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From Aviation to Maritime: An approach to define target safety levels for the safety assurance of autonomous ship systems

Meriam Chaal
Risks and Intelligence in Marine System, Marine and Arctic Technology Group, Department of Mechanical Engineering, Aalto University, Finland, E-Mail: meriam.chaal@aalto.fi

Victor Bolbot
Risks and Intelligence in Marine System, Marine and Arctic Technology Group, Department of Mechanical Engineering, Aalto University, Finland, E-Mail: victor.bolbot@aalto.fi

Axel Berres
German Aerospace Center, Braunschweig, Germany, E-Mail: Axel.Berres@dlr.de

Osiris.A Valdez Banda
Risks and Intelligence in Marine System, Marine and Arctic Technology Group, Department of Mechanical Engineering, Aalto University, Finland, E-Mail: osiris.valdez.banda@aalto.fi

The safety assurance of autonomous ship systems is anticipated to present various challenges in the near future, necessitating the establishment of unambiguous procedures and references to facilitate the risk-based design of future ship systems. The International Maritime Organization's (IMO) guidelines, as outlined in the current version of the Formal Safety Assessment (FSA), Goal-Based Standards, and the rules from classification societies lack in detail for the risk-based design of autonomous ship systems. In the meantime, the aviation industry's regulations include more structured techniques for aircraft systems engineering, including a risk matrix that is employed as a benchmark to set the system safety objectives throughout various stages of system design. Consequently, this research suggests a methodology to establish target safety levels for the safety assurance of future ship systems, guided by aviation standards, to support the development of risk-based procedures and regulations that ensure the design of safe autonomous ship systems.

Keywords: Risk matrix, system safety assurance, risk-based design, aviation safety, marine risk assessment, Marine Autonomous Surface Ships

1. Introduction

1.1. The background

Multiple research institutions and ship systems providers are developing Marine Autonomous Surface Ships (MASSs). It is expected that the introduction of MASSs will result in paradigm shift in the maritime industry (Pedersen et al., 2020), even if the advancement of MASSs is expected to be slow and gradual due the associated safety obstacles (Chaal et al., 2022; de Vos et al., 2021; Kim et al., 2022). That's why the MASS design and safety assurance constitute a topic of intense research.

1.2. The problem

For the arise of MASSs it is necessary to advance first the enabling concepts and systems. A significant obstacle to the certification of enabling concepts constitute the lack of clear assurance guidance for the MASS systems acceptance (Heikkilä et al., 2017). According to certain regulatory statements such as in SOLAS, equivalence to the existing regulations should be demonstrated in the novel systems (IMO, 2019a). Besides, a risk assessment is deemed necessary as referred in Goal-Based standards (IMO, 2011). However, there is a diffusion in the industry on what should constitute the acceptable risk level in the risk assessment and how to do risk assessment (EMSA, 2015; Itoh et al., 2021). Whilst there are well defined societal and individual risk acceptance criteria in the maritime (EMSA, 2015), their application to the individual systems under the scope remains challenging (Vander Maelen et al., 2019). In this way, the implementation of effective functional hazard assessments and assignment of specific target safety requirement is complicated. Conducting a hazard assessment at the system level in a smooth and systematic manner necessitates a comprehensive risk matrix to map the effects of system functional failures and assign target safety levels.

1.3. Existing body of research

Several researchers attempted to solve the problem. Vinnem., (2021) investigated the applicability of current risk acceptance criteria in the context of autonomous offshore installations. Bolbot et al., (2022) interconnected the risk matrix to the societal and individual risk and proposed risk acceptance criteria for an inland waterway MASS. Yang and Utne., (2022) have employed a risk matrix for the risk assessment of autonomous marine systems, without providing the rationale behind the risk matrix ratings. Sun et al., (2018) proposed a method to establish acceptable societal risks in connection to the Safety Level Approach by IMO, which is a statistical ship-level approach. In the Risk Based Assessment Tool (RBAT), a modified HAZID approach with a risk matrix is employed (EMSA, 2021). The tool is dedicated to assessing only the risks associated with system control actions. Besides, the risk matrix includes consequences severity and mitigation effectiveness instead of frequency of event occurrence, without providing a comprehensive risk acceptance criteria to use for system functional safety.

On the other hand, aviation industry has been using for decades a concise and consistent approach for selecting appropriate safety target levels for different functions with the support of functional hazard assessment and risk matrices. The aviation industry can boast much better risk assessment procedures, risk matrices and safety levels in comparison to the maritime (Turan et al., 2016). Safety approaches initially employed by the aviation industry have already influenced the maritime rules and standards in other cases such the adoption of safety management systems and safety culture (Amanyire, 2007). Therefore, it would worthy of investigating the potential of employing similar risk approaches and risk acceptance criteria when designing MASS systems.

1.4. The aim and objectives

Therefore, the aim of this research is to first to identify the risk matrix and target safety levels that are provided in the aviation as support for the hazard and risk assessments, and second to investigate on how and under which limitations the aviation risk matrix and the target safety levels can be applied to the MASS systems.

1.5. Structure

This paper is structured as follows. First the similarities and differences between the aviation and maritime risk acceptance perspectives are discussed and the conditions for the application of similar risk matrix and target safety levels are found. Then a thorough and diligent examination and comparison of the two industries is presented, which aiming to derive a careful adaptation of risk matrix from aviation to maritime. In section three the results of our methodology are presented and critically discussed. Lastly the main findings of our research are summarised.

2. Methodology

The methodology adopted in this study aims at providing a consistent comparison of the aviation and maritime industries focusing on the way risk is accepted in order to derive a comprehensive marine risk matrix. It is constituted of four main steps as depicted in Figure 1. The arrows in figure denote the way information flowed and influenced the consequent steps.

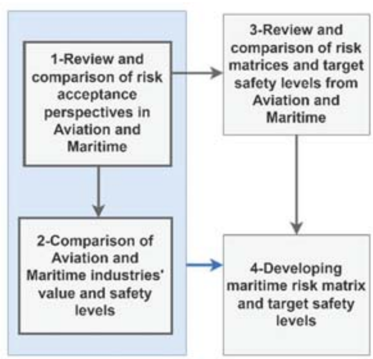

Figure 1: Methodology steps

In Step 1, the risk acceptance perspectives generally adopted in different industries are reviewed and the perspectives taken by aviation and maritime are examined and compared according to these.

Next, in Step 2 a more thorough and diligent comparison of the two industries is conducted based on a set of relevant comparison factors as follows:

Factors related to the value at stake in each industry: because safety risk is ultimately impacting the value of assets and lives that we aim to protect.

- Share of EU GDP (dollar): The GDP per worker of each industry
- World fleet: Total number of units (aircrafts or ships) in the world commercial fleet
- Asset value (dollar): Global fleet value
- Average value of a new unit (dollar): Average value of a newly built (commercial ship or aircraft)
- Transported cargo (ton.mile/year): Total volume of cargo transported by the fleet
- Value of cargo (dollar): Total value of the transported cargo by the world fleet
- Transported passengers (persons/year): Total number of passengers transported by the fleet

Safety levels factors:

- Fatal accidents (accidents/year): Yearly number of accidents/casualties
- Fatalities (persons/year): Yearly total number of fatalities of the transport mode
- Hull - Total loss (units/year): Yearly number of accidents that resulted in total loss of the unit

In step 3 a comparison of the risk matrices from both industries is conducted parallelly. To do so the reference risk matrices are first identified from the guidance documents and regulation.

Lastly, in Step 4 a comprehensive maritime risk matrix based on the above-described steps is developed.

3. Results and Discussion

3.1. Review and comparison of the risk acceptance perspectives in aviation and maritime

There are three main approaches to the risk analysis and therefore three categories of acceptance criteria. In the first one, according to the absolute rationality perspective, the four main types of risk acceptance criteria can include a) the societal risk usually represented by an F-N curve, b) the individual risk, c) the risk matrix, d) cost-benefit criteria (Perrow, 1999). These types of criteria are usually used in the risk assessment process in the multiple industries and are in line with risk realist view, who perceive risk as inherent and measurable property of the systems (Goerlandt and Montewka, 2015). The realist acceptance criteria are usually measured in numbers or semi quantitatively. Generally, the risks are classified as intolerable, ALARP or negligible based on these criteria (EMSA, 2015).

The second approach is informed by the theories of bounded rationality and social rationality, which recognize that decision-making under uncertainty is often subject to heuristics and influenced by public perception of risk (Perrow, 1999). This approach aligns with the risk constructivist worldview, which posits that risk is not an inherent property of an object or system but is instead product of social perception and interpretation (Goerlandt and Montewka, 2015).

Lastly, the proceduralist approach emphasizes the importance of following a well-defined process for making decisions about risk and avoids relying solely on quantitative or qualitative criteria (Goerlandt and Montewka, 2015). Following qualitative criteria in terms of regulations, rules and standards constitutes this approach.

A wholistic risk assessment would involve all the above into consideration. However, whilst in the maritime industry individual, societal and cost-benefit criteria are used, for the aircraft design risk matrices are heavily employed (EMSA, 2015). This can be attributed to the historical evolution of safety science and regulations in these two transportation domains, and not to the fact that risk matrices are not useful in the maritime domain. Instead, they have been extensively used in maritime as well (Daryanto et al., 2020; IMO, 2018; Shao et al., 2022). In this way, the risk assessment processes and criteria in maritime and aviation are considered heavily inclined toward the risk realist worldview with some considerations from the risk constructivist worldview. This constitutes the first communality between the two industries when addressing the safety.

This similarity alone is not enough to be able to use the risk matrix from aviation in the maritime. Generally transferring risk acceptance criteria from one industry to another is not recommended, as the economics are different (Duijm, 2009). The risk perception is also different, especially when we refer to the nuclear industry. The aversion to big accidents can be also different among the industries. Yet we can investigate the similarities in the previously explained risk criteria (societal, individual, cos-benefit, risk aversion policy) and the conditions under which, the risk matrices used in aviation can be adopted for the maritime. This is investigated in the next paragraphs.

The societal criteria in the maritime are not independent from the safety levels achieved in the aviation. As described in (IMO, 2000), the parameter q for passenger vessels (second or third parties' victims), reflecting fatalities per economic activity, is defined based on the aviation safety and economic performance. For the crew members (first party victims), this number is specified based on the overall fatalities in the whole economy, which is naturally worse than the aviation performance due to the industry characteristics. This is due to the higher number of crewmembers onboard ships and to the hazardous events in machinery spaces which can result in fatalities without ship accidents. Thus, at least in terms of targets for the societal risk, the aviation criteria are more stringent than the one used in the maritime.

The individual risk acceptance criteria in the maritime are specified in line with the HSE requirements (EMSA, 2015). There are no such considered in aviation (EMSA, 2015). However, for the airports, the individual criteria for the users (second parties) coincide with the one in maritime (EMSA, 2015). This together with much better safety records in aviation can be an indication, as shown in Section 3.3.2, that the individual risk criteria are on similar or better levels in aviation.

The cost-benefit criteria are of monetary nature and depict the cost of averting a fatality in a society. They depend on the economic activity in the society, and the life expectancy and therefore they will not differentiate in a single country or differentiate significantly in one specific region e.g. Scandinavia. The observant values for cost-benefit criteria in developed countries fluctuate, but they do not have a difference of scale (EMSA, 2015).

In terms of risk perception and risk aversion, in the maritime industry generally a neutral standing against the big accidents is considered. It means that the acceptance for risk from multiple small accidents is treated equally as for a big one with the same fatalities as described in (IMO, 2000). For the aviation this can be different, as accidents there often result in catastrophic outcomes and negative public coverage (IATA, 2022). Meanwhile, maritime generally remains under shadow, and even complete crew loss does not result in public outcry, unless it results in a large oil spill. All together, these factors suggests that aviation can be considered risk-aversive industry compared to maritime as also indicated in (IATA, 2022).

Concluding we can generally observe that the risk matrix from aviation can be transferred to the maritime under these conditions:

- Willingness to move the future maritime industry towards better safety and less neutrality against large accidents.
- The considered ships have similar financial value as the considered aircrafts.
- The considered ships economic performance and contribution to the global economy are similar to the considered aircrafts.

Even in that condition, the acceptance criteria will be more stringent due to better safety levels in aviation. However, this is not problematic if we consider the case of autonomous ships, as the IMO regulations prescribe generally more stringent levels of acceptable safety for novel systems (IMO, 2018, 2019a). Additionally, with the willingness of the maritime industry to move towards better safety (DNV, 2021; IMO, 2019b), the risk neutrality towards large accidents should be avoided.

3.2. Comparison of aviation and maritime industries' value and safety levels

A basic initial criterion to compare both industries risks is the type of risk inherent to each activity (Fixed Facility Risk vs Transportation Risk). This is related to whether the perimeter of risk is the same or changes, which depends on whether the subject of study is a fizxed or a moving facility. In this respect, both aircrafts and ships are transportation systems, and their inherent risk has a perimeter that changes because they change location. Another basic criterion relates to the fact that both aircrafts and ships transport cargo and passengers. Furthermore, the results of applying the comparison of the main factors are then listed under their categories and depicted in the next sections.

3.2.1. Comparison of industry value

The comparison between the aviation and maritime industries, as presented in Table 1, highlights that both industries provide significant value to the international community.

Table 1: Aviation and maritime industries value and economic performance

Factor	Unit of calculation	Timespan	Aviation	Timespan	Maritime
Share of EU GDP	dollar	2012	71000 (Goodwin, 2016)	2012	88000 (Goodwin, 2016)
World fleet	units	2019	33299 (IATA, 2019)	2019	98140 (UNCTAD, 202)
Asset value	dollar	2021	1.36B (Hellenic shipping,2022)	2021	1.37B (Hellenic shipping,2022)
Average value of a new unit	dollar	2019	157M (JADC,2021)	2021	71M (VesselsValue,2022)
Transported cargo	ton.mile/year	2019	137631 (The World Bank,2023)	2019	60000B (UNCTAD, 2019)
Value of cargo	percentage of global cargo	2021	24% (Eurostat,2022)	2021	48% (Eurostat,2022)
Transported passengers	pax/year	2019	4.56B (The World Bank,2023)	2015-2019	1.6B (UNCTAD, 2020)

While the maritime industry contributes more to the EU GDP (data of World GDP shares is not available), the value of a ship is on average lower than an aircraft. Notwithstanding, autonomous ships and the more digitalised ships are expected to significantly increase in value (DNV, 2021).

In terms of transported value, Table 1 shows that commercial ships transport a higher percentage of the total cargo in terms of value (48%) than commercial aircrafts (24%). In contrast, commercial aircrafts transport significantly more passengers. As a result, the two industries can be considered to have a comparable value to society and a similar level of exposure to risk in terms of the fleet assets and the value of the assets they transport (taking into account both passengers and cargo).

3.2.2. Comparison of safety statistics from accident records

With respect to accident records, the Table 2 presents the most important statistics of maritime and air transportation. According to the Table 2 aviation industry seems to have a higher number of fatalities compared to maritime. However, the number of transported passengers by air (Table 1) is three times greater than passengers transported by sea, which can explain the traditionally better safety levels in aviation. On the other hand, total ship hull losses are significantly higher than aircrafts, which can also generate more severe impact to the environment.

Table 2: Aviation and maritime transport safety records

Safety event	Unit	Timespan	Aviation	Timespan	Maritime
Fatal accidents	accidents/year	2019	8 (IATA,2020)	2019	7 (DNV,2021)
Fatalities	persons/year	2019	247 (IATA,2020)	2019	135 (DNV,2021)
Hull loss-Total loss	units/year	2019	15 (IATA,2020)	2019	57 (DNV,2021)

All taken together, these results demonstrate that aviation industry still has a better level of safety, but it can be considered close to maritime if loss of lives and property are considered.

3.3. Review and comparison of risk matrices and target safety levels from aviation and maritime

As the regulation is the source of the acceptance criteria, the main regulatory instruments for risk assessment procedures applied to commercial aircrafts and ships are reviewed. Both aviation and maritime industries are regulated by a complex web of national and international laws and regulations, as well as industry standards and guidelines.

3.3.1. Target safety levels in aircraft systems design rules

In general, aviation has a more centralized regulatory framework, with the International Civil Aviation Organization (ICAO) providing standardized regulations and guidelines that are adopted by most countries. Therefore, the main three regulations that cover the systems safety engineering of commercial aircrafts are reviewed:

- ARP4754A and ARP4761 (SAE Aerospace, 2010, 1996): The reference regulations of aircraft development process
- CS25 (EASA, 2007): The reference regulation of aircraft design requirements and constraints

Regarding risk assessment, the regulation ARP4761 includes hazard identification, analysis, and assessment as well as risk mitigation. ARP4761 can be applied on the whole development cycle of aircraft and systems. To conduct a risk analysis ARP4754A provides detailed information on applicable methods like FHA, FTA or FMEA. For the assessment of the severity and probability of a risk, the safety objectives are provided in the risk matrix presented in Table 3. The matrix is used to verify whether a system risk passes of fails to meet the safety objectives. Additionally, the qualitative and quantitative description of these severities and probabilities are provided in ARP5761 and CS25. The detailed matrix is presented in Section 3.3.3 for comparison with maritime risk matrix.

Table 3: Aviation target safety levels-Safety objectives

Safety Objectives without Failsafe					
	Frequent	*Reasonably Probable*	*Remote*	*Extremely Remote*	*Extremely Improbable*
Catastrophic	FAILED	FAILED	FAILED	FAILED	FAILED
Hazardous	FAILED	FAILED	FAILED	MAYBE	MAYBE
Major	FAILED	FAILED	MAYBE	MAYBE	MAYBE
Minor	PASSED	PASSED	PASSED	PASSED	PASSED
No Effect	PASSED	PASSED	PASSED	PASSED	PASSED

Safety Objectives with Failsafe					
	Frequent	*Reasonably Probable*	*Remote*	*Extremely Remote*	*Extremely Improbable*
Catastrophic	FAILED	FAILED	FAILED	FAILED	PASSED
Hazardous	FAILED	FAILED	FAILED	PASSED	PASSED
Major	FAILED	FAILED	PASSED	PASSED	PASSED
Minor	PASSED	PASSED	PASSED	PASSED	PASSED
No Effect	PASSED	PASSED	PASSED	PASSED	PASSED

3.3.2. Risk matrices and acceptance criteria in maritime rules and regulations

The maritime industry, on the other hand, has a more decentralized regulatory framework, with different countries and regions implementing their own safety regulations. However, the International Maritime Organization (IMO) provides a framework for international shipping regulations and standards. In addition, Classification Societies play a vital role in the maritime industry by providing technical expertise and assessing vessels' compliance with relevant IMO regulations and standards. Hence, in this methodology the instruments that regulate the risk-based design mainly by the IMO and their interpretation by Classification Societies are reviewed:

- IMO Formal Safety Assessment (FSA) and Guidelines for alternative design

As stated in the FSA by the IMO (2018), risk assessments should be conducted using a structured approach. FSA is the main guidance for marine risk assessment for regulatory purposes and adoption of new systems. Although it is meant for assessing the aggregate risks of implementing a certain ship activity or ship system, FSA is still based on the general risk management processes such as the ISO standard which are used also for single risks. On the other hand, the guidelines of alternative design as provided by IMO emphasise on the risk assessment process of the novel ship systems. The guidelines for alternative design do not present the risk acceptance criteria. On the other hand, a standard example of risk matrix is provided in the FSA together with recommendations of the risk assessment methods and the calculation method of ALARP according to the acceptable individual risk and societal risk. The acceptance criteria are thus calculated on case by case following the given method. it still does not provide a straightforward risk matrix with safety objectives for system functional safety as given in aviation.

- Classification Societies guidelines for novel systems design

For the classification societies, the rules by the members of International Association of Classification Societies (IACS) are considered for their popularity and relatively harmonized procedures. Official guidelines as published in the Classification Societies websites provide risk assessment recommendations as interpretation of the FSA, and interpretation of the IMO guidelines on adoption of alternative design. Reviewing these documents provides that only examples of risk matrices are presented together with reference to the calculation of the ALARP according to the methods proposed in FSA. Examples of risk matrices are presented in (ABS, 2003; Bureau Veritas, 2020; IACS, 2021).

As stated earlier, the aim of this study is to provide a straightforward approach of evaluating the autonomous ship systems risks as conducted in the aviation, which has been known for its strict safety procedures and levels. Therefore, in this section we conclude that the most appropriate approach to compare the maritime and aviation risk matrices is to use the most standardized matrix from the FSA, which is presented in section 3.3.3.

3.3.3. Comparison of Risk Matrices

The risk matrices as provided by the commercial aircraft design regulation, reviewed is Section 3.1, are considered in this study. On the other hand, and as specified previously, the standard risk matrix provided by IMO in the FSA is used in this comparison. In order to set the scene for comparison of the risk matrices, the average lifetime of commercial aircrafts and commercial ships is

Table 4:Side by side comparison of aviation and maritime risk matrices

Aviation	**Effect description**	Failure Conditions that would have no effect on safety; for example, Failure Conditions that would not affect the operational capability of the aeroplane or increase crew workload.	Failure Conditions which would not significantly reduce aeroplane safety, and which involve crew actions that are well within their capabilities. Minor Failure Conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some inconvenience to occupants	Failure Conditions which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to the flight crew, or physical distress to passengers or cabin crew, possibly including injuries.	Failure Conditions, which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating, conditions to the extent that there would be: (i) A large reduction in safety margins or functional capabilities; (ii) Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or (iii) Serious or fatal injury to a relatively small number of the occupants other than the flight crew.	Failure Conditions, which would result in multiple fatalities, usually with the loss of the aeroplane. (Note: A "Catastrophic" Failure Condition was defined in previous versions of the rule and the advisory material as a Failure Condition which would prevent continued safe flight and landing.)
	Severity classification	No safety effect	Minor	Major	Hazardous	Catastrophic
	Probability (qualitative)	No probability requirement	Probable	Remote	Extremely remote	Extremely improbable
	Probability (quantitative) per flight hour	No probability requirement	Less than 1.0E-3	Less than 1.0E-5	Less than 1.0E-7	Less than 1.0E-9
Maritime	**Consequence description**	NA	Single or minor injuries Local equipment damage	Multiple or severe injuries Non-severe ship damage	Single fatality or multiple injuries Severe ship damage	Multiple fatalities Total loss
	Severity classification	NA	Minor	Significant	Severe	Catastrophic
	Probability (qualitative)	NA	Frequent	Reasonably probable	Remote	Extremely remote
	Probability (quantitative) per ship year	NA	10	1.0E-1	1.0E-3	1.0E-5
	Probability (quantitative) per operation hour (year devided by 0,8E-4)	**NA**	**1.0E-3**	**1.0E-5**	**1.0E-7**	**1.0E-9**

identified from the relevant literature. The average lifetime of a commercial aircraft is 25-30 years (Elsayed et al., 2018), while the average lifetime of a commercial ship is 25-30 years (SAFETY4SEA, 2020). In addition, considering that the risk matrix in aviation accounts for the frequency in terms of flight.hour, the average operation time of a commercial ship is identified.

For a commercial ship, the time of operation per year is relatively high as a ship operation is interrupted only at drydocks, which are in average 30days per year. Therefore, the number of operation hours per year of a commercial ship is ($335x24=0.8x10^4$). Using this number of hours per year, the yearly frequency in the FSA risk matrix is transformed to frequency per operation hours. A direct parallel comparison of the risk matrices is then conducted as in the table below.

As presented in Table 4, the matrices from aviation and maritime are slightly different, which, as expected, is coming from the fact that aviation has more stringent safety rules. For example, the Minor consequences in aviation are the hazards that cause increase in crew workload, slight decrease in safety margins, and inconveniences to passengers, while in maritime, the same severity is considered when there are minor injuries and local ship equipment damage. For the catastrophic severity both in aviation and maritime this involves multiple fatalities and total asset loss. With regards to probabilities, the last row in the table shows the transformed values from the FSA. It can be noticed from Table 4 that aviation and maritime qualitative and quantitative probability classes are comparable.

Overall, the different comparisons highlight the importance of both industries and the need for effective risk management strategies to ensure the safety of both passengers and cargo. However, the aviation industry shows more stringent risk acceptance compared to maritime. This urges the maritime industry to rise its target safety levels as the impact on the marine environment can be significant in parallel to the impact of aviation accidents. In contrast, the impact of the public coverage is higher at the aviation which is another aspect of risk consequences to the industry. Thus, the results suggest that the risk matrix and target safety levels from aviation can be adopted in maritime with a slight adaptation, which consists of merging the quantitative probabilities and their effects/consequences description from aviation and maritime. The developed matrix is then presented in the next section.

3.4. The developed maritime risk matrix and target safety

Merging the descriptive matrices from aviation and maritime results in the matrix illustrated in Tables 5 and 6, while the target safety levels are presented in the Table 7.

Table 5: Developed matrix consequences classes

Classification	Description of consequences
Catastrophic	- Total loss of ship - Multiple fatalities
Severe	-Large reduction in safety margins or functional capabilities -Physical distress or excessive workload such that the crew cannot be relied upon to perform their tasks accurately or completely -Severe ship damage -Single fatality or multiple severe injuries
Significant	-Significant reduction in safety margigs or functional capabilities -Significant increase in crew workload or in conditions impairing crew efficiency -Non severe ship damage -Multiple or severe injuries
Minor	-Slight reduction in safety margins -Slight reduction of functional capabilities -Slight increase in crew workload, such as routine voyage plan execution changes -Local equipment damage -Single or minor injuries
No Effect	- No effect on safety -No affect on the operational capability of the ship -No increase of crew workload

Table 6: Developed risk matrix: Probability classes

Probability	Probability per operation hour
Frequent	1 - 10-3
Reasonably	10-3 - 10-5
Remote	10-5 - 10-7
Extremely remote	10-7 - 10-9
Extremely improbable	< 10-9

Table 7: Developed matrix: Target safety levels-Safety objectives

Safety Objectives without Failsafe					
	Frequent	*Reasonably Probable*	*Remote*	*Extremely Remote*	*Extremely Improbable*
Catastrophic	UNACCEPT	UNACCEPT	UNACCEPT	UNACCEPT	UNACCEPT
Severe	UNACCEPT	UNACCEPT	UNACCEPT	MAYBE	MAYBE
Significant	UNACCEPT	UNACCEPT	MAYBE	MAYBE	MAYBE
Minor	ACCEPT	ACCEPT	ACCEPT	ACCEPT	ACCEPT
No Effect	ACCEPT	ACCEPT	ACCEPT	ACCEPT	ACCEPT

Safety Objectives with Failsafe					
	Frequent	*Reasonably Probable*	*Remote*	*Extremely Remote*	*Extremely Improbable*
Catastrophic	UNACCEPT	UNACCEPT	UNACCEPT	UNACCEPT	ACCEPT
Severe	UNACCEPT	UNACCEPT	UNACCEPT	ACCEPT	ACCEPT
Significant	UNACCEPT	UNACCEPT	ACCEPT	ACCEPT	ACCEPT
Minor	ACCEPT	ACCEPT	ACCEPT	ACCEPT	ACCEPT
No Effect	ACCEPT	ACCEPT	ACCEPT	ACCEPT	ACCEPT

The proposed matrix with detailed description can guide a systematic system functional safety in maritime, which is a challenging and ambiguous task nowadays. The lack of a standardized methodology for evaluating the safety performance of autonomous ship systems is major hindrance to the liberalization of the autonomous shipping. In the absence of such a common approach, different stakeholders such as national safety authorities are compelled to conduct their own assessments to approve the acceptance of a system or its components, without a common risk evaluation scale.

While aviation mainly considers the FHA as a hazard assessment technique, other studies emphasised the similarities between FHA and other hazard analysis methods such as System-Theoretic Process Analysis (STPA) and its practical integration in the aircraft system safety engineering procedures (Leveson et al., 2014). Therefore, the current study provides a clear ground for facilitating the application of different effective methods for the risk assessment and assurance of autonomous ships systems.

3.5. Assumptions and Limitations

While this study provides valuable results for the evaluation of autonomous ship systems risks systematic risk-based design, it is important to acknowledge the research limitations. These are primarily associated with the assumptions we made.

- This research article focuses on comparing the aviation and shipping industries in terms of safety regulations. The comparison is based on the total world fleet because the relevant safety regulations of aviation apply to commercial aircrafts including passengers and cargo aircraft. In maritime, there are different types of ships, but the main regulations apply to all types with additional special instruments applicable to specific ships. Therefore, to ensure a fair comparison, this study covers the regulations applicable to all ships. However, when assessing system risks specific to special ship types, adequate considerations should be taken.
- We use world fleet statistics to compare risks from both industries and assess the possibility of adopting aviation target safety levels for system-level risk assessments. Depending on the available data, different time spans are used, which may introduce inaccuracies. Meanwhile, these uncertainties are believed to be insignificant since the covered timespans are very close.
- The proposed risk matrix is used to set the target safety levels of single risks for systems safety assurance. However, this study does not cover the aggregation of risks to identify whether the utmost risk is tolerable. It is worth mentioning that the IMO rules motivate the ALARP in addition to the risk matrices. In order to avoid misleading total risk evaluation, it is suggested to use the outcome of the current study in connection to the ALARP to ensure that the individual aggregated risk is acceptable. However, this connection between single risks and ALARP is not clear. Therefore, a topic of future research is to deepen the research on the harmonized and transparent combination of risk matrix of single risks and the ALARP. Nonetheless, integrating both risk criteria methods can be a subject of further research.
- We did not compare explicitly the accidents impact on the environment and the industry reputation. However, we believe that the implicit comparison of the impact of these elements was considered as compensation of the discrepancies in the stringent aviation safety compared to maritime.

4. Conclusion

In conclusion, this research emphasizes the importance of a consistent and standardized approach to risk assessment in the maritime industry especially for autonomous ships systems and enablers. By defining a detailed risk matrix for evaluating system functional risks, various stakeholders can assess the risk level of a particular system using the same criteria. This consistency can improve communication and collaboration among stakeholders, facilitating a better understanding of risk across the industry, particularly during the transition toward autonomy. Thus, this study has attempted to learn from the structured procedures and transparent risk criteria from aviation and transfer them to maritime. To do so, the proposed approach compared the risk matrices of the aviation and maritime industries, examining the value, safety, and qualitative and quantitative elements of each. As a result, we have provided a comprehensive and informative overview of the risk and safety levels in both industries, which was the basis for the proposed comprehensive risk matrix and target safety levels.

Finally, this study serves as a valuable tool for assessing risk levels of autonomous ship systems. In future research, the application of hazard assessment methods such as STPA or FHA to autonomous ships will be conducted, utilizing the achieved results of this study as a facilitator. Overall, this research can provide a foundation for enhancing safety in the maritime industry and facilitating its continued growth and development.

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