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A 4-zone concept for operational risk assessment in ship-ship encounters incorporating human performance and data analysis

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This paper reviews and synthesises operational methods for assessing ship-ship collision risk, with particular emphasis on human performance and data-driven analysis, within a 4-zone concept inspired by ALARP (As Low As Reasonably Practicable) principle. An integrated conceptual approach is proposed that combines an expert-based declarative arena defining outer risk zone with the Collision Avoidance Dynamic Critical Area and the Event Horizon to delimit inner risk zone. The central challenge addressed is the representation of risk progression within the middle zone, with specific attention to the role of human performance. Selected qualitative and quantitative approaches are reviewed, including Human Reliability Analysis, Event Risk Classification Methods, systems-theoretic methods, and AIS-based (Automatic Identification System) traffic analysis. Their applicability, limitations, and compatibility with the Event Horizon concept are critically discussed within the 4-zone concept tailored to ship-ship collision scenarios. The paper concludes that no single method is sufficient. However, an AIS-based approach, enhanced by a selected human reliability approach, provides the most promising basis for a meaningful and operationally relevant assessment of collision risk progression.

Keywords: Ship-ship collision risk, Operational risk assessment, ALARP principle, 4-zone concept, Collision avoidance, Risk gradient, Ship-ship encounters, Human performance, Maritime safety, Navigational safety

1. Introduction

In the maritime industry, accidents are a constant threat. This is due to the unique and ever-changing nature of the industry. As accidents usually have significant consequences, there are numerous methods and formal procedures for controlling and preventing them (Goerlandt and Montewka (2015); Huang et al. (2023); IMO (2012)). In literature, human error is often attributed as causing 80 % of unfavourable events at sea (Ma et al. (2024); Coraddu et al. (2020); Chowdhury et al. (2024)), although some authors question the truthfulness of this statement (Wróbel (2021)).

A considerable body of maritime risk assessment research focuses on ship-ship collision avoidance and navigational safety (Marino et al. (2023); Tam and Bucknall (2010)). Despite the increasing level of automation in modern shipping, most vessels are still operated by qualified navigators. However, most existing collision-avoidance approaches and navigational Decision Support Systems (DSS) primarily focus on optimisation or manoeuvre selection, typically providing binary outcomes regarding corresponding risk – either present or not (Gil et al. (2020); Pietrzykowski et al. (2022); Goerlandt et al. (2015)). Such results offer limited insight into how risk evolves during the development of an encounter and often require navigators on the bridge to interpret the situation independently.

Therefore, there is a need for a methodological approach that represent collision risk as a continuous gradient associated with clearly defined and easy to understand qualitative classification. In this context, the As Low As Reasonably Practicable (ALAPR) principle, widely applied in maritime risk management and formally embedded in the Formal Safety Assessment (FSA) framework (IMO (2012)), provides a structured approach for interpreting risk. This approach could help navigators to understand how potentially dangerous situations progress, which could reduce the number of collisions.

The literature on the applicability of the ALARP principle in the operational setting, specifically for the risk assessment of maritime collisions, is sparse. This may be due to the inherent complexity of modelling ship-ship encounters at sea and the need to adopt a holistic analytical framework. Furthermore, defining appropriate and operationally meaningful risk thresholds and the corresponding risk gradient is challenging (Xin et al. (2023); Sur and Kim (2020); Liu et al. (2023)). This can result in a limited reliance on qualitative risk assessment approaches.

To close the knowledge gap, this research presents a framework based on the ALARP principle that introduces a 4-zone concept for ship-ship collision risk assessment. It also reviews applicable methods for assessing risk gradients and discusses their relevance for practical risk evaluation in maritime navigation.

2. Framework

To incorporate risk into the decision-making process, it is essential to establish risk acceptance criteria. One of those, well known in risk science, is called ALARP: "*As Low As Reasonably Practicable*". Its purpose is to classify risk levels according to defined acceptance thresholds. In the context of collision avoidance within the 4-zone concept, this requires classifying risk and defining appropriate limits for each zone. Accordingly, three risk areas in ship-ship encounters have been established (Fig. 1):

(1) The **outer zone**, where risk is deemed acceptable. This is determined by eliciting the knowledge of experts.
(2) The **middle zone** represents a tolerable risk level, characterized by a risk gradient and quantified using human performance indicators and empirical data analysis.
(3) The **inner zone** represents an unacceptable risk level, where collision can be mitigated only through the use of special available measures, such as larger rudder deflections. The dimensions of this zone are determined by in-house collision simulator applying ship motion model.

The fourth zone is the **inevitable collision zone**, defined by the Event Horizon (EH). The EH refers to the boundary around the ship beyond which a collision can no longer be avoided, regardless of the actions taken. Consequently, the collision risk at this point is equal to 1.

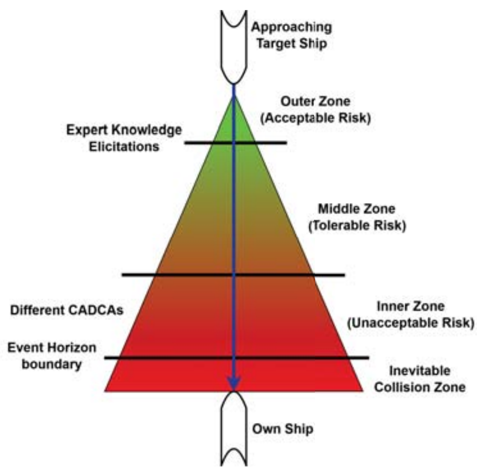

Fig. 1. A 4-zone concept framework for ship-ship collision risk assessment

Building on this conceptual foundation, the following section outlines the methods used to define the boundaries of the outer, middle and inner zones in the 4-zone concept. Furthermore, it reviews selected approaches to modelling risk progression, with particular emphasis on the influence of human performance.

3. Methods

3.1. *A method to define the outer risk zone*

To enhance understanding of practical collision risk assessment, it is essential to identify the distance at which navigators perceive the need to initiate evasive maneuvers. This distance defines the boundary between outer and middle risk and serves as the point at which the navigator begins to assess the severity of an encounter.

To determine this limit, expert knowledge elicitation was conducted in which navigators indicated their preferred manoeuvre initiation distances under favourable conditions for 12 relative bearings. The data were collected via an online survey, which considered the manoeuvring characteristics of the vessel in question and the prevailing environmental conditions. Importantly, only one single, clearly dangerous target was always present, whereby the Closest Point of Approach (CPA) was 0 Nautical Miles (NM) and enough time for an effective evasive manoeuvre was established. The aggregated responses were combined using a weighted geometric mean that reflected the respondents' maritime experience. This resulted in a dodecagonal area surrounding the own ship, referred to as the declarative arena. This concept and its results are described in more detail in Zarzycki et al. (2025). Entry into this arena marks the transition into the middle risk zone, within which the risk gradient is determined with consideration of human performance and its influence on evasive maneuver.

3.2. *A method to define the inner risk zone and Event Horizon*

At the opposite side of the 4-zone triangle, the inner risk region corresponds to encounter conditions where only last-chance evasive actions remain available and the associated risk cannot be considered tolerable from an operational perspective. To define the region of inner risk, the Collision Avoidance Dynamic Critical Area (CADCA) concept is adopted (Gil (2021)). The CADCA is the safety zone around a vessel that indicates the minimum manoeuvring area required to avoid a collision. It is derived from simulation studies that consider an exhaustive set of geometrical configurations between the own ship and stationary or moving obstacles, allowing the determination of the Minimum Distance to Collision (MDTC) for various evasive maneuvers and operating parameters.

Since CADCA models last-chance maneuvers for selected ship parameters, it represents an operationally unacceptable risk level, although collision may still be avoided by applying more decisive actions, such as larger rudder deflections. When the maximum maneuvering capability of the vessel is considered, reaching the outermost CADCA boundary indicates that collision can no longer be avoided. Consequently, intermediate CADCA envelopes can be used to represent an unacceptable risk level. The EH is defined by the boundary of the ultimate CADCA; crossing this boundary inevitably leads to a collision.

3.3. *Methods for defining the risk gradient within the middle risk zone*

The probabilistic frame of the EH boundary naturally draws attention towards quantitative methods of estimating risk gradient; however, qualitative representations may be more meaningful for safety management purposes. This is not a forced choice, as both approaches can be applied in parallel to provide complementary perspectives and insights. Accordingly, the following section presents four complementary perspectives for representing the risk gradient toward the EH boundary.

3.3.1. *Human reliability analysis*

Human Reliability Analysis (HRA) techniques may be appealing to represent human performance compatible with the probabilistic frame of the EH. HRA tools have appealing features as they require decomposition of the task, classification by of the task by task type, and identification of foreseeable Performance Shaping Factors (PSFs) and their strength of effect to ultimately generate a Human Error Probability (HEP). In principle this could enable a generic representation of assumed increasing task difficulty and time pressure as a vessel approaches the EH.

Montewka et al. (2017) explored the application of the Nuclear Action Reliability Assessment (NARA) method to model human performance in the context of ship collision and grounding accidents. The study demonstrated that embedding NARA within a Bayesian Network (BN) for maritime applications lies at, or potentially beyond, the limits of its prudent use, as the method was originally developed for the nuclear industry.

Such difficulties affecting the validity and calibration of NARA as a HRA tool were not unexpected and in line with the multitudinous fundamental challenges associated with the application of HRA tools. Numerical representations also convey the illusion of accuracy and validity that is often not justified (Rae et al. (2014)). As HRA focuses narrowly on error only, it also misses the positive contribution of human performance to maintain safety margin in volatile, uncertain, complex and ambiguous environments (Wróbel (2021)).

While PSFs within HRA are valid in terms of their known effects on human performance, an analytical focus based on task decomposition and error classification was not adopted as the primary means of representing proximity to the EH. Instead, the methodological emphasis was placed on the temporal and physical dynamics of ship encounters, which provide a direct and system-level representation of how safety margins evolve during interaction. This choice reflects the understanding that encounter dynamics are shaped by interacting human, technical, and organisational factors embedded within their operational environment, many of which may persist over long periods as latent conditions (Reason (1990)). Such long-term interactions progressively moving a system toward a safety boundary have been characterised as a drift into failure (Cook and Rasmussen (2005)) as cited in Hollnagel et al. (2008).

3.3.2. *Event Risk Classification Method*

The Event Risk Classification Method (ERC-M) is derived from the Aviation Risk Management Solutions Operational Risk Assessment in Aviation Organisations (ARMS ORA) methodology and abstracts risk by focusing on the presence and effectiveness of remaining controls between an event and a credible unwanted outcome. In the ERC-M, the event is defined as a ship–ship encounter, while the reasonably foreseeable worst-case outcome is a collision, although more specific consequences (e.g. fatalities or pollution) may also be considered. Rather than employing a numerical or ordinal probability measure, the method uses the presence, absence, or ineffectiveness of barriers as a proxy for increasing likelihood toward the EH boundary.

While not probabilistic, ERC-M can provide meaningful representation of how close the EH boundary is based on remaining barriers and their effectiveness, and whether the boundary is getting closer or further away. Unlike HRA, ERC-M is not limited to a single class of causal or contributory factors, as any type of barrier may be included in the analysis. As noted by Rasmussen (1997), making proximity to safety boundaries visible can increase actors' awareness and enable the preservation or recovery of safety margins when such information reaches those with the authority to act.

3.3.3. *Methods based on systems theories*

Depending on the application of the EH model, a more comprehensive exploration may be sought of the factors and complexity of their interplay within socio-technical systems and their embedded environment before the EH boundary. Two potential alternatives providing greater penetration into complexity are Leveson's STAMP (Systems Theoretic Accident Modelling and Processes) model and associated STPA (Systems Theoretic Process Analysis) (Leweson and Thomas (2018)) and Hollnagel's FRAM (Functional Resonance Accident Model) (Hollnagel et al. (2008)).

STPA is a qualitative method that focuses on hazard identification (Basnet et al. (2023)) based on systems theory (Leweson and Thomas (2018)). Unlike traditional failure-focused approaches based on system decomposition, systems theory treats the system as a whole. It enables the identification of unwanted outcomes as a result of emergent complex system interactions and not only failures. Based on STAMP, ”safety is treated as a dynamic control problem rather than a failure prevention problem” (Leweson and Thomas (2018)). A ship encounter breaching the EH boundary can be clearly defined as a loss scenario in STPA. However, other, more nuanced loss scenarios that align with the transition across the middle zone may be identified. The hazards associated with loss of control functions linked to inner zone boundary transitions may be considered progressively more critical the closer one gets to the EH boundary.

FRAM offers a view into complexity and emergence from a more neutral perspective, but still incorporating the importance of control (Hollnagel (2017)). FRAM's position is that accidents are an ”outcome of unexpected combinations of normal performance variability” (Hollnagel et al. (2008)). Aligned with systems resilience theory, the variability and underspecification that enables adjustments to help a system maintain operation is therefore also the mechanism that may produce unwanted outcomes such as accidents. In this context, the transition through the middle and inner zones toward, and ultimately beyond, the EH can be interpreted as a deviation from normal operating conditions, driven by increasingly pronounced variability in system function performance.

In terms of compatibility with the probabilistic frame of the EH boundary, previous work has shown that both STPA and FRAM may be represented in BNs. In the case of STPA, BNs model the probability of a loss of control due to emergent hazards. Recent examples can be found in maritime for remote pilotage operation (Basnet et al. (2023)) and autonomous ships (Chaal et al. (2022)). Basnet et al. (2023) also proposed that STPA-based BNs could be updated in real time as a basis for showing the effects of hazards at system level. Examples also exist of FRAM models represented using BNs in maritime (Qiao et al. (2022)) and other industries (e.g. Guo et al. (2024)). These researchers were looking to add a quantitative perspective to the qualitative system representation generated by FRAM models. The overall approach entails converting a FRAM to BNs whereby FRAM functions become BNs nodes (Slater (2016)). Slater also describes an approach to FRAM-BNs that enables dynamic temporal elements to be incorporated with critical time windows for interactions.

3.3.4. *Traffic analysis based on AIS data*

Ultimately, the decision on the distance to perform an evasive maneuver in the event of a risk of a collision is at the judgement of the human operator. It may be postulated that different distances when collision avoidance maneuvers are carried out correspond to different levels of risk as perceived by navigators. Therefore, reverse engineering and the spatial-temporal analysis of distances could be employed to determine how risk is perceived and to determine its gradient. To achieve this, it might be helpful to consider utilising large Automatic Identification System (AIS) data sets that record dynamic properties of a vessel such as course speed or position. Based on these data, it is possible to identify encounter situations and then, through traffic analysis, to determine triggering evasive action distances. By drawing up a histogram of maneuver execution distance frequencies over a given distance, it is possible to derive a relationship to estimate the perceived risk for validation with operators.

3.4. *Case study*

Based on the method described above, ship traffic distributions derived from AIS data were analysed and interpreted in terms of the risk of ship-ship collision encounters. The analysis covers a 6-months period and used data provided by the Danish Maritime Authority for the adjacent sea areas, focusing exclusively on Ro-Pax vessels. They were selected as representative safety-critical cases, with their lengths further constrained to reflect standard seagoing operations and to exclude short-distance ferries.

To analyze the data in terms of risk, 103 candidate curves were fitted to the histogram of 2,263 anti-collision manoeuvres. Using statistical criteria, the *gamma distribution* was identified as the best-fit for the histogram shape. Firstly, the histogram was described by the probability density function (PDF) curve, the analysis proceeded to the cumulative distribution function (CDF), and subsequently to the complementary CDF (1-CDF), in order to obtain the risk distribution as a function of anti-collision manoeuvre distances (Fig. 2).

The horizontal X-axis represents separation distance between two ships in meters, while the vertical Y-axis denotes the corresponding risk level. In addition, the CADCA concept and the ship arena were incorporated into the traffic distribution analysis to define the boundary of the acceptable risk (outer zone) on one side and the boundary of the unacceptable risk (inner zone) and the EH on the opposite side.

At distances greater than 6,260 m (median value for the declarative arena), an approaching target ship remains within the acceptable risk region and does not pose a risk. As the distance decreases below this threshold, the vessel enters the tolerable risk zone, where the risk gradient derived from AIS data rises. Crossing the 2,380 m threshold (median value of CADCA for a 5° rudder deflection) marks the transition into the unacceptable risk region. At this point, the corresponding risk value is 0.59. Once the separation falls below 1,716 m (median value of CADCA for a 35° rudder deflection), the risk value increases to 1. This means that manoeuvres initiated at a shorter distance are in the EH area and are associated with a certain collision outcome.

4. Discussion on the applicability of risk gradient assessment methods in the middle zone

The proposed approach provides a framework for assessing the risk of ship-ship collisions, supporting decision-making with a more comprehensive set of evaluation criteria. Crucially, the model identifies risk at the moment of manoeuvre initiation, rather than providing a set of abstract, post-manoeuvre decision support indicators. Incorporating the ALARP principle ensures that the results are intuitive. As the target ship approaches and the separation distance decreases, navigators may receive quantitative information about the gradually increasing risk of a collision. Importantly, this risk is categorised into one of four safety regions based on ALARP principle, providing easy-to-understand feedback. This integration facilitates a shift from the unintuitive interpretation of purely geometric safety margins to a qualitative, descriptive risk approach based on operational data that reflects human perception.

The main challenge lies in finding an appropriate way to represent manoeuvring spaces through the gradient between the inner and outer zones before the EH. Choosing techniques and representations that can be populated with reliable data from the available sources and that allow for efficient and balanced risk communication to various possible users according to their role and task context create additional practical problems. A summary of the potential methods, along with their respective pros and cons, is provided in Table 1.

From an interpretative perspective, the results indicate that detailed task-based human error analyses do not necessarily provide greater insight into how close an encounter is to the EH or an accident than analyses grounded in temporal and physical encounter dynamics. These dynamics capture how safety margins between vessels are retained or eroded during an encounter and therefore offer a more constructive framing of operational risk than a narrow focus on specific human failures. Emphasising margin management at the ship-interaction level also aligns more closely with how risk manifests and evolves in real navigational situations.

From an application perspective, the use of ERC-M requires particular care in the identification of barriers, as only those that can be logically substantiated as causal or contributory to the outcome – or to the preservation of safety margin – should be included. Such barriers are inherently context-dependent and may vary significantly between encounters. Furthermore, although ERC-M offers a meaningful representation of proximity to the EH boundary, it is not designed as a real-time tool, which limits its ability to capture rapidly fluctuating risk in dense or highly dynamic traffic environments. This constrains its use primarily to retrospective or planning-oriented analyses rather

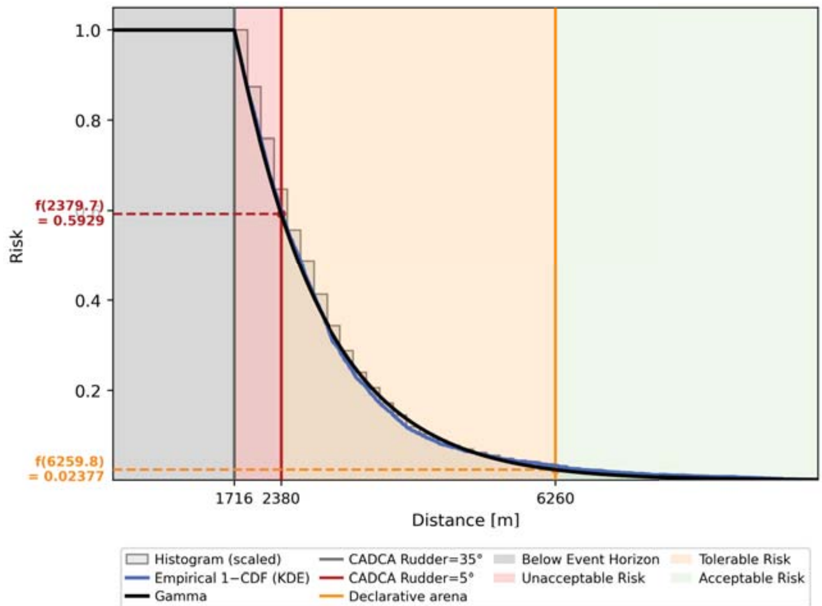

Fig. 2. Numerical representation of the continuous risk gradient within 4-zone concept

Table 1. Summary of risk gradient assessment methods in the middle zone

Method	**HRA**	**ERC-M**	**STPA/FRAM**	**AIS data**
Output	Qualitative	Qualitative	Qual. / Quant.	Quantitative
Suitability for purpose	• Focus on human performance (dominant in accidents) • Compatible with probabilistic EH frame	• Uses safety barriers to prevent accidents • Represents EH proximity via barrier effectiveness	• Holistic, system-wide approach • Identifies complex system interactions • Explains transition to tightly coupled states	• High precision via large datasets • Easy to generalize • Direct risk quantification
Limitations	• Nuclear industry origin • Limited crew-ship-condition interactions • Not for real-time use	• Aviation industry origin • Requires detailed task decomposition • Complex barrier identification	• Difficult to quantify • Case-specific; low generalization • Requires high-quality input data	• Requires data preprocessing • Lacks info on external factors • No data on maneuver causality

than continuous operational risk monitoring.

The application of STPA and FRAM provides a structured means of interpreting how ship–ship encounters migrate from nominal conditions toward collision. This framing aligns well with the EH concept, as the transition across zones can be understood as an increasingly constrained system state characterised by reduced margins and tighter coupling. Consequently, collision risk is interpreted not as a discrete event, but as the emergent outcome of interacting socio-technical factors evolving over time. Representing STPA and FRAM in BNs provides a way to translate qualitative system-level insights into quantitative risk metrics. This facilitates understanding of how interactions and variability in system functions contribute to increasing proximity to the EH boundary. Nevertheless, this integration of qualitative and quantitative approaches is still at an early stage and primarily serves to illustrate potential risk progression rather than deliver definitive probabilistic predictions.

The analysis of maneuvering spaces by means of empirical data would undoubtedly allow the risks to be defined quantitatively with reasonable precision, which would be justified in relation to the probabilistic EH boundary. However, the analysis of a large AIS data set requires preprocessing and assumptions as it does not provide information on external and internal factors influencing the encounters. Therefore, it does not lay out a complete picture but only analyses the effect of these actions. Thus, it can be challenging to correctly distinguish between evasive maneuvers and those resulting from normal navigational operations, such as course alterations at waypoints. For this reason, it may be necessary to assume an evasive intention when the relative bearing changes by a fixed value or when other navigational indicators justify interpreting the course alteration as a collision-avoidance manoeuvre. Furthermore, the granularity of AIS messages sent by ships can also present a challenge. To obtain accurate movement trajectory data, interpolation may be necessary, which is only an approximation of the actual traffic distribution.

The case study section demonstrates the potential of utilizing a comprehensive AIS dataset to assess risk progression in ship-ship encounters. The introduction of risk thresholds based on the 4-zone concept, combined with the analytical methods employed, improves the interpretability of risk. Integrating this approach with human-perception-based methods in the future could enable a more nuanced evaluation, supporting the identification of an appropriate balance between data-driven accuracy and a holistic understanding of operational risk.

5. Conclusion

This study aimed to take the first steps towards developing a 4-zone concept, based on the ALARP principle, for the reliable and easy-to-understand operational assessment of ship-ship collision risk, tailored to the perspective of the navigator. The incorporation of the declarative arena and the CADCA enables to define the risk boundaries between each of the zone. These are the limit within the risk ceases to be negligible and the EH boundary preceded by inner zone where risk is unacceptable. The principal challenge is to ascertain the risk gradient.

The latter can be achieved in several ways, both qualitative and quantitative. While HRA provides only a narrow perspective on accident causation and is not tailored to maritime risk, ERC-M deliberately departs from quantitative approaches. Similarly, methods such as STPA and FRAM face difficulties in translating qualitative assessments into quantitative risk measures and are typically developed for specific cases, limiting their generalizability. An accurate quantitative risk gradient can be obtained through AIS data analysis, as presented in the case study. However, this approach does not consider external factors or the human interpretation of collision threat.

A comprehensive AIS dataset may be combined with the methods discussed above to achieve a balance between accuracy and a more holistic assessment. Further research is required to identify approaches that support real-time risk estimation based on an advanced understanding of operational conditions tailored to sea conditions.

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