e.g., one year) (Vinnem, 2014). This type of risk can be used for the risk estimation to the first and third parties. The levels of intolerable and negligible risk can be estimated by using: (a) statistical analysis of accidents as reported in (army, 2002) or (b) by using the predefined individual set risk criteria from IMO (IMO, 2018) (following assumption 1) and categorisation into intolerable, ALARP, negligible (following assumption 4); (c) the criteria set by the national authorities guidelines. The selected levels for the individual risk constitute 'anchoring points' (Ball and Floyd, 1998) and directly influence the developed risk matrix. The levels of intolerable and negligible individual risks can vary for different parties (first or third) and also between different groups of each party.

2.2.3 Exposure calculation

The exposure for the crew and passengers can be estimated using the following equation, which is based on the time that crew and passengers spend onboard ship on an annual basis as reported in (IMO, 2008):

$$E_p[-] = T_p[h]/T_a[h] \quad (1)$$

where T_p denotes the annual time a person from a specific group is exposed to the considered risk (in h), where T_a denotes the hours of one year (8,760 h).

Equation (1) can also be used to estimate the exposure for the personnel of the remote control centre and the personnel maintaining autonomous ships. For third parties that can be found onboard the ship, e.g., passengers, the exposure can also be estimated according to eq. (1).

The estimation of exposure for the third parties, located outside the ships is more challenging, as the ships are not fixed objects (apart from the cases in anchorage and at port), and therefore, the exposure estimation requires consideration of navigational factors. Approaches as presented in (Blom et al., 2021) can be properly marinised and subsequently employed to estimate the average exposure of third parties; however, they are rather computationally expensive. For this reason, this study estimates the time of exposure based on the time the third parties are located in the autonomous ship safety domain as explained below. First, the average duration of the encounter (T_E in h) is estimated according to the following equation:

$$T_E[h] = \frac{SD\,[m]}{1852\left[\frac{m}{nm}\right]V[kn]} \quad (2)$$

Where SD is the safety domain diameter (in m) and V is average speed (in kn)

Subsequently, the SD can be approximated according to the following formula (Namgung and Kim, 2021):

$$SD[m] = \begin{cases} \left(8 - 0.6(10 - V[kn])\right)L[m], \; V \leq 10\;kn \\ \left(8 + 0.6(\mathrm{V[kn]} - 10)\right)L[m], \; V > 10\;kn \end{cases} \quad (3)$$

Where L is the ship length (in m).

It should be noted that eq. (3) constitutes an oversimplification and a very conservative approach to define the safety domain. Other approaches define the safety domain as an ellipse (Hansen et al., 2013; Namgung and Kim, 2021; Pietrzykowski and Wielgosz, 2021), as block areas (Kijima and Furukawa, 2003), as quaternion (Wang, 2010) or as a polygon (Bakdi et al., 2020). This simplification is used to facilitate the implementation and investigation of the overall methodology, whereas the consideration of other representations for the safety domain and the selection of the most appropriate is left as an area for future research. Eq. (3) provides the advantage of rendering the safety domain dependent on the ship length (representing the generic manoeuvrability characteristics) and the ship speed. A comprehensive review of safety domains can be found in (Du et al., 2021; Szlapczynski and Szlapczynska, 2017).

Lastly, the exposure E_p is estimated according to the following equation by using the number of encounters between the ship and the individual per year (N_E) and the average duration of encounter (T_E):

$$E_p[-] = N_E\,[-]\;T_E[h]/T_a\,[h] \quad (4)$$

To simplify the calculation procedure, the next step considers the most exposed person either among the first parties or third parties, based on pertinent concepts from the chemical industry ((EPA), 2011).

2.2.4 Estimation of single fatality frequency tolerable and negligible levels

The Individual Risk *(IR in fatalities per year)* can be estimated according to the following equation as reported in the IMO FSA guidelines (IMO, 2018):

$$IR = F_{ue}\,P_p\,E_p \quad (5)$$

Where F_{ue} is the frequency of an undesired event, P_p denotes the probability of the event resulting in a casualty, whereas E_p is the individual's exposure.

By manipulating Eq. (5), the following equations for estimation of the limits of intolerable and negligible accidental frequencies for a single fatality (fatality of an individual) (in line with assumption 4) ($F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$, respectively) are derived:

$$F_{int}^{N_F=1}[fatalities/a] = F_{ue}^{int}\,P_p^{int} = IR_{int}\,[fatalities/a]/E_p\,[-] \quad (6)$$

$$F_{neg}^{N_F=1}[fatalities/a] = F_{ue}^{neg}\, P_p^{neg} = IR_{neg}[fatalities/a]/E_p\,[-] \quad (7)$$

The values of $F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$ are used as the reference points for the development of the risk matrix ratings in phase 3.

2.3 Phase 2: Estimation of single fatality annual frequency based on societal risk

The societal risk is the "average risk, in terms of fatalities, experienced by a whole group of people (e.g., crew, port employees or society at large) exposed to an accident scenario" (IMO, 2018). The societal risk can be represented using the F-N curve or the Potential Loss of Life (PLL) metric (EMSA, 2015). The levels of risks for different types of ships can be assured by using the relevant IMO guidance (IMO, 2000) and ensuring that the number of accidents associated with the economic activity and societal benefits will be similar for the specific type of ship as in other industries. In this guidance, the financial benefits and the safety level for the whole of economy constitute 'anchoring point' (Ball and Floyd, 1998) considered in Phase 2. This may result in rather conservative estimation of acceptable and negligible risks, as the actual accidents levels can vary among the different industries even up to twenty times (HSE, 1992, 2020), whereas it is widely recognised that the maritime industry lags behind the other sectors in terms of safety levels. However, by considering the safety performance in other industries, motivation for pursuing the safety improvement in the maritime industry is provided.

The approach for estimating the societal risks is described in (IMO, 2000). Whilst this approach is applicable for conventional ships, it is employed herein, in line with assumption 3, for autonomous and crewless ships. The crewless ships do not employ crew onboard, however, third parties exposed to safety risks still exist, as the most likely scenario for autonomous ships in the short- to medium-term includes the coexistence of crewless and conventional ships. The following equations that are reported in (IMO, 2000) are employed for calculating the pertinent safety metrics:

$$q[fatalities/\$B] = N_F\,[fatalities/a\,]/GNP\,[\$B\,/a] \quad (8)$$

$$PLL_A[fatalities\,/a] = q\,[fatalities\,\$B^{-1}]\,R[\$B/a] \quad (9)$$

$$F_A[single\ fatality/a] = \frac{PLL_A}{\sum_{N_F=1}^{N_F=Nu}\frac{1}{N_F}} = k[-]\,PLL_A[fatalities\,/a] \quad (10)$$

Where q is the ratio of annual fatalities to the annual gross national income ($GNP\ in\ \$B$), N_F is the number of the occupational fatalities per annum, R denotes the annual economic value (revenue) in $B per annum, PLL_A denotes the probability of the loss of life in fatalities per annum and F_A denotes the frequency of single fatality per annum, whilst Nu denotes the maximum fatalities number.

The parameter k can be approximated by using second of the assumptions referred in 2.1, as follows (EMSA, 2015):

$$k = \frac{1}{\sum_{N_F=1}^{N_F=Nu}(\frac{1}{N_F})} \approx \frac{1}{0.577+\ln(Nu+1)} \text{ [-]} \tag{11}$$

The following equation is used to calculate the intolerable risk for a single fatality expressed in terms of the fatality frequency per annum (IMO, 2000) (according to assumption 4):

$$F_{int}^{N_F=1}[single\ fatality/a] > 10\ F_A[single\ fatality/a] \tag{12}$$

Based on assumption 4, the negligible risk is defined by the following equation (IMO, 2000):

$$F_{neg}^{N_F=1}[single\ fatality/a] < 0.1\ F_A\ [single\ fatality/a] \tag{13}$$

The values of $F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$ refer to a single fatality for a single ship per annum, the revenue R represents the annual revenue for a single ship, whilst N_F and GNP refer to these parameters annual values.

2.4 Phase 3: Risk matrix and risk ratings development

As it can be observed, eq. (6) and eq. (12) provide the estimation of $F_{int}^{N_F=1}$. Similarly, eq. (7) and eq. (13) provide the estimation of $F_{neg}^{N_F=1}$. During this phase, through the comparison of different estimations, a decision with respect to the $F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$ values is made. This is rather qualitative methodology that involves judgement from the decision makers. Preference is given to the most conservative values of $F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$, so that both the societal and individual risk criteria are satisfied.

The actual single fatality frequency refers to the total risk to the individual resulting from different types of accidents, such as collision, fire, flooding, etc. To account for the risk associated with different hazardous scenarios that can arise from functional failures, in line with (transportation, 2011) this value is reduced by a factor of 10 (assumption number 6). In other words, it is considered that maximum 10 critical scenarios/functional failures can be encountered for the investigated ship there are, which can lead to the consequences equivalent to single fatality with annual frequency $F_{int}^{N_F=1}/10$. This is one of the important limitations of this study.

According to (IMO, 2000) the scaling up of the ratings is implemented using a logarithmic rule without risk aversion (in line with assumptions 1 and 2). Thus, the intolerable and negligible frequencies for N fatalities per annum for a single ship can be calculated according to the following equations:

$$F_{int}^{N_F=N}[N\ fatalities/a] > F_{int}^{N_F=1} N^{-1}/10 \quad (14)$$

$$F_{neg}^{N_F=N}[N\ fatalities/a] < F_{neg}^{N_F=1} N^{-1}/10 \quad (15)$$

Employing eq. (14) and (15) bears the advantage of incorporating the isorisk assumptions more effectively in the risk matrix compared to when the linear scale is employed (Duijm, 2015; Levine, 2012).

The IMO regulations (IMO, 2018) prescribe that the interrelation between the Frequency Index (FI) (used for ranking the frequency in the risk matrix) and the frequency (F) is provided by the following equation:

$$F[events/a] = 10^{FI-const} \Leftrightarrow FI = \log F + const \quad (16)$$

Therefore, based on eq. (14)–(16), the intolerable and tolerable regions in the risk matrix (risk matrix ratings) can be estimated. Rounding downwards the values calculated by eq. (16) is employed for the selection of the frequency index risk ratings (FI).

The risk matrix scales in terms of severity are derived by considering one level of magnitude higher than the single fatality (up to 10 fatalities) in line with IMO FSA risk matrix, as well as three levels of magnitude lower (to severity equivalent to 10^{-3} fatalities), so there are severities equivalent to 10^{-3}, 10^{-2}, 10^{-1}, 10^{0} and 10^{1} fatalities. This scaling is implemented to allow for the ranking of very serious accidents as well as minor accidents. For ships that carry a large number of passengers, the scaling up in terms of severity can increase further to include disastrous consequences (equivalent to 100 fatalities).

The risk matrix scales in terms of frequency are derived by considering that the frequency increases two levels of magnitude up and decreases two levels of magnitude down compared to the FI that corresponds to $F_{int}^{N_F=1}/10$. Therefore the FI values correspond to $F_{int}^{N_F=1}/1000$, $F_{int}^{N_F=1}/100$, $F_{int}^{N_F=1}/10$, $F_{int}^{N_F=1}$, $10\,F_{int}^{N_F=1}$.

In this way, the developed risk matrix has 5x5 cells. 10 cells are dedicated to intolerable risk, 9 to the tolerable and 6 to negligible. In cases where the higher severity scale is considered, the risk matrix consists of 30 cells, with 15 cells dedicated to the intolerable risk, 9 to the tolerable and 6 to negligible.

2.5 Phase 4: Determining the safety equivalence

The equivalence between the safety risks and the other risks is determined by using the 5th assumption from section 2.1. For the financial risks, the cost-benefit criteria, which support the identification of cost-effective control measures, such as Cost of Averting the Fatality (CAF), is used to determine the equivalence between the safety and financial risks. This is the only equivalence that is determined quantitatively. All the other equivalences are determined qualitatively based on the literature review. For the equivalence of oil pollution, the relevant scales existing in the IMO FSA guidelines are employed (IMO, 2018). The equivalence with other environmental and reputational risks is implemented by thorough comparison with similar risk matrices existing in the pertinent literature (Ahluwaja, 2018; Bureau Veritas, 2019; EMSA, 2020; 2018). The psychological effects and political consequences were excluded from the scope of this study, although they can be important in particular cases as reported in (Ball and Floyd, 1998; Vinnem, 2014).

3 INVESTIGATED CASE STUDY

This study investigates an Inland Water Ways (IWW) barge, considering its theoretical next-generation autonomous design including the ship and its systems as well as the Remote Operations Centre (ROC) (or the Remote Control Centre (RCC) which is a part of the ROC). The description of this integrated autonomous system is carried out based on information acquired from the pertinent literature (Bolbot et al., 2019; Chaal et al., 2020a; Eloranta and Whitehead, 2016; Geertsma et al., 2017; Höyhtyä et al., 2017; Rødseth and Burmeister, 2015a; van Cappelle et al., 2018) and the AUTOSHIP project deliverables (Wennersberg and Nordahl, 2019). The main particulars of the existing IWW ship (which will be used as a demonstrator in the AUTOSHIP project) are provided in Table 1. It must be noted that whilst the demonstrator of the AUTOSHIP project and the case study autonomous system (ship and its

RCC) share some similarities, they have different installed systems/sub-systems and levels of autonomy.

Table 1 IWW barge main particulars.

Property	**Value / Reference**	**Unit**
Length	50	[m]
Breadth	6.6	[m]
Sailing speed	17	[km/h]
Draft - fully loaded	1.9	[m]
Carrying Capacity design	300	[t]

The investigated case study considers an Autonomy Degree Three (or above) according to IMO guidelines (IMO, 2020). This pertains to: “Remotely controlled ship without seafarers on board, whereas the ship is controlled and operated from another location”. According to some other definitions provided by CCNR (Central Commission for the Navigation of the Rhine (CCNR), 2018), the investigated case study can be classified at level 3 which corresponds to constrained autonomous crewless ship operation.

Conventional IWW barges are primarily operated at inland waterways within Belgium and the Netherlands. A potential expansion of future operations can include all waterways of member states of the European Union, as well as Switzerland, UK and Norway. This study considers the investigated barge operation under the Flemish authorities’ regulatory framework.

In this analysis, the development of the risk matrix predominantly focuses on the third-party risks. Still some results for the first party risk are included to demonstrate the applicability of the methodology. The emphasis is placed on those persons who exposed to safety risks.

It should be noted that the particular ship operates outside the normative legislation of IMO and is covered by another set of national and international regulations (Nzengu et al., 2021). However, the concepts and tools used in the presented methodology have a general validity and therefore have applicability to the investigated case.

4 RESULTS

4.1 Phase 1: Estimation of single fatality frequency based on individual risk

4.1.1 Identification of person group's exposed to safety risks

The parties that are involved in the risk taking for the investigated IWW ship are listed in Table 2. These parties were identified with the support of the information provided in (Chaal et al., 2020b; Wróbel et al., 2018) and with the assistance of relevant questionnaires. The characterisation of each person (first or third party) is implemented considering whether the persons receive direct benefits from the relevant activity or not. For instance, the governmental bodies receive taxes from the operation of the IWW ship, cargo unloading/loading staff receive their wages. Not all these parties are exposed to safety risks and have the same control over safety risks. The cargo owner and ship owner are exposed to financial risks, but not to the safety risks. The persons exposed to safety risks are highlighted in bold in Table 2. For these persons, the developed methodology can be implemented leading to the determination of the corresponding risk matrices.

Table 2 Parties involved in risk management or undertaking risk.

Persons	**Categorisation**
Governmental bodies	First party
Cargo agent, ship owner, Insurer, cargo owner	First party
Original equipment designer and manufacturer	First party
Ship builder	First party
ROC and RCC personnel	**First party**
Personnel involved in cargo loading/unloading operations	**First party**
Personnel involved in maintenance	**First party**
Ship crew (present only on crewed ships)	**First party**
ROC and RCC neighbours. This might include civilians but also fire fighting organisations, ambulances, hospitals, etc.	**Third party**
Recreation ships (sailboats, high speed crafts, amphibious vehicles, etc.)	**Third party**
Very small recreation ships (kayaks, water scooters, water skiers, etc.)	**Third party**
Cargo ships	**Third party**
Passenger ships	**Third party**
Dredgers, tugboats	**Third party**
People on shore	**Third party**
Humans in the water	**Third party**
Intruders onboard the own autonomous ship	**Third party**

4.1.2 Selection of tolerable and negligible individual risk level

The pertinent IMO guidelines adapted the individual risk levels from the Health and Safety Executive (IMO, 2018). A similar level of individual risk have been accepted in other industries, for example, the nuclear, and offshore (EMSA, 2015). For novel designs, IMO recommends to reduce the acceptance criteria by one order of magnitude (IMO, 2018), however, this contradicts to the assumption of the equivalence between crewless and conventional ships, considered herein (assumption 3). However, the Belgian authorities recommend more stringent criteria for the third parties broadly acceptable and maximum tolerable individual risks, due to the onshore activities (Duijm and Universitet, 2009). Considering that the same criteria should apply for assessing the risks from inland waterway ships operating in Belgian waters, criteria from (Duijm and Universitet, 2009) are selected for the third parties risk assessment. Hence, for the investigated crewless ship, the lower bound of individual risk can be set to 10^{-6} fatalities per annum for the first parties, and 10^{-7} fatalities per annum for the third parties. The respective upper bounds are set to 10^{-3} fatalities per annum for the first parties and 10^{-5} fatalities per annum for the third parties.

Table 3 Selected individual risk levels

	Lower bound for ALARP risk region Broadly acceptable [fatalities/a]	Upper bound for ALARP risk region Maximum tolerable [fatalities/a]
First parties	10^{-6}	10^{-3}
Third parties	10^{-7}	10^{-5}

4.1.3 Exposure calculation

The estimated exposure for different first parties (personnel involved in maintenance and cargo operation, ROC/RCC personnel) is illustrated in Table 4. This estimation was based on the following assumptions: typical annual working period of 1768 hours (8 hours per day, 5 days per week and 40 days of holidays). It is expected that the risks associated to maintaining, loading/unloading operations of the conventional and the crewless ships will be the same. Therefore, the aggregated risk accumulated during work should not exceed the thresholds specified in Table 3. For the conventional IWW crew working hours, it was assumed that they are identical with the ones for other working personnel.

It should be noted that the safety risks these first party persons are exposed to are diverse. The ROC/RCC personnel will be exposed to all risks pertinent to operating and controlling a safety critical infrastructure (e.g., fires, evacuation or physical phenomena). The maintenance personnel will additionally be exposed to the potential injuries and death during the maintenance activities both ashore and on-board the ship. Similarly, the cargo loading/unloading personnel will be exposed to the risk of death or injuries due to the improper cargo handling. The ship crew on-board conventional ships are also exposed to much greater variety of risks, such as the risk of falling from the ship and drowning and occupational hazards as has been demonstrated by some accident investigation reports, the authors confidentially received.

Table 4 Exposure for different first parties

Persons exposed to safety risks	Type	Exposure interval [h]	Exposure [–]
ROC and RCC personnel Personnel involved in cargo loading/unloading operations Personnel involved in maintenance Ship crew	First party	1768	0.2

The majority of third parties listed in Table 5 are exposed to the risk of collision with the IWW ship. The risk for the third parties does not change whether the ship is crewed or crewless. The intruders onboard the ship are exposed to the risks of incidences including fires, collisions, etc., whereas the ROC and RCC neighbours are exposed to generic risks associated with buildings of high value and critical importance for the economy. By using eq. (2), the encounter duration T_E is estimated equal to approximately 1.7 min. The number of encounters between the investigated ship and a typical ship from each group is estimated based on the operator responses to the developed questionnaire and is provided in Table 5. This questionnaire was part of the Environmental Survey Hazard Analysis method for Maritime applications (ESHA-Mar), a new method developed by the authors in the context of autonomous ships (Bolbot V, 2022). The questionnaire includes questions to collect information for the ships and objects in the proximity of the investigated IWW ship, which was employed for the estimation of the encountered ship types and the associated frequencies.

Considering that the encounter number involves high uncertainty due to the subjectivity of the operator, a conservative assumption for the daily encounters with the crewless IWW ship is used for the third parties exposure estimation and the fatality risk estimation in the next steps of this study. More accurate estimations could be generated if Automatic Identification System (AIS) data was used. Unfortunately, such data was not readily available for the investigated ship. However, for this data limitations exists, as small recreational boats are not required to carry AIS transponder (COLREGS, 1972), therefore the estimation of encounters with these ships would have to be based on operational experience. The estimated exposure for each person group is provided in Table 5.

Table 5 Third parties' exposure.

Person groups exposed to safety risks	Number of encounters [per annum]	Exposure [–]
ROC and RCC neighbours	–	1
Recreation boats (sailboats, high speed crafts, amphibious cars, etc.)	26	$8.17\ 10^{-5}$
Very small recreation ships (kayaks, water scooters, water skiers etc.)	26	$8.17\ 10^{-5}$
Cargo ships	**221**	**$6.95\ 10^{-4}$**
Passenger ships	50	$1.57\ 10^{-4}$
Technical ships (dredgers, tugboats)	26	$8.17\ 10^{-5}$
People on the stakes	1	$3.14\ 10^{-6}$
Humans in the water	1	$3.14\ 10^{-6}$
Intruders onboard ships	1	$9.13\ 10^{-4}$ (assuming intrusion duration of 8 h)
Conservative approximation	**365 (one per day)**	**$1.15\ 10^{-3}$**

4.1.4 *Estimation of single fatality frequency tolerable and negligible levels*

By considering the person's group with the highest exposure (calculated in the previous step), the single fatality frequency levels for first and third parties are calculated and presented in Table 6. By comparing the results in Tables 5 and 6, it is inferred that despite the lower exposure, due to more strict requirements, the limits for the third parties are not significantly higher than for the technical/ROC personnel benefiting from this particular activity. The last two rows of Table 6 are derived based on the analysis results in section 4.2.

Table 6 Tolerable and negligible limits for a single fatality.

	$F_{int}^{N_F=1}$ [$single\ fatality/a$]	$F_{neg}^{N_F=1}$ [$single\ fatality/a$]
First parties	$4.95\ 10^{-3}$	$4.95\ 10^{-6}$
Third parties (related to the IWW ship operation)	$8.71\ 10^{-3}$	$8.71\ 10^{-5}$
Societal risk criteria for Nu =1	$1.22\ 10^{-3}$	$1.22\ 10^{-5}$
Societal risk criteria for Nu =30	$3.05\ 10^{-4}$	$3.05\ 10^{-6}$

4.2 Phase 2: Estimation of single fatality annual frequency based on societal risk

Although the investigated IWW ship does not lay in the jurisdiction of the IMO regulatory framework, the pertinent guidelines (MSC 72-16) (IMO, 2000) can be used as a reference for deriving the risk matrix criteria from societal risk in this study.

The number of occupational fatalities per year that occurred in several countries is provided in Table 7, whereas the Gross National Product (GNP) in $B, and the Gross Domestic Product (GDP) for European Union (EU28) are provided in Table 8. The number of fatalities was retrieved from (EUROSTAT, 2020; statistics, 2020), the GNP from (MacroTrends, 2020) and GDP from (EUROSTAT, 2021). GDP is not the same as GNP, but it can be used as an approximation of GNP if GNP is missing. The Euro to USD exchange rate was assumed to 1.15 (approximate average value for 2016 – 2020). As it will be demonstrated in the next sections, these approximations do not bear significant influence on the derived results of this study. The calculated values for the ratio of fatalities per GNP (q) for the considered countries are listed in Table 9.

Table 7 Number of fatal accidents at work

	Belgium	Norway	USA	EU 28
2016	64	45	5190	3588
2017	59	44	5147	3552
2018	77	37	5250	3581
Average	67	42	5196	

Table 8 Countries GNP and EU28 GDP in $B

	Belgium	Norway	USA	EU 28
2016	491.39	428.23	18,476.30	17,232.80
2017	483.38	402.15	19,200.74	17,743.91
2018	526.82	428.37	20,637.49	18,329.60
Average	500.53	419.58	19,438.18	17,768.79

Table 9 Ratio of Fatalities and GNP (q) in fatalities/ $B

Country	q (fatalities/$B)
Belgium	0.133
Norway	0.100
USA	0.267
EU 28	0.201

The annual revenue for the manned IWW ship (one ship) fluctuates between $500k and $720k, as it was indicated by the ship operator. Based on these estimates, the PLL_A and F_A are calculated and provided in Table 10. It should be noted that in the context of autonomous operations, the revenue needs to be estimated for the ROC/RCC operations, for cargo operations and for maintenance operations. Therefore, the estimated societal criteria herein have applicability only to the specific third parties (passenger ships, cargo ships, etc.). However, these societal criteria will be identical for the crewed ship and can be used for the crew and the third parties exposed to the risk from this ship operation, whether crewed or uncrewed.

The resultant F-N curve as well as the F-N curves from other shipping sectors are plotted in Figure 2 (only the limit between ALARP and intolerable risk regions are plotted). As it can be observed, the estimated F-N curve for the IWW ships is lower than the other ship types F-N curves, as the IWW ship is relatively small (compared to the other ship types) and because more recent data were employed (compared the data used compared to the other ship types cases). The other ship types F-N curves exhibit worse safety levels, since they correspond to older time periods. The IWW F-N curve is still comparable with the F-N curves for the bulk carrier. The estimations are repeated for the following two different maximum number of fatalities: Nu =1 and Nu =30. The reason is that for the manned IWW ships, the current accidents with the third parties involve the either single fatalities, e.g., collisions with kayaks or collisions with other ships, where the consequences can be very high (in the collision between Hableány and Viking Sigyn, 28 fatalities were reported (Wikipedia, 2021)).

Comparing minimum, mean and maximum values of the estimated metrics provided in Table 10, it is observed that in some metrics, the minimum is two times less than the mean and the mean is almost two times less than the maximum. The mean is still selected herein, as the employed q (used for these metrics calculation) is closest to the EU 28 value reported in Table 9. It should be noted that these estimations are independent from the ship type and are applicable to both the conventional and crewless ships.

Table 10 Estimations of PLL_A and F_A for an IWW ship

	Minimum	Mean	Maximum
q [fatalities/ $B]	0.10	0.2	0.27
Revenue [$B/year]	$0.504\ 10^{-3}$	$0.612\ 10^{-3}$	0.7210^{-3}
PLL_A [fatalities/year]	$5.04\ 10^{-5}$	$1.22\ 10^{-4}$	$1.94\ 10^{-4}$

k (Nu =1)	1	1	1
k (Nu =10)	0.34	0.34	0.34
k (Nu =30)	0.25	0.25	0.25
F_A[single fatality/year] (Nu =1)	5.04 10^{-5}	1.22 10^{-4}	1.94 10^{-4}
$F_{int}^{N_F=1}$ [single fatality/year] (Nu =1)	5.04 10^{-4}	1.22 10^{-3}	1.94 10^{-3}
$F_{neg}^{N_F=1}$ [single fatality/year] (Nu =1)	5.04 10^{-6}	1.22 10^{-5}	1.94 10^{-5}
F_A [single fatality/year] (Nu =30)	1.26 10^{-5}	3.05 10^{-5}	4.85 10^{-5}
$F_{int}^{N_F=1}$ [single fatality/year] (Nu =30)	1.26 10^{-4}	3.05 10^{-4}	4.85 10^{-4}
$F_{neg}^{N_F=1}$ [single fatality/year] (Nu =30)	1.26 10^{-6}	3.05 10^{-6}	4.85 10^{-6}

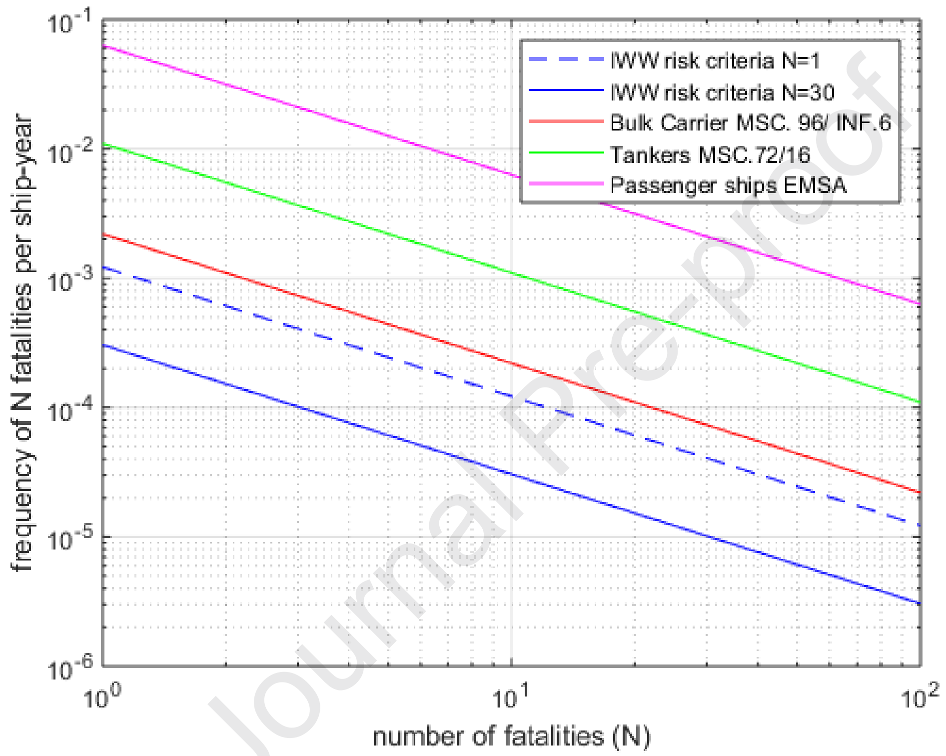

Figure 2 Societal risk acceptable level (only the border between tolerable and intolerable levels are depicted).

4.3 Phase 3: Risk Matrix and risk ratings development

It is observed from Table 6 results that the frequency criteria estimations based on the societal or individual risks are different. The societal risk-based frequency can be one order of magnitude more conservative compared to the individual risk-based frequency. This can be attributed to the fact, that the societal risk derived criteria incorporate information comparable to the current safety level in other industries and the financial benefits coming from the investigated activity. The individual risk acceptance criteria are also influenced by the operational context of the specific ship, as the jurisdiction of each country define different levels of intolerable and negligible risk and the exposure is dependent on the ship operating profile. In another operational context, the individual risks and exposure might have stronger influence on the selected frequency criteria.

Therefore, based on the societal criteria using a maximum single fatality (Nu =1), the single fatality is considered intolerable for values greater than 1.22 10^{-3} fatalities per year. Consequently, a functional failure leading to single fatality is considered as intolerable when its frequency is higher than 1.22 10^{-4} events per year based on assumption number 6. Considering maximum 30 fatalities (Nu =30), the values of the frequency per year for a single fatality higher than 3.05 10^{-4} are categorised as intolerable. This corresponds to values of the functional failure frequency leading to a single fatality higher that $3.05\ 10^{-5}$ events per year being intolerable, or to multiple fatalities frequency intolerable with frequency above 3.05 10^{-5} (equivalent functional failure higher than 3.05 10^{-6} events per year if we apply assumption 6). Based on the preceding considerations (using the most conservative value), the risk matrix and ratings are developed as illustrated in Table 11.

The multiple fatalities are considered as ALARP provided that they are very rare, or their potential frequency has been reduced to minimum (equivalent functional failure less than 3.05 10^{-6} events per year). This is considered for the risk matrix development to depict potentially devastating, but extremely low frequency, accidents (black swans), which cannot be predicted or controlled. Accidents, such as the collision between Hableány and Viking Sigyn demonstrate an example of such a case (Wikipedia, 2021).

The developed risk matrix and ratings also satisfy the Cox arching assumptions (Anthony Cox Jr, 2008). The risk matrix cells with higher ranking denote higher risk, as a logarithmic relationship between the rankings and risks was employed (weak consistency satisfied). Moreover, moving from the green to red areas, yellow cells appear (betweenness axiom satisfied). Due to the logarithmic relationship between the ranking and risks and the use of risk neutral attitude to risk aversion/taking, the consistency criteria in colouring are also satisfied.

It should be noted that the derived risk matrix is suitable for assessing third party risks exposed to risks due to the operation of autonomous ships. The criteria for the first party safety risk can slightly vary, as the revenue for the ROC, cargo operator and maintenance personnel can be different. Nonetheless, the proposed approach in this study can be followed to derive the risk matrix for the other parties as well.

It is also worth highlighting that if the decision-maker is risk-averse towards the large disasters involving multiple fatalities and treats them as unacceptable, the use of societal criteria with Nu =30 is no longer valid. In this case, societal criteria for Nu =1 can be used and the risk matrix will become as the one shown in Table 12. This risk matrix considers all major accidents as unacceptable, however it allows for the use of less stringent requirements for ranking single fatalities. Although it is possible to apply this consideration, it is not aligned with assumption 2 (section 2.1); additionally, the consistency criteria provided in (Anthony Cox Jr, 2008) is also violated.

The generated risk matrix and risk matrix ratings of Table 11 do not change whether it is used for conventional or crewless ships risk assessments. This can be attributed to the fact that the $F_{neg}^{N_F=1}$ and $F_{int}^{N_F=1}$ for the first parties derived from the individual risk (IR) are still less conservative than the one derived based on societal risk criteria (Table 6). Therefore, the societal risk criteria that influence the risk matrix, and the societal risk criteria (as explained in section 4.2) can be used for both conventional and crewless IWW ships. This final effect is influenced by the values of the following parameters: exposure of crew and the number of scenarios identified with severity index equal to 4. If the crew exposure increases, then the individual risk exposure will drive the selection of the risk matrix ratings, and therefore, the risk matrix will vary. If the crew exposure reduces, then the individual risk criteria will be of less importance as for now. Additionally, higher number of safety critical scenarios can be anticipated on conventional ships due to the crew exposure to safety risks. This might challenge the validity of sixth assumption according to which, the overall risk can be attributed to maximum 10 functional failures with severe consequences (leading to single fatality).

Table 11 Derived risk matrix for third parties.

FI	Frequency of functional failure leading to consequences (events per ship year)	Severity Index (SI)				
		1	2	3	4	5
		Negligible Minor first-aid injury to a single person in the workforce	Minor One or more first-aid injury.	Significant One or more injuries, not severe.	Severe Single fatality or multiple severe injuries	Catastrophic 10 fatalities and more
5	10^{-2}	6	7	8	9	10
4	10^{-3}	5	6	7	8	9
3	10^{-4}	4	5	6	7	8
2	10^{-5}	3	4	5	6	7
1	10^{-6}	2	3	4	5	6
High (H) =Intolerable Risk			Medium (M) =Tolerable Risk (ALARP)		Low (L) =Negligible Risk	

Table 12 Derived risk matrix for third parties taking into account risk aversion.

FI	Frequency of functional failure leading to consequences (events per ship year)	Severity Index (SI)				
		1	2	3	4	5
		Negligible Minor first-aid injury to a single person in the workforce	Minor One or more first-aid injury.	Significant One or more injuries, not severe.	Severe Single fatality or multiple severe injuries	Catastrophic 10 fatalities and more
5	10^{-1}	6	7	8	9	10
4	10^{-2}	5	6	7	8	9
3	10^{-3}	4	5	6	7	8
2	10^{-4}	3	4	5	6	7
1	10^{-5}	2	3	4	5	6
High (H) =Intolerable Risk			Medium (M) =Tolerable Risk (ALARP)		Low (L) =Negligible Risk	

4.4 Phase 4: Consequences types equivalence

Considering the equivalence of consequences between the safety and other types of risks, the interrelation of the various consequences categories and the corresponding consequences are provided in Table 13. The cost of averting the fatality was set at $3m in 1999 (IMO, 2018). By using a 5% inflation rate, as recommended by the FSA guidelines (IMO, 2018), the cost of averting the fatality approximates to $8m in 2021.

The correlation between other types of risks and safety risks was derived from FSA (2018), BV (Bureau Veritas, 2019), DNV GL RP A-203 guidelines (Ahluwaja, 2018) and EMSA report (EMSA, 2020). It should be noted that the small oil spills by IWW ships exhibit higher consequences on the environment, as the spillage will occur in a more confined environment and close to inhabited areas, compared to other ship types.

It should be noted that a hazardous scenario can exhibit diverse impact for different consequences categories (Bolbot et al., 2021a). A hazardous scenario can result in minor safety risks, but significant financial risks to the third parties, e.g., collision with a bridge. By using different consequences categories, such considerations can be captured in the risk assessment methodology. For the consequences ranking table, no difference between conventional and uncrewed ships should be considered.

Table 13 Interrelation between safety and other consequences categories.

		Safety	Environmental			Financial	Reputation
Ranking (SI)	Severity	Effects on humans safety	Oil spillage definition	Air pollution	Other e.g., for ballast water treatment failures or collision with marine mammals	Effect from ship operation disruption / litigation costs / insurance costs / fines / Effect on ship	Effect on company reputation
5	**Catastrophic**	Multiple fatalities (1–10 and more)	Oil spill size between 100 – 1000 t	Major air pollution with long-term environmental consequences	Impact, such as persistent reduction in ecosystem function or significant disruption of a sensitive species	\$80,000,000 (>\$25,000,000) Total loss	Extensive negative attention in international media/industry
4	**Severe**	Single fatality or multiple severe injuries. Full recovery with extensive medical treatment	Oil spill size between 10 – 100 t	Air pollution resulting in air evacuation	Impact, such as significant widespread and persistent changes in habitat, species or environment media	\$8,000,000 (\$2,500,000 – \$25,000,000) Severe damage	National impact and public concern; Mobilisation of action groups
3	**Significant**	One or more injuries, not severe. Full recovery with medical treatment	Oil spill size between 1 – 10 t	Limited environmental impact due to air pollution involving reporting to authorities	Impact, such as localised but irreversible habitat loss or widespread, long-term effects on habitat, species or environmental media	\$800,000 (250,000 – 2,500,000) Non-severe ship damage	Considerable impact; regional public/slight national media attention
2	**Minor**	One or more first-aid injury. Treatment is minimal or not necessary.	Oil spill size < 1 t	Limited to no air pollution	Impact, such as localised, long-term degradation of sensitive habitat or widespread short-term impacts to habitat, species or environmental media	\$80,000 (\$25,000 – \$250,000) Local equipment damage	Limited impact; local public concern may include media
1	**Negligible**	Minor first-aid injury to a single person in the workforce. Treatment is minimal or not necessary.	Non-significant spill	Minor environmental impact	Impact, such as localised or short-term effects on habitat, species and environmental media	\$8,000 (<\$25,000) No damage	Slight impact; local public awareness, but no public concern

4.5 Comparison with other risk matrices

An exemplary risk matrix with its rating schemes from the DNV guidelines for the risk assessment of novel technology used in the oil exploratory industry (DNV GL, 2011) is provided in Table 14. The risk matrix of Table 14 constitutes an adaptation of the original risk matrix, modified suitably to allow for the comparison, as the frequency scales are different in the DNV guidelines risk matrix compared to the ones employed herein (Table 11). In the DNV risk matrix, a range of frequencies is used for the risk rankings, in comparison to the crisp values of the FSA risk matrix and the employed methodology. For this reason, the risk matrix of Table 14 includes cells consisting of two different colours.

Nonetheless, comparing this exemplary adapted risk matrix, it can be observed that the ALARP region is wider in the DNV guidelines compared to the current approach. This can be attributed to the fact that the third parties risk ratings were influenced by the societal risk acceptance criteria, which allows two orders of magnitude difference between the negligible and intolerable risk. If the ALARP region was set using the individual risk criteria for the first parties, potentially three orders of magnitude would be assigned for ALARP in the derived risk matrix in this study (Table 11). Most importantly though, in the derived risk matrix, the ratings are approximately two levels more conservative. This can be attributed to the fact that the risk matrix of this study incorporates the safety levels from other industries, which have been improved over time and uses more stringent individual risk criteria set by the Belgian authorities. The risk matrix of Table 14 is also exemplary, however, the application area was not reported, and additionally it is not known whether the ratings refer to the first or third parties.

A similar risk matrix (shown in Table 15) compared to the one from DNV RP A203 (DNV GL, 2011) was employed in (EMSA, 2020). As it can be observed, the acceptable risk levels in the particular application were more stringent than the ones in Table 14; however, less conservative compared to Table 11. It should be noted that the risk matrix of Table 11 has applicability to the ship as a whole, whilst the risk matrix of Table 15 was applied to specific system with crew present on the ship. This significantly limits the comparison.

Table 14 Risk Index matrix adapted from DNV RP A203 (DNV GL, 2011).

FI	Frequency of functional failure leading to consequences (events per ship year)	Severity Index (SI)				
		1	2	3	4	5
		Negligible Minor first-aid injury to a single person in the workforce	Minor One or more first-aid injury.	Significant One or more injuries, not severe.	Severe Single fatality or multiple severe injuries	Catastrophic 10 fatalities and more
5	10^{-2}	6 6	7	8	9 9	10
4	10^{-3}	5	6 6	7	8	9 9
3	10^{-4}	4	5	6 6	7	8
2	10^{-5}	3	4	5	6 6	7
1	10^{-6}	2	3	4	5	6 6
High (H) =Intolerable Risk		Medium (M) =Tolerable Risk (ALARP)			Low (L) =Negligible Risk	

Table 15 Risk Index matrix adapted from (EMSA, 2020).

FI	Frequency of functional failure leading to consequences (events per ship year)	Severity Index (SI)				
		1	2	3	4	5
		Negligible Minor first-aid injury to a single person in the workforce	Minor One or more first-aid injury.	Significant One or more injuries, not severe.	Severe Single fatality or multiple severe injuries	Catastrophic 10 fatalities and more
5	10^{-2}	6	7	8 8	9	10
4	10^{-3}	5 5	6	7	8 8	9
3	10^{-4}	4	5 5	6	7	8 8
2	10^{-5}	3	4	5 5	6	7
1	10^{-6}	2	3	4	5 5	6
High (H) =Intolerable Risk		Medium (M) =Tolerable Risk (ALARP)			Low (L) =Negligible Risk	

To determine which of the risk matrix indexes from Table 11, Table 14, Table 15 seems to be better addressing the needs of autonomous technology, we have conducted a following simple comparison through the use of the corresponding Safety Integrity Levels (SILs) from IEC 61508 (IEC, 2010). Assuming that the investigated crewless ship operates in its sailing or manoeuvring modes 70% of its annual operation (taking into account that the use of autonomy will allow higher ship availability since the crew workhours will not need to be followed and the ship will be able to sail during night). In one of our previous studies, the severity index for the situation awareness system failure and collision avoidance system failure was ranked as 4 (SI=4) for the same IWW crewless ship (Bolbot et al., 2021a). This corresponds to different maximum functional frequency failure based on the ALARP. From for risk matrix and ratings of Table 11, it corresponds to FI=2 or F=10^{-5} events per ship year. Similar frequency values can be found from the other risk matrices, and are depicted in Table 16. These frequencies, in turn, correspond to different SILs, which are calculated and depicted in Table 16. Intuitively judging, it would be anticipated that the investigated ship situation awareness and collision avoidance functions should have stringent safety requirements due to their importance for the ship safety. Hence, SIL=3 that was derived based on Table 11 seems to be a more reasonable target level, compared to SIL=1 or SIL=2.

Table 16 SILs estimation for the investigated IWW ship situation awareness and collision avoidance functions

Different Risk index matrices	Maximum tolerable frequency for functional failure with SI=4 [per ship year]	Equivalent SIL (ranges are provided in ship year with the assumption of 70% operational time in autonomous mode)
Based on risk index matrix depicted in Table 11	10^{-5}	SIL3 (6 10^{-5} – 6 10^{-4})
Based on risk index matrix depicted in Table 14	5 10^{-2} (10^{-2} – 10^{-1})	SIL1 (6 10^{-3} – 6 10^{-2})
Based on risk index matrix depicted in Table 15	5 10^{-3} (10^{-3} – 10^{-2})	SIL2 (6 10^{-4} – 6 10^{-3})

4.6 Influence of the assumptions on the derived risk matrix

This section elaborates the impact of the made assumptions on the generated risk matrix.

The first assumption has a fundamental influence on the structure of the developed risk matrix. For instance, if linear scales were used (instead of logarithmic) for the risk matrix development, the shape of the risk matrix would be more skewed, with more cells dedicated to particular areas. This would render the compliance with the Cox arching assumptions (Anthony Cox Jr, 2008) very challenging. Additionally, considering a different equivalence relationship between fatalities and injuries, the consequence type equivalence during Phase 4 would be different.

If aversion to large accidents is considered, then the risk matrix ratings will be altered. This was demonstrated in detail from the comparison between Table 11 and Table 12 in section 4.3. In this case, higher frequency for smaller accidents will be tolerated and more stringent frequency requirements for larger scale accidents will be provided. Therefore, the second assumption affects the “inclination” of risk matrix.

If more stringent safety requirements are applied to autonomous ships compared to conventional ships (for instance one level of magnitude more stringent requirements for IR and PLL_A), the calculated $F_{int}^{N_F=1}$ and $F_{neg}^{N_F=1}$ affected by IR and PLL_A would also change accordingly, resulting in one order of magnitude more stringent requirements. This can be attributed to the linear relationship between $F_{int}^{N_F=1}$, $F_{neg}^{N_F=1}$ and IR, PLL_A.

With a different categorisation of risks, for example, when four categories were employed (instead of three categories), as for the London underground system (EMSA, 2015), the risk matrix ratings and classification would obviously include four regions for risk ratings.

By employing and alternative consideration to treati the different risk types (as per fifth assumption), the use of a single risk matrix would not be possible. It would be required to consider various risk matrixes and acceptance criteria for different types of consequences. This would increase the complexity of the risk assessment process and the associated effort required for the safety assurance.

The sixth assumption is highly influential on the risk matrix ratings. For instance, the assumption of 20 maximum functional failures with severe consequences (leading to single fatality) and Nu =1 results in a value of 6.11 10^{-5} for the acceptable functional failure frequency (instead of 1.22 10^{-4}). Therefore, the selected acceptable frequency would have become one level more stringent in the risk matrix. The influence of Nu on the derived matrix has been discussed in detail in section 4.3.

It is challenging to quantify the influence of seventh assumption on the derived risk matrix. However, it could result in more or less stringent requirements for IR and PLL_A based on the societal, political risk perception and trust. This would, in turn, influence the risk matrix ratings. The analysis of influence of these aspects on IR and PLL_A is a consideration for future research.

A daily encounter frequency between the investigated ship and a general cargo ship was considered in this study. This is a conservative estimation, as the investigated ship rarely operates in a specific area, and visits several locations. Therefore, the daily encounters between this ship and other ships are unlikely. More realistic estimations could be made if the AIS data was used as input. Nonetheless, even with such a conservative estimation, the individual risk criteria exhibit negligible effects on the derived risk matrix.

4.7 Discussion

The main advantage of the developed methodology is that it directly interconnects the risk matrix ratings with the individual and societal risk acceptable criteria in a smooth pattern. The presented methodology is repeatable, and the results are correlated with the financial benefits of the selected activity and the current risk levels in other industries. The methodology can be applied for developing risk matrices for both conventional and crewless ships. It is also expected that the use of such a risk assessment matrix will support the implementation of the goal-based standards and development of novel designs demonstrating ALARP and equivalent safety, as it supports the ship design with both individual and societal risk acceptance criteria being determined early in the design process. The developed methodology can support the implementation of functional based design and analyses in the maritime industry as well as the designation of safety integrity levels (SIL) to different functions, as already followed in aviation (SAE, 1996b).

The ‘anchor points’ (the set levels of individual risk, as well as the compared industries and countries financial and safety levels) have an important influence over the methodology results, as the country overall safety level, economy size and acceptance criteria for individual risk, affect the resultant risk matrix. Therefore, this methodology allows for contextualisation of these factors. Moreover, this risk matrix and risk matrix ratings are valid only at a specific time snapshot. In case where the safety levels or revenue levels or the set acceptable individual risk levels change, the proposed methodology need to be repeated to determine the updated risk matrix.

As the risk matrix and ratings are also contextualised for a specific application, these ratings can be different in other ships (and ship types) and need to be re-estimated/selected. It is highly likely that in another operational context, due to different exposure of the individuals, the individual risk (not the societal risk) will drive the risk matrix development. The methodology also requires the development of separate risk matrixes for different person groups, due to the differences in the exposure/societal benefits, although it is expected that similar results may be obtained.

The introduction of the factor of 10 when moving from the ship level to scenarios level is a critical assumption employed in this study. It must be crosschecked that there will not exist more than 10 scenarios with the selected frequency (e.g., 10^{-5} for the investigated IWW ship) and severe consequences, so that this assumption or equivalent risk index is sufficient. In cases where such scenarios are only few, relaxation of the risk matrix ratings can potentially be investigated. Nonetheless, as it is not recommended to aggregate the different scenarios risk (ISO, 2009), it should be finally checked and verified that the estimated risk levels comply with the individual and societal risk criteria by employing more detailed methods at a later design stage. However, the proposed methodology caters the preliminary risk matrix to facilitate the risk assessment at the initial design stages.

It should be pointed out that the risk matrix was developed for use at a ship level and in a specific operational concept. For the use of the risk matrix at a system level, potentially even stringent requirements are required; for example, by dividing the acceptable frequency by another factor of 10 or by ensuring that the frequency of scenarios with severe consequences is adequately reduced.

Based on the developed methodology results, some stringent criteria and risk matrix ratings are recommended for the investigated IWW crewless ship with respect to third party risks. The other compared risk matrixes exhibit less conservative ratings. It seems that the proposed herein more stringent risk matrix ratings need to be followed, as they include information on both the societal and individual risks. However, it is important to investigate whether the current fleet of conventional IWW ships satisfies these criteria in order to avoid overdesigning of crewless IWW ships, which is expected to increase their costs associated to the design and building. Nonetheless, it is expected that by using these criteria, similar, if not enhanced safety levels will be achieved for the autonomous and crewless ships.

Finally, it should be noted that the developed risk matrix incorporated primarily the safety and secondarily, other types of risks. The decision-making with respect to the introduction of the autonomous ships still depends on a number of additional factors, including the overall impact on the economy, sector competitiveness, emissions reduction, quality of life, as autonomous shipping has much wider implications. We also have kept the aspects related to uncertainty in rankings and epistemic uncertainty outside the analysis scope, as they were addressed in other publications (see for instance Goertlandt and Reniers (2016)). These factors are also important for decision-making for autonomous ships safety approval, yet, they were left outside the scope of this study. For this reason, it is anticipated that the decision-making for autonomous ships should be made following a case-by-case scenario. Still, it is expected that this risk matrix and risk matrix development methodology will support the final decision-making and will constitute a useful tool for the decision-makers.

5 CONCLUSIONS

In this study, a novel methodology for developing the risk matrix and risk matrix ratings based on individual and societal risk acceptance criteria was proposed. The applicability of the methodology was demonstrated for the theoretical case study of an uncrewed IWW ship.

The main findings of the study are summarised as follows.

- The proposed methodology allowed for developing the risk matrix based on a set of defined individual and societal risk acceptance criteria.
- The use of the societal risk acceptance criteria allows the consideration of safety levels in other industries and the financial benefits generated by a specific activity during the development of the risk matrix, whilst the use of individual risk allows to consider the exposure of different individuals.
- As the methodology results are context and case study dependent, the developed risk matrix will be capable of providing different acceptance criteria for different ship types operating in different areas with different operating profiles.
- The methodology results are influenced by the anchoring points and assumptions of the decision/makers, therefore are highly dependent on the selected policy of each decision maker.
- The societal risk acceptance criteria resulted in more stringent matrix ratings compared to the individual risk criteria for the investigated IWW ship, which can be attributed to the relatively small revenue for this ship.
- The developed risk matrix ratings were also more conservative compared to the risk matrix ratings reported in the literature due to the influence of societal risk. Still, the selected safety integrity levels for some functions based on the risk matrix ratings proposed by the methodology seem to be reasonable.

It is anticipated that this methodology will constitute a useful tool for the involved industry stakeholders. Future research could focus on the determination of the current safety level for the fleet of conventional IWW ships as well as the adaptation of the proposed methodology for application in other industries and investigations for other ship types.

ACKNOWLEDGMENTS

This study was carried out in the framework of the AUTOSHIP project, which is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 815012. The authors kindly acknowledge the comments and input provided from Sifis Papageorgiou from the European Maritime Safety Agency (EMSA), Antoon Van Coille from Zulu Associates, Sárkány Gábor and Veres Gábor Tamás from Transportation Safety Bureau of Hungary and especially from Prof Rolf Skjong from DNV. The authors affiliated with the MSRC greatly acknowledge the funding from DNV AS and RCCL for the MSRC establishment and operation. The opinions expressed herein are those of the authors and should not be construed to reflect the views of DNV AS, RCCL, EMSA, the AUTOSHIP partners or the acknowledged organisations and individuals.

REFERENCES

(EPA), U.S.E.P.A., 2011. Exposure Factors Handbook: 2011 Edition. Springfield, VA, National Center for Environmental Assessment, Washington, DC.

Abaei, M.M., Hekkenberg, R., BahooToroody, A., 2021a. A multinomial process tree for reliability assessment of machinery in autonomous ships. Reliability Engineering & System Safety 210, 107484.

Abaei, M.M., Hekkenberg, R., BahooToroody, A., Banda, O.V., van Gelder, P., 2021b. A probabilistic Model to Evaluate the Resilience of Unattended Machinery Plants in Autonomous Ships. Reliability Engineering & System Safety, 108176.

ABS, 2017. Qualifying new technologies.

Ahluwaja, A., 2018. Managing New Technology Risks - DNV GL Technology qualification process.

Anthony Cox Jr, L., 2008. What's wrong with risk matrices? Risk Analysis: An International Journal 28 (2), 497-512.

army, U., 2002. Numerical criteria for airworthiness.

Bakdi, A., Glad, I.K., Vanem, E., Engelhardtsen, Ø., 2020. AIS-based multiple vessel collision and grounding risk identification based on adaptive safety domain. Journal of Marine Science and Engineering 8 (1), 5.

Ball, D.J., Floyd, P.J., 1998. Societal risks. Report submitted to HSE.

Blom, H.A.P., Jiang, C., Grimme, W.B.A., Mitici, M., Cheung, Y.S., 2021. Third party risk modelling of Unmanned Aircraft System operations, with application to parcel delivery service. Reliability Engineering & System Safety, 107788.

Bolbot V, T.G., Wennersberg LA, 2022. A method to identify and rank objects and hazardous interactions affecting autonomous ships navigation Journal of Navigation.

Bolbot, V., Theotokatos, G., Andreas Wennersberg, L., Faivre, J., Vassalos, D., Boulougouris, E., Jan Rødseth, Ø., Andersen, P., Pauwelyn, A.-S., Van Coillie, A., 2021a. A novel risk assessment process: Application to an autonomous inland waterways ship. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 1748006X211051829.

Bolbot, V., Theotokatos, G., Boulougouris, E., Vassalos, D., 2019. Safety related cyber-attacks identification and assessment for autonomous inland ships, Internation Seminar on Safety and Security of Autonomous Vessels, Helsinki, Finland.

Bolbot, V., Theotokatos, G., Boulougouris, E., Vassalos, D., 2020. A novel cyber-risk assessment method for ship systems. Safety Science 131, 104908.

Bolbot, V., Theotokatos, G., Wennersberg, L.A., Faivre, J., Vassalos, D., Boulougouris, E., Rødseth, Ø.J., Andersen, P., Pauwelyn, A.-S., Van Coillie, A., 2021b. A novel risk assessment process with application to autonomous inland waterways vessels. Part O: Risk and Reliability.

Bureau Veritas, 2019. Guidelines for Autonomous Shipping, in: Veritas, B. (Ed.), NI 641 DT R01E. Bureau Veritas, Paris.

BV, 2019. Guidelines for autonomous shipping - Guidance Note NI 641DT R01 E, in: BV (Ed.).

Central Commission for the Navigation of the Rhine (CCNR), 2018. Definitions on various forms of automated navigation.

Chaal, M., Banda, O.V., Basnet, S., Hirdaris, S., Kujala, P., 2020a. An initial hierarchical systems structure for systemic hazard analysis of autonomous ships, Proceedings of the International Seminar on Safety and Security of Autonomous Vessels (ISSAV) and European STAMP Workshop and Conference (ESWC) 2019. Sciendo, pp. 140-153.

Chaal, M., Valdez Banda, O.A., Glomsrud, J.A., Basnet, S., Hirdaris, S., Kujala, P., 2020b. A framework to model the STPA hierarchical control structure of an autonomous ship. Safety Science 132, 104939.

Chang, C.-H., Kontovas, C., Yu, Q., Yang, Z., 2021. Risk assessment of the operations of maritime autonomous surface ships. Reliability Engineering & System Safety 207, 107324.

COLREGS, 1972. International Regulations for Preventing Collisions at Sea - Articles of the Convention on the International Regulations for Preventing Collisions at Sea.

de Vos, J., Hekkenberg, R.G., Valdez Banda, O.A., 2021. The Impact of Autonomous Ships on Safety at Sea – A Statistical Analysis. Reliability Engineering & System Safety 210, 107558.

DNV GL, 2011. Qualification of new technology, DNV-RP-A203.

DoD, U., 2012. Mil-std-882e, department of defense standard practice system safety. US Department of Defense.

Du, L., Banda, O.A.V., Huang, Y., Goerlandt, F., Kujala, P., Zhang, W., 2021. An empirical ship domain based on evasive maneuver and perceived collision risk. Reliability Engineering & System Safety 213, 107752.

Duijm, N.J., 2015. Recommendations on the use and design of risk matrices. Safety Science 76, 21-31.

Duijm, N.J., Universitet, D.T., 2009. Acceptance criteria in Denmark and the EU. Citeseer.

EASA, 2010. Certification specifications for large aeroplanes CS-25.

Eloranta, S., Whitehead, A., 2016. Safety aspects of autonomous ships, in: Gl, D.N.V. (Ed.), 6th International Maritime Conference, Germany, Hamburg, pp. 168-175.

EMSA, 2015. Risk Acceptance Criteria and Risk Based Damage Stability. Final Report, part 1: Risk Acceptance Criteria.

EMSA, 2020. Study on electrical energy storage for ships.

EUROSTAT, 2020. Fatal Accidents at work by NACE Rev. 2 activity.

EUROSTAT, 2021. Gross domestic product at market prices.

FAA, 2011. System safety analysis and assessment for part 23 airplanes.

Garvey, P.R., 2008. Analytical methods for risk management: A systems engineering perspective. Chapman and Hall/CRC.

Geertsma, R.D., Negenborn, R.R., Visser, K., Hopman, J.J., 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy 194, 30-54.

Goerlandt, F., Reniers, G., 2016. On the assessment of uncertainty in risk diagrams. Safety Science 84, 67-77.

GOVINFO, 2002. Federal Aviation Administration, DOT.

Hansen, M.G., Jensen, T.K., Lehn-Schiøler, T., Melchild, K., Rasmussen, F.M., Ennemark, F., 2013. Empirical ship domain based on AIS data. The Journal of Navigation 66 (6), 931.

Hiroko Itoh, Tomohiro Yuzui, Megumi Shiokari, Eiko Ishimura, Rina Miyake, Kudo, J., 2021. Risk assessment of autonomous ship systems. ClassNK technical Journal 4.

Hoem, Å.S., 2019. The present and future of risk assessment of MASS: literature review, Proceedings of the 29th European Safety and Reliability Conference (ESREL), Hannover, Germany, pp. 22-26.

Höyhtyä, M., Huusko, J., Kiviranta, M., Solberg, K., Rokka, J., 2017. Connectivity for autonomous ships: Architecture, use cases, and research challenges, 2017 International Conference on Information and Communication Technology Convergence (ICTC). IEEE, pp. 345-350.

HSE, 1992. The tolerability of risk from nuclear power stations.

HSE, 2020. Workplace fatal injuries in Great Britain, 2020, Annual statistics.

Hsu, W.-K.K., Huang, S.-H.S., Tseng, W.-J., 2016. Evaluating the risk of operational safety for dangerous goods in airfreights – A revised risk matrix based on fuzzy AHP. Transportation Research Part D: Transport and Environment 48, 235-247.

Hu, Y., Park, G.-K., 2020. Collision risk assessment based on the vulnerability of marine accidents using fuzzy logic. International Journal of Naval Architecture and Ocean Engineering 12, 541-551.

IEC, 2010. IEC 61508-1: 2010. Functional Safety of Electrical/electronic/programmable Electronic Safety-Related Systems—Part 1.

IMO, 2000. MSC 72/16 Decision parameters including risk acceptance criteria.

IMO, 2008. Formal Safety Assessment - Cruise ships - MSC 85/INF.2. International Maritime Organisation.

IMO, 2013. MSC. 1/Circ 1455 Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments, United Kingdom, London.

IMO, 2018. Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process, London, p. 71.

IMO, 2020. Regulatory scoping exercise.

ISO, 2009. Risk management — Risk assessment techniques, ISO 31010. International Organization for Standardization, Switzerland, Geneva, p. 92.

Iverson, L.R., Matthews, S.N., Prasad, A.M., Peters, M.P., Yohe, G., 2012. Development of risk matrices for evaluating climatic change responses of forested habitats. Climatic Change 114 (2), 231-243.

Jensen, R.C., Bird, R.L., Nichols, B.W., 2022. Risk Assessment Matrices for Workplace Hazards: Design for Usability. International Journal of Environmental Research and Public Health 19 (5), 2763.

Kijima, K., Furukawa, Y., 2003. Automatic collision avoidance system using the concept of blocking area. IFAC Proceedings Volumes 36 (21), 223-228.

Kim, T.-e., Sharma, A., Gausdal, A.H., Chae, C.-j., 2019. Impact of automation technology on gender parity in maritime industry. WMU Journal of Maritime Affairs 18 (4), 579-593.

Kontovas, C.A., Psaraftis, H.N., 2009. Formal safety assessment: a critical review. Marine Technology and SNAME News 46 (01), 45-59.

Lawrence, E., 2011. System Safety Analysis and Assessment for Part 23 Airplanes. United States Federal Aviation Administration, Washington, DC, Report No. AC.

Lee, E.-J., Ruy, W.-S., Seo, J., 2020. Application of reinforcement learning to fire suppression system of an autonomous ship in irregular waves. International Journal of Naval Architecture and Ocean Engineering 12, 910-917.

Levine, E., 2012. Improving risk matrices: the advantages of logarithmically scaled axes. Journal of Risk Research 15 (2), 209-222.

Li, J., Bao, C., Wu, D., 2018. How to design rating schemes of risk matrices: A sequential updating approach. Risk Analysis 38 (1), 99-117.

MacroTrends, 2020. GNP for countries.

Meyer, T., Reniers, G., 2016. Engineering risk management. De Gruyter.

Montewka, J., Wróbel, K., Heikkilä, E., Valdez Banda, O., Goerlandt, F., Haugen, S., 2018. Challenges, solution proposals and research directions in safety and risk assessment of autonomous shipping. Probabilistic Safety Assessment and Management PSAM 14, 16-21.

Namgung, H., Kim, J.-S., 2021. Collision Risk Inference System for Maritime Autonomous Surface Ships Using COLREGs Rules Compliant Collision Avoidance. IEEE Access 9, 7823-7835.

Ni, H., Chen, A., Chen, N., 2010. Some extensions on risk matrix approach. Safety Science 48 (10), 1269-1278.

Nzengu, W., Faivre, J., Pauwelyn, A.-S., Bolbot, V., Lien Wennersberg, L.A., Theotokatos, G., 2021. Regulatory framework analysis for the unmanned inland waterway vessel. WMU Journal of Maritime Affairs.

Oliveira, M.D., Bana e Costa, C.A., Lopes, D.F., 2018. Designing and exploring risk matrices with MACBETH. International Journal of Information Technology & Decision Making 17 (01), 45-81.

Pietrzykowski, Z., Wielgosz, M., 2021. Effective ship domain–Impact of ship size and speed. Ocean Engineering 219, 108423.

Poggi, L., Gaggero, T., Gaiotti, M., Ravina, E., Rizzo, C.M., 2020. Recent developments in remote inspections of ship structures. International Journal of Naval Architecture and Ocean Engineering 12, 881-891.

Rødseth, Ø., Burmeister, H.-C., 2015a. New ship designs for autonomous vessels. MUNIN project, p. 36.

Rødseth, Ø.J., Burmeister, H.-C., 2015b. Risk assessment for an unmanned merchant ship. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation 9 (3), 357--364.

Rozell, D.J., 2018. The ethical foundations of risk analysis. Risk Analysis 38 (8), 1529-1533.

Ruan, X., Yin, Z., Frangopol, D.M., 2015. Risk Matrix Integrating Risk Attitudes Based on Utility Theory. Risk Analysis 35 (8), 1437-1447.

SAE, 1996a. ARP4761 - Guidance and methods for conducting the safety assessment process on civil ariborn systems and equipment.

SAE, 1996b. Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment. SAE International.

Skjong, R., 2002. Risk Acceptance Criteria: current proposals and IMO position. Surface transport technologies for sustaninable development, Spain, 4-6.

statistics, U.S.B.o.l., 2020. Fatal occupational injuries for selected industries, 2015-19.

Szlapczynski, R., Szlapczynska, J., 2017. Review of ship safety domains: Models and applications. Ocean Engineering 145, 277-289.

Tam, K., Jones, K., 2018. Cyber-risk assessment for autonomous ships, 2018 International Conference on Cyber Security and Protection of Digital Services (Cyber Security). IEEE, pp. 1-8.

Thomas, P., Bratvold, R.B., Bickel, E., 2014. The risk of using risk matrices. SPE Economics & Management 6 (02), 56-66.

transportation, U.d.o., 2011. System safety analysis and assessment for part 23 airplanes AC No: 23.1309-1E.

Utne, I.B., Rokseth, B., Sørensen, A.J., Vinnem, J.E., 2020. Towards supervisory risk control of autonomous ships. Reliability Engineering & System Safety 196, 106757.

van Cappelle, L.E., Chen, L., Negenborn, R.R., 2018. Survey on Short-Term Technology Developments and Readiness Levels for Autonomous Shipping, in: Cerulli, R., Raiconi, A., Voß, S. (Eds.), Computational Logistics. Springer International Publishing, pp. 106-123.

van Lieshout, P., van Dijk, T., Dam, C.H., van den Brink, A., Vredeveldt, A., 2021. A risk based approach for equivalent safety assessment of alternative fuels for green shipping, Developments in the Analysis and Design of Marine Structures. CRC Press, pp. 532-537.

Vinnem, J.-E., 2014. Offshore Risk Assessment vol 1. Springer.

Vinnem, J.E., 2021. Assessment of risk tolerance for future autonomous offshore installations. Safety Science 134, 105059.

Wang, H., Theotokatos, G., Boulougouris, E., 2020. D4.3 Risk Control and Improvements. Tram Project.

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

Wennersberg, L.A., Nordahl, H., 2019. D2.1 - Complete supply chain mapping & identifications of interactions between SSS and IWW demonstrators.

Wikipedia, 2021. Sinking of Hableány.

Wróbel, K., Montewka, J., Kujala, P., 2017. Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. Reliability Engineering & System Safety 165 (Supplement C), 155-169.

Wróbel, K., Montewka, J., Kujala, P., 2018. Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels. Reliability Engineering & System Safety 178, 209-224.

Yang, J.-M., Tseng, C.-M., Tseng, P., 2015. Path planning on satellite images for unmanned surface vehicles. International Journal of Naval Architecture and Ocean Engineering 7 (1), 87-99.

Zhou, J., Ding, F., Yang, J., Pei, Z., Wang, C., Zhang, A., 2021. Navigation safety domain and collision risk index for decision support of collision avoidance of USVs. International Journal of Naval Architecture and Ocean Engineering 13, 340-350.

APPENDIX A ABBREVIATION AND NOMENCLATURE LIST

Abbreviation	Definition
a	Annum
AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
CAF	Cost of Averting the Fatality
E_p	Individuals exposure [-]
F	Frequency [per ship-year]
F_A	Frequency of single fatality per annum
F_{ue}	Frequency of an undesired event
FI	Frequency Index
$F_{int}^{N_F=1}$	Intolerable single fatality rate [per ship-year]
$F_{neg}^{N_F=1}$	Negligible single fatality rate [per ship-year]
FSA	Formal Safety Assessment
GDP	Gross Domestic Product
GNP	Gross National Product in
IMO	International Maritime Organisation

IR	Individual Risk
IWW	Inland Waterway
k	Parameter k
L	Ship length in [m]
N_F	Number of the occupational fatalities per annum
N	number of people
Nu	maximum fatalities number
N_E	Encounter number
PLL	Potential Loss of Life
PLL_A	Probability of the loss of life [fatalities per annum]
P_p	Probability of event resulting in casualty
q	Ratio of fatalities to the gross national income (GNP) [$B^{-1}]
R	The economic value (revenue) in [$B] per year
ROC	Remote Operation Centre
RCC	Remote Control Centre
SD	Safety domain diameter [nm]
SI	Severity Index

SIL	Safety Integrity Level
T_E	The average duration of encounter
T_p	The annual time a person from a specific group is exposed to the considered risk (in hours)
T_a	the hours of one year (8,760 h)
V	Ship speed [kn]

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: