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A RISK AGGREGATION APPROACH TO SUPPORT RISK ASSESSMENT FOR FUTURE CREWED AND UNCREWED VESSELS

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SUMMARY

This paper addresses the need for risk aggregation within Risk-Informed Decision Making (RIDM) for crewed and uncrewed vessels. It defines, explores, and applies risk aggregation methods, evaluating their applicability based on risk characteristics. We identify and formalise three aggregation approaches: Type 1 (same risk type, independent), Type 2 (different risk types, independent) and Type 3 (dependent risks). Using practical examples for each type, we demonstrate the technical feasibility of risk aggregation to present the overall risk to support RIDM, while highlighting significant challenges and limitations. Consequently, we argue that aggregated risk approaches should support, rather than replace, detailed risk assessments and contextual information in RIDM. We recommend that future risk aggregation strategies be guided by top-down policy frameworks to ensure consistency, transparency, and robustness in RIDM for future crewed and uncrewed vessels.

1. INTRODUCTION

1.1 DEFINING RISK

There are various definitions of risk [1], with ongoing debate over the merits and rationale of each [2, 3, 4]. For the purposes of this paper, we define risk as a ‘combination of consequence and likelihood’. This definition is consistent with United Kingdom (UK) Ministry of Defence (MOD) submarine [5] and surface ship [6] safety management procedures.

When considered in isolation, risks are termed single risks [7, 8]. Single risks are categorised by type, e.g., safety, environmental and operational, each with different consequence measures [9]. Combining two or more single risks is termed overall risk [2]. The process of combining single risks to present the overall risk is termed risk aggregation [8].

1.2 DEFINING RISK ASSESSMENT

Risk assessments determine single risk consequence and likelihood using qualitative, semi-quantitative, or quantitative methods [10]:

- Qualitative methods use descriptive values (e.g., ‘minor’).
- Quantitative methods use numeric values (e.g., ‘3 deaths).
- Semi-quantitative methods uses both descriptive and numerical values in ranges (e.g., ‘Critical / 1 to 10 deaths’).

For maritime vessels, single risks are typically assessed semi-quantitatively per UK MOD surface ship [6] and International Maritime Organization (IMO) [11] guidance. The assessed risks are compared to risk tolerability frameworks [8], which establish maximum tolerable levels of risk. For safety risks, these levels are established by regulatory authorities such as the UK Health and Safety Executive (HSE). However, for other risk types, no such regulatory frameworks currently exist. In these cases, organisations often develop their own or utilise industry guidance.

In the UK, the tolerability framework for safety risk is established by the HSE through Reducing Risks, Protecting People (R2P2) [12]. This framework establishes the:

- Basic Safety Level (BSL) - the highest level of safety risk that is tolerable if shown to be ALARP (As Low As Reasonably Practicable); and,
- Basic Safety Objective (BSO) - the level of risk considered broadly acceptable if shown to be ALARP.

These levels apply to both individual and societal risk. Although these terms may appear analogous to single and aggregated risk, they have different meanings:

- Individual risk refers to the probability that a specific person will experience harm within a defined time period [13].
- Societal risk refers to the probability of events causing harm to multiple individuals within a population or group [13].

1.3 DEFINING RISK INFORMED DECISION MAKING

Risk assessment is typically performed by a risk assessor, separate from the decision maker who acts on the results [14]. This process of making decisions on the presented risk information is termed Risk-Informed Decision Making (RIDM) [15,16]. In a UK defence context, the decision maker is referred to as the Accountable Person (AP) [5, 6]. Throughout this paper, we use the term 'AP' to refer the RIDM decision maker in both defence and commercial maritime vessel contexts.

Maritime vessels inherently carry significant risks due to their function and operation. APs must make strategic, financial, and operational decisions based on the presented safety, environmental, and operational risk types. For crewed vessels, first-party safety risk is typically dominant, driven by the presence of onboard crew and regulatory frameworks (e.g., HSE R2P2 [12]). However, as vessels adopt uncrewed and autonomous systems [17], it is generally perceived that first-party safety risks decrease with the removal of onboard crew [18], while third-party safety, environmental, and operational risks may increase due to reduced human intervention in hazardous scenarios. Therefore, RIDM requires APs to consider single risk and the overall risk, and with the increase in uncrewed vessels increasingly across all risk types, which results in a requirement for aggregated risk. In addition to this reason, David [8] identifies several further requirements to aggregate risk:

- To account for different risk types arising from the same event.
- To assess tolerability against regulatory frameworks such as BSL and BSO for individual and societal risk.
- To compare total exposure with apportionment targets.
- To understand the platform's overall risk.
- To evaluate system-of-systems risk across multiple platforms.
- To consider dependent events across systems.

In addition to David's [8] points, we emphasise that, in the context of crewed and uncrewed vessels, understanding aggregated risk enables a more meaningful comparison of the relative risks between these platform types.

Beyond the requirements, recent research underscores the value of risk aggregation in supporting RIDM [19, 20, 21, 22]. Reflecting this, UK MOD APs increasingly advocate the need for risk aggregation in RIDM, as evidenced by the UK MOD Royal Navy (RN) [23] and Military Aviation Authority (MAA) [24] direction.

This emphasis is not new. Prior policy, review and guidance recognises the need for aggregated risk in RIDM, including:

- Defence Equipment and Support (DE&S) Safety and Environmental Protection (S&EP) Leaflet 02/2011, requires understanding of "aggregated risk posed by the whole system" to avoid exceeding tolerability criteria or allocating the entire risk budget to a single project [25].
- The Nimrod Review recommends appropriate resource allocation to reduce overall risk [26].
- Tolerability of Risk from Submarines (TOR(SM)), outlines aggregation methods for submarines, both new-build and in-service [5].

Yet despite this policy foundation and supporting research, practical implementation remains limited. We argue this is largely due to the complexity of aggregation methods, challenges in application and the lack of mature practical guidance on suitable approaches. A clear gap exists between risk aggregation research, policy, and practice.

This paper seeks to help bridge that gap by developing a strategy for risk aggregation and highlighting the complexities and challenges of adopting such approaches in support of RIDM for future crewed and uncrewed vessels.

2. THE CONCEPT OF RISK AGGREGATION

2.1 A CONCEPTUAL FRAMEWORK FOR RISK AGGREGATION

Like "risk," the term risk aggregation is defined differently across sectors, including safety [8] and finance [27]. Additionally, terms such as cumulative risk, risk profile, hazard footprint, and integrated risk picture are sometimes used interchangeably [8]. This has created much confusion, aptly captured in the title of Bjørnsen et al.'s paper, *"Risk aggregation: What does it really mean?"* [7]. Despite ongoing debate [20, 21, 22], no universal definition has emerged.

While not seeking to expand the debate, we note that this confusion hampers the closing of the aforementioned risk aggregation research-policy-practice gap. Therefore, a conceptual framework is necessary to underpin this papers discussion. Drawing on the literature [7,8,20] and ISO guidance [10, 28], we define risk aggregation as 'The process of combining different risk information from two or more single risks through a risk aggregation process, to gain an understanding of the bigger risk picture'. This paper explores risk aggregation processes that may be used to achieve this understanding of the bigger risk picture and discusses application for crewed and uncrewed vessels.

Risk aggregation methods fall into two distinct forms, although the two forms are often conflated in the available literature [20]:

- Visual aggregation – visually displaying multiple single risks together, such as in matrices, tables or dashboards.
- Mathematical aggregation – combining risks through mathematical methods, potentially across assessors, types, scenarios, systems, or assessment methodologies.

This paper focuses on mathematical aggregation in the context of maritime vessels. Visual methods, such as risk matrices, are widely used and extensively critiqued [29, 30]. We do not wish to add to this, but it is important to emphasise that visual methods merely display multiple single risks without quantifying an aggregated overall risk or capturing interactions and dependence between the risks [31]. Aggregation can be attempted qualitatively (e.g., 'by eye' [8]); however, such approaches are neither accurate nor robust. Crucially, declaring a single risk as tolerable within a matrix does not guarantee that overall individual or societal risk is tolerable. While visual tools can aid RIDM, they do not constitute risk aggregation.

Mathematical aggregation has gained interest [2, 22, 32] and encompasses various methods [8, 20, 22]. However, there remains practitioner confusion when and how these methods can be applied. This confusion arises from ambiguous guidance, for example, the ISO standard on risk assessment techniques [10] states that "qualitative or semi-quantitative measures of risk cannot be directly aggregated" but states that they can be "combined" and that "relevant data about different risks can be brought together to assist decision makers." This ambiguity leaves practitioners without clear guidance, reinforcing the research-policy-practice gap.

The absence of a universally accepted definition of risk aggregation, coupled with uncertainty around the availability and suitability of methods, has led some authors to suggest: "As a general rule, one should avoid the need for aggregation" [33, p. 26]. While this is a strong position, it is largely informed by the inherent challenges in risk aggregation (discussed in the following section). Acknowledging this caution and the associated challenges, we argue that the specific drivers for risk aggregation in the context of crewed and uncrewed vessels (discussed in the previous section) justify exploring available approaches to help bridge the research–policy–practice gap.

2.2 THE CHALLENGES OF RISK AGGREGATION

The challenges of risk aggregation are well illustrated by its use, and misuse, in the financial sector. In the financial sector, standardised aggregation methods are well established [27], shaped by lessons learnt from the Gaussian copula (Equation 1).

$$\Pr[T_A < 1, T_B < 1] = \Phi_2(\Phi^{-1}(F_A(1)), \Phi^{-1}(F_B(1)), \gamma)$$

Equation 1

The Gaussian copula was used to aggregate collateralised debt obligations (CDOs) into a single metric by combining individual default probabilities (A and B) through a dependency parameter (γ). Its apparent simplicity appealed to decision-makers and led to widespread adoption, supporting the trading of millions of CDOs, often presented through colour-coded dashboards. However, the copula masked underlying uncertainty and failed to capture real-world interactions and dependencies between seemingly independent CDOs [8]. This misapplication contributed to systemic failure and played a key role in the 2007–2008 financial crisis, earning the Gaussian copula the name "the formula that killed Wall Street" [34].

This example rightly raises caution about aggregating risk, and more broadly reducing complex systems to single metrics. However, as we have highlighted, to support RIDM risk aggregation should not necessarily be avoided. Based on the example of the Gaussian copula, and in the context of crewed and uncrewed vessels, we identify five key challenges in the application of risk aggregation methods which must be addressed to bridge the research-policy-practice gap:

- Loss of contextual information – There is a desire to view risk assessment as objective, but there are always underlying assumptions, dependencies and biases [35]. Aggregating across multiple risk assessments compounds distortions. Therefore, aggregation methods must transparently document assumptions, dependencies, and assessor information for the underlying risks.
- Risk interactions and dependencies – Different risks may occur simultaneously, because of another risk, or be inadvertently captured more than once, especially where different processes or assessors are used. This is further compounded in 'system of systems', such as the use of 'swarm 'uncrewed vessel technology [36]. Therefore, aggregation methods must explicitly account for dependencies.
- The illusion of safety - complex formulas and metrics can falsely appear to 'prove' safety. While useful for decision support, aggregated risk values should never substitute engineering judgement or detailed risk understanding. Therefore, aggregation methods must be framed as a support tool for RIDM, not a standalone decision-making mechanism.
- Overconfidence in visualisations – colour-coded dashboards (e.g., Red-Amber-Green) may falsely imply precision or compliance if unsupported by robust analysis [37]. Therefore, aggregation methods resulting in risk visualisations must be clear, understandable and evidence based.
- Different risk types - Different types of risk may be measured on incompatible consequence scales, especially for crewed and uncrewed vessels, making their consequences difficult to compare directly. Therefore, aggregation methods must use a clearly defined and consistent consequence scale, or a justified conversion method, to ensure comparability across risk types.

In light of these challenges, this paper seeks a careful balance: avoiding falling into the trap of the aforementioned challenges whilst identifying risk aggregation strategies for crewed and uncrewed vessels. We recognise both the inherent drivers and benefits of risk aggregation for RIDM, alongside the inherent challenges of implementation and interpretation. Bridging the research-policy-practice gap requires addressing these tensions. The following section develops a guiding strategy, grounded in these challenges, to support risk aggregation for crewed and uncrewed vessels.

3. RISK AGGREGATION STRATEGY FOR CREWED AND UNCREWED VESSELS

3.1 INTRODUCTION

The choice of an appropriate mathematical risk aggregation method depends on key characteristics of the single risks:

- Whether risks are assessed qualitatively, semi-quantitatively, or quantitatively.
- Whether risks are of the same risk type.
- Whether risks are dependent or independent.

Given the scope and focus of this paper, clear boundaries must be drawn. Risk assessments for vessels are typically conducted using semi-quantitative methods, e.g., following either UK MOD [6] or IMO [11] surface ship risk assessment guidance. As such, this paper focuses on mathematical aggregation of semi-quantitative risks and does not attempt to develop a strategy for aggregating purely qualitative or purely quantitative risks. This focus reflects:

- Aggregating qualitative risks may be possible, via expert judgement, interviews, or consensus frameworks [10]. However, it is generally not recommended for robust decision-making due to subjectivity and lack of standardisation [38]. We therefore do not wish to explore these methods further.

- Aggregating quantitative risks is possible, using established methods, such as FN curves, Expected Value (EV), and Risk Integral (RI) for independent risks, and copula-based or multicriteria frameworks for dependent risks [20, 22]. As such methods are well established [8, 16, 32], we do not wish to explore these methods further.

We therefore focus on developing a strategy to aggregate semi-quantitative single risks for crewed and uncrewed vessels. We recognise there are various methods to do so, including adapting the aforementioned methods for quantitative risks, and the suitability of each method depends on the single risk characteristics. To determine the suitability of these methods, we provide the following definitions:

- We define aggregation of risks that are of the same risk type and independent as 'Type 1' risk aggregation.
- We define aggregation of risks that are of different risk types and independent as 'Type 2' risk aggregation.
- We define aggregation of risks that are dependent as 'Type 3' risk aggregation.

We highlight that it is critical that the dependence of single risks be examined carefully before any aggregation method is selected or applied. If risks are incorrectly assumed to be independent, then applying a Type 1 or Type 2 approach will not only be mathematically invalid, it may also produce dangerously misleading results. In practice, risk practitioners often assume independence for simplicity, but do not always verify this assumption [30]. This is a dangerous assumption to make, see previous discussion on the Gaussian Copula. Vessels are inherently complex and tightly coupled systems and therefore some risks are likely to be dependent. The integration of multiple subsystems and increasingly autonomous technologies to support uncrewed vessels only amplifies this complexity and resulting dependency [35].

3.2 RISK AGGREGATION STRATEGY – TYPE 1 RISK AGGREGATION

Type 1 risk aggregation aggregates single risks of the same risk type assuming independence to present the overall risk. To illustrate Type 1 risk aggregation, four example semi-quantitative first-party safety risks were assessed for both a crewed and an uncrewed vessel, using the UK MOD surface ship risk assessment guidance and Risk Classification Matrix (RCM) [6], as shown in Table 1.

Table 1. Example Safety Single Risks for Crewed and Uncrewed Vessels

Vessel	**Risk**	**Consequence**	**Likelihood**	**Risk Type**	**Risk Class**
Crewed	Risk 1 (R_1)	Disastrous	Incredible	Safety	D
	Risk 2 (R_2)	Critical	Incredible	Safety	D
	Risk 3 (R_3)	Marginal	Remote	Safety	C
	Risk 4 (R_4)	Critical	Improbable	Safety	C
Uncrewed	Risk 1 (R_1)	Negligible	Incredible	Safety	D
	Risk 2 (R_2)	Negligible	Incredible	Safety	D
	Risk 3 (R_3)	Negligible	Remote	Safety	D
	Risk 4 (R_4)	Negligible	Improbable	Safety	D

In this RIDM scenario, it is visually apparent to the AP that the uncrewed vessel exhibits lower overall safety risk, given the lower classification of single risks, e.g., quantity of C vs D class risks between the respective vessels. However, such qualitative aggregation (e.g., 'by eye') is inadequate for larger risk sets or formal decision-making as it lacks traceability and quantification. A formal mathematical aggregation method is therefore required for Type 1 risk aggregation.

We have selected the RI method (Equation 2) as an appropriate approach for this demonstration, though other methods are available [20]. The RI method is derived from the EV method [39], which calculates aggregated risk as the area under a frequency-fatality (f–N) curve. The RI method extends EV by incorporating a scale aversion index (a) that assigns greater weight to higher consequence events, thereby reflecting societal aversion to catastrophic accidents [12]. The HSE recommends a value of 1.4 for this scale aversion index [40], and this value is applied in the present example for both crewed and uncrewed vessels. However, we highlight that further research is advised to determine an appropriate scale aversion index specific to both crewed and uncrewed vessel contexts.

$$RI = \sum fN^{a}$$

Equation 2

As previously stated, the RI method is intended for aggregating quantitative risks to provide a measure of societal risk [40]. However, we apply it to aggregate the semi-quantitative safety risks in Table 1, with adaptions to suit the risk characteristics for the crewed and uncrewed vessels as outlined in the following paragraphs.

Because the RI method requires numeric values for both consequence and likelihood, it is necessary to derive equivalent fatality values where the assessed consequence of the single risks represents an injury rather than fatality (e.g., crewed vessel R_3 and uncrewed vessel R_1, R_2, R_3 and R_4). The UK MOD surface ship RCM provides numeric bounds for fatal consequences (e.g., 'critical' is '1 to 10 deaths'), but no equivalents for non-fatal consequences (e.g., major, marginal, negligible). To address this, we adopt equivalent fatality factors from IMO guidance [11]:

- Major: 0.1 to <1 fatality.
- Marginal: 0.01 to <0.1 fatality.
- Negligible: 0.001 to <0.01 fatality.

This mapping allows non-fatal consequences to be expressed on a fatality-equivalent scale, enabling subsequent aggregation. It is important to identify that such equivalence is subjective, and, given the scope of this paper, the conversion factors used to equate different consequences of different risk types have not been considered in detail at this point in time. Different stakeholders might disagree, and even within the referenced IMO guidance the chosen equivalence is a policy decision and should not be made by the individual assessor. Although we have applied the IMO guidance in this example, we understand there is no one correct fatality-equivalent scale suit all scenarios. One should treat these factors as assumptions and therefore document them in RIDM and conduct sensitivity analysis, noting that altering the fatality–injury equivalence or introducing risk aversion for large accidents would affect the scale [40]. We therefore declare that any aggregated risk is fragile to the weighting scheme applied in a fatality-equivalent scale and highlight that further research is recommended to determine an appropriate fatality-equivalent scale tailored to both crewed and uncrewed vessel contexts.
Figure 1 presents an updated RCM from the UK MOD surface ship risk assessment guidance integrating these equivalent fatality intervals.

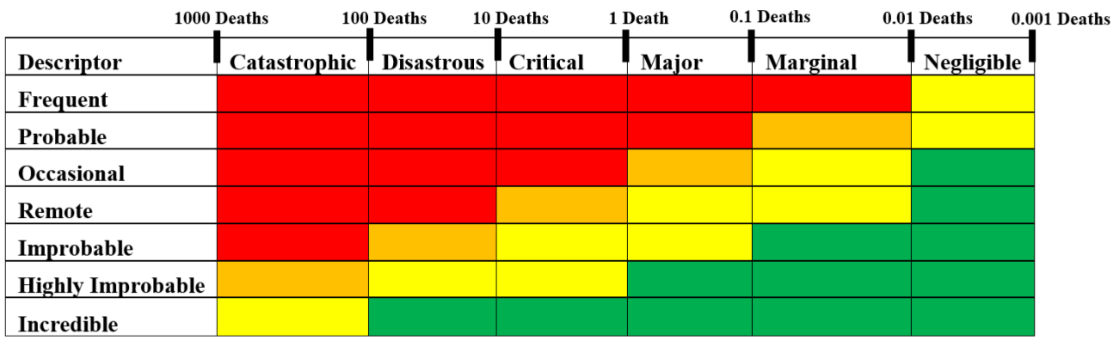

Figure 1: Updated MOD Surface Ship Risk Assessment Guidance RCM Showing Consequence (Equivalent Fatality) Intervals

Because the UK MOD surface ship RCM [6] is semi-quantitative, both consequence and likelihood are expressed as upper and lower bounded intervals rather than exact numeric values. Therefore, the use of semi-quantitative assessment methods, such as risk matrices, introduces uncertainty or 'fuzziness' for the assessed single risks [33]. This uncertainty is exacerbated further by inherent flaws in the construction of risk matrices, such as rank reversals and poor resolution. Given the scope of this paper, we do not expand further on these flaws but highlight that this uncertainty in the single risks is compounded when the single risks are aggregated [30].

Therefore, we apply the RI method to produce an interval-based output, bounded by the upper and lower limits of the aggregated risk distributions, rather than a single deterministic value. This interval representation is illustrated on an fN basis in Figure 2 for the crewed vessel's identified risks from Table 1, showing the maximum, midpoint, and minimum values for each risk.

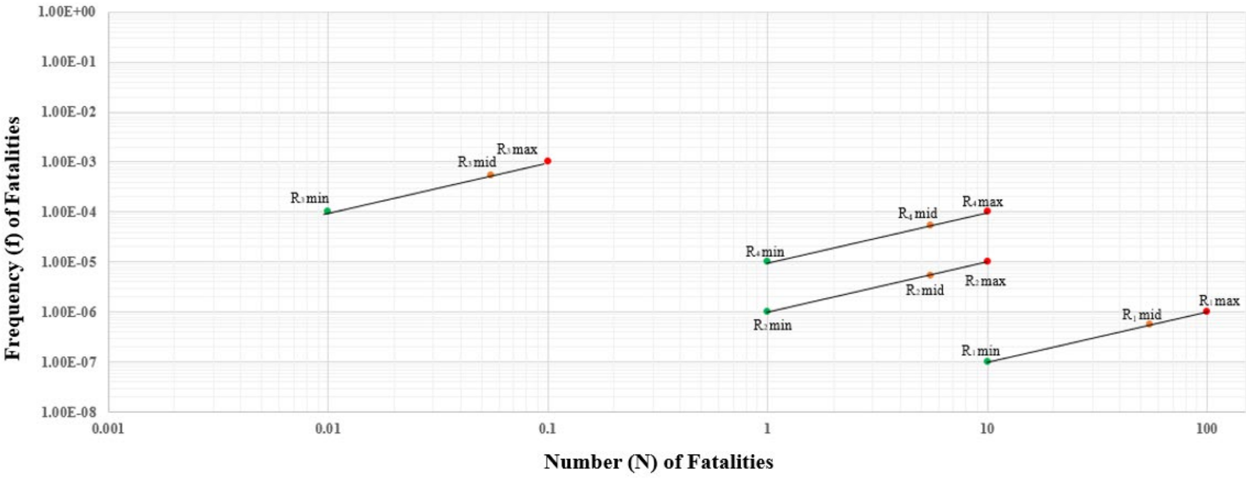

Figure 2: fN Representation for Crewed Vessel Risks

It is important that this uncertainty is clearly communicated to support RIDM, ideally in a form more accessible to APs than the technical representation in Figure 2. Reporting a single aggregated risk value without acknowledging these bounds could misrepresent the underlying uncertainty. While academic techniques have been proposed to provide a single value when aggregating semi-quantitative risks, such as fuzzy set theory, interval number theory, or probability density functions [2], these methods remain theoretical with practical challenges around error propagation and traceability [41]. Therefore, considering the challenge of 'loss of contextual information' identified in the previous section, we recommend retaining and reporting interval bounds to ensure transparency and preserve uncertainty within the aggregated risk values.

The resulting aggregated risk values, using the RI method, for the crewed and uncrewed vessels are shown in Table 2. As expected, 'by eye', the uncrewed vessel exhibits a lower overall risk. While this approach offers interim value for aggregating risks of the same risk type, and can be expanded further for larger risk sets, we recognise it carries significant limitations; there is a risk of hiding the underlying assumptions of the scale aversion index and the fatality-equivalent scale, and both can materially influence the resulting aggregated risk value. We therefore highlight that further research is recommended to determine an appropriate approach to present the underlying assumptions to the AP in RIDM along with the overall risk values.

Table 2. RI Aggregated Risk for Crewed and Uncrewed Vessels

Vessel Type	**RI Value**	
	Upper	**Lower**
Crewed	$3.434\text{x}10^{-3}$	$1.367\text{x}10^{-5}$
Uncrewed	$1.588\text{x}10^{-6}$	$6.322\text{x}10^{-9}$

3.3 RISK AGGREGATION STRATEGY – TYPE 2 RISK AGGREGATION

Type 2 risk aggregation aggregates single risks of different risk types assuming independence to present the overall risk. For reasons highlighted earlier in this paper, Type 2 aggregation is particularly relevant for uncrewed vessels, especially in RIDM scenarios that compare crewed and uncrewed vessels. In these scenarios, APs are likely required to consider single and overall risk covering safety, environmental and operational risk types in the decision-making process.

To illustrate Type 2 risk aggregation, ten example semi-quantitative risks were assessed for both a crewed and an uncrewed vessel covering safety, environmental and operational risk types. The safety risks were assessed using the UK MOD surface ship risk assessment guidance and RCM [6]. As the RCM assesses safety risks only, an equivalence framework was developed to align consequence categories across safety, environmental, and operational risk types.

This equivalence framework draws on approaches from available literature [5, 9] and uses past precedent for equivalence established by the IMO [11] and Bureau Veritas (BV) [42] to map the consequences from different risk types onto a common scale. Table 3 presents the equivalent safety, environmental and operational consequences.

We acknowledge that this equivalence framework is inherently subjective and has limitations; in current form, it treats all risk types as equally weighted and assumes equivalence between consequence categories. Alternative mapping, such as conversion to equivalent monetary value (e.g., as proposed by Bao et al. [43]), may be more appropriate and, critically, while we have made equivalences to facilitate risk aggregation this does not resolve differences in risk tolerability thresholds across risk types (although we have classified all risks using UK MOD surface ship risk assessment guidance [6] for the purposes of this example). Given the scope of this paper, we have developed this equivalence framework to support the development of a strategy for Type 2 risk aggregation, but highlight that further research is recommended to determine an appropriate equivalence framework for crewed and uncrewed vessels.

Table 3. Equivalence Framework for Consequence Types

Consequence	**Safety**	**Environmental**	**Operational**
Catastrophic	More than 100 Deaths	Prohibition of Operation (International)	Loss of Asset
Disastrous	10 to 10 Deaths	Prohibition of Operation (Local)	Withdrawal from Operations for Repair in Dockyard
Critical	1 to 10 Deaths	Restriction of Operation	Withdrawal from Operations for Repair in Naval Base
Major	Permanent Injury / Illness	Nuisance Duration >1 Month	Withdrawal from Operations for Repair at Sea
Marginal	Recoverable Injury / Illness	Nuisance Duration 1 Month to 1 Week	Temporary Reduction in Capability
Negligible	Major Injury / Illness	Nuisance Duration Up To 1 Week	No Reduction in Capability, but Some Reconfiguration Required

Table 4 presents the ten example risks assessed for the crewed and uncrewed vessels, covering safety, environmental, and operational risk types.

Table 4. Example Safety, Environmental and Operational Single Risks for Crewed and Uncrewed Vessels

Vessel	**Risk**	**Consequence**	**Probability**	**Type**	**Risk Class**
Crewed	Risk 1 (R_1)	Major	Remote	Environmental	C
	Risk 2 (R_2)	Major	Improbable	Environmental	C
	Risk 3 (R_3)	Critical	Highly Improbable	Environmental	C
	Risk 4 (R_4)	Disastrous	Incredible	Safety	D
	Risk 5 (R_5)	Critical	Highly Improbable	Safety	C
	Risk 6 (R_6)	Marginal	Remote	Safety	C
	Risk 7 (R_7)	Critical	Improbable	Safety	C
	Risk 8 (R_8)	Major	Incredible	Operational	D
	Risk 9 (R_9)	Marginal	Improbable	Operational	D
	Risk 10 (R_{10})	Negligible	Improbable	Operational	D
Uncrewed	Risk 1 (R_1)	Major	Remote	Environmental	C
	Risk 2 (R_2)	Critical	Improbable	Environmental	C
	Risk 3 (R_3)	Critical	Highly Improbable	Environmental	C
	Risk 4 (R_4)	Negligible	Incredible	Safety	D
	Risk 5 (R_5)	Negligible	Incredible	Safety	D
	Risk 6 (R_6)	Negligible	Remote	Safety	D
	Risk 7 (R_7)	Negligible	Improbable	Safety	D
	Risk 8 (R_8)	Major	Incredible	Operational	D
	Risk 9 (R_9)	Major	Improbable	Operational	C
	Risk 10 (R_{10})	Critical	Improbable	Operational	C

In this RIDM scenario, it is not immediately clear which vessel presents a lower overall risk. A risk matrix could be used to visualise the ten single risks (Tables 5 and 6). A comparison of the matrices could be used to visually infer lower overall risk for the uncrewed vessel based on fewer Class C risks. However, noting the issues of visual risk aggregation highlighted earlier in this paper, such a 'by eye' interpretation lacks rigour and traceability. As with Type 1 aggregation, a mathematical aggregation method is required to support RIDM.

Table 5. Risk Matrix for Crewed Vessel Showing Single Risks

Descriptor	Catastrophic	Disastrous	Critical	Major	Marginal	Negligible
Frequent						
Probable						
Occasional						
Remote				**R1**	**R6**	
Improbable			**R7**	**R2**	**R9**	**R10**
Highly Improbable			**R3, R5**			
Incredible		**R4**		**R8**		

Table 6. Risk Matrix for Uncrewed Vessel Showing Single Risks

Descriptor	Catastrophic	Disastrous	Critical	Major	Marginal	Negligible
Frequent						
Probable						
Occasional						
Remote				**R1**		**R6**
Improbable			**R2, R10**	**R9**		**R7**
Highly Improbable			**R3**			
Incredible				**R8**		**R4, R5**

The RI method used for Type 1 aggregation can also be used for Type 2 aggregation. As before, because the input data of the single risks is semi-quantitative, the resulting aggregated risk values are interval-based. The resulting aggregated risk values, using the RI method, for the crewed and uncrewed vessels are shown in Table 7.

In this case, despite a visual aggregation suggesting lower overall risk for the uncrewed vessel, mathematical aggregation identifies that the uncrewed vessel exhibits a higher overall risk. This outcome reflects the influence of magnitude of consequences of the single risks, amplified by the applied scale aversion index (a) of 1.4. This example demonstrates how Type 2 risk aggregation provides a more accurate picture of the overall risk than visually aggregating the single risks or presenting the single risks in isolation.

While this approach offers interim practical value for aggregating different risk types, we recognise it carries significant limitations. In addition to the limitations of consequence equivalence framework, 'boiling down' the multi-dimensional risk types may hide the type and respective domain which drives the overall risk. We therefore highlight that further research is recommended to determine an appropriate weighting framework for different risk types.

Table 7. RI Aggregated Risk for Crewed and Uncrewed Vessels

Vessel Type	RI Value	
	Upper	**Lower**
Crewed	4.790×10^{-3}	1.907×10^{-5}
Uncrewed	6.378×10^{-3}	2.539×10^{-9}

3.4 RISK AGGREGATION STRATEGY – TYPE 3 RISK AGGREGATION

Type 3 risk aggregation aggregates single risks that are dependant to present the overall risk. Noting that if the single risks are of different risk types then an equivalence framework, as identified for Type 2 risk aggregation, can first be used to map the consequences onto a common scale. Dependency of single risks can be categorised as either:

- Probabilistic interaction, where the likelihood of one affects another [14]; or,
- Consequential interaction, where the consequence of one affects another [44].

Several mathematical methods are proposed in the literature to account for dependence of single risks, including:

- Copula-based models, which capture statistical dependence between the single risks; and,
- Multi-criteria evaluation framework, which utilise fuzzy logic, Choquet integrals, or multiple linear regression models to model dependence between the single risks.

These methods, as discussed by Bao et al., [20] and Hassel et al., [22], are inherently quantitative in nature and require significant computational resources. Advanced techniques, such as Monte Carlo simulation, are used to model scenarios and quantify dependencies and interactions over time. As such, these methods rely on single risks being quantitatively assessed.

Applying these methods to semi-quantitative risks, as would be required for typical vessel RIDM, presents challenges. Similarly to Type 1 and Type 2 risk aggregation, the semi-quantitative nature of the single risks results in an interval-based output, rather than a deterministic value. While technically feasible, in practice the literature highlights limited appetite for deploying such complex probabilistic models in real-world settings due to concerns around traceability, interpretability, and escalating complexity [32]. We highlight that further work is required to develop practical quantitative methods for semi-quantitative dependent risk aggregation; however, this lies beyond the scope of this paper.

An alternative approach involves subjectively identifying dependencies through structured review of the single risks [20]. This method is inherently qualitative in nature and requires expert judgement and Suitably Qualified and Experienced Personnel (SQEP) input to quantify dependencies and interactions over time. This judgement can be supported by tools such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), or double-layer network analysis [43]. Bao et al. [43] propose a guiding question set for this method, which can be used to determine dependency of single risks, as follows:

- Does the occurrence of one risk affect the likelihood of another?
- Does the occurrence of one risk affect the consequence of another?
- Does the simultaneous occurrence of multiple risks trigger a greater consequence than their individual effects?

In this example, we have applied these questions to the risks identified in Table 4 for crewed and uncrewed vessels to highlight the following, illustrative, dependencies:

- For the crewed vessel the occurrence of Risk 5 increases the likelihood of Risk 4. Therefore, a likelihood factor is applied to quantify the likelihood increase. In this example, by two likelihood intervals from ‘Incredible’ to ‘Improbable’.
- For the uncrewed vessel the occurrence of Risk 3 increases the consequence of Risk 4. Therefore, a consequence factor is applied to quantify the consequences increase. In this example, by one consequence interval from ‘Critical’ to ‘Disastrous’.

The remaining risks are therefore deemed to be independent and aggregated using the Type 2 risk aggregation approach. The resulting aggregated risk values, applying the RI method and adjusted for dependence, for the crewed and uncrewed vessels are shown in Table 8. When dependencies are accounted for, the crewed vessel exhibits a higher overall risk compared to the assumption of independence of the crewed vessel single risks, and as such a higher overall risk than the uncrewed vessel.

This example illustrates how modelling dependencies can materially influence the aggregated risk values and therefore the overall risk. However, we highlight that qualitative adjustments to reflect dependence, such as applying the aforementioned semi-quantitative interval shifts in likelihood and consequence, introduce inherent subjectivity and uncertainty. Beyond obvious direct dependencies easily identifiable by SQEP (e.g., failure of a power system leading to system-wide shutdown), there are often latent or systemic interactions such as the effects of reduced staffing, deferred maintenance, or organisational constraints, which can indirectly influence multiple risk pathways. These ‘hidden dependencies’ may not be identified by qualitative judgement alone.

While this approach offers interim practical value for aggregating dependent risks, we recognise it carries significant limitations. We therefore advise caution in relying on such qualitative adjustments for RIDM at this point in time; we highlight that further research is required to develop robust, transparent, and validated methods for qualitatively aggregating dependent semi-quantitative risks however this currently lies beyond the scope of this paper.

Table 8. RI Aggregated Risk for Crewed and Uncrewed Vessels Considering Dependency

Vessel Type	**RI Value (Assuming Independence)**		**RI Value (Modelling Dependence)**	
	Upper	**Lower**	**Upper**	**Lower**
Crewed	4.790×10^{-3}	1.907×10^{-5}	2.819×10^{-2}	1.779×10^{-4}
Uncrewed	6.378×10^{-3}	2.539×10^{-9}	6.787×10^{-3}	4.282×10^{-5}

4. DISCUSSION

The preceding section demonstrates that selecting an appropriate risk aggregation approach depends on the characteristics of the single risks, specifically dependence, type, and assessment method. We defined three approaches: Type 1, Type 2 and Type 3 risk aggregation, and practically applied the RI method as an illustrative strategy to aggregate risks for crewed and uncrewed vessels. This work helps bridge the research-policy-practice gap, showing how aggregated risk can support RIDM.

This work provides a guiding strategy for ‘how’ risk aggregation can be conducted, complementing the earlier rationale for ‘why’ it should be conducted for crewed and uncrewed vessels. Whilst we demonstrate that risk aggregation is technically feasible, each approach introduces distinct challenges affecting the usability and interpretation. These distinct challenges align with the broader challenges of risk aggregation identified earlier e.g., loss of contextual information, modelling dependencies, accounting for different risk types and the illusion of safety. Throughout this paper, we have identified these distinct challenges and provided recommendations for further research. A summary of the distinct challenges is as follows.

Type 1 risk aggregation appears mathematically simple but poses key challenges:

- Aggregating the interval-based inputs of semi-quantitative single risks yields interval-based outputs, requiring transparent communication to support RIDM.
- Selecting equivalence factors introduces assumptions that can materially influence aggregated risk.
- The RI method depends on the chosen scale aversion index, which directly affects the aggregated risk.

Type 2 risk aggregation invokes the same challenges as Type 1, and additionally:

- Requires a consequence equivalence framework to map different risk types onto a common scale, embedding assumptions and ethical, tolerability, and value judgments.

Type 3 risk aggregation invokes the same challenges as Type 1 and Type 2, and additionally:

- Quantitative aggregation methods to model dependency require quantitative inputs, limiting applicability to semi-quantitative risks.
- Qualitative adjustments to model dependency introduce subjectivity and additional uncertainty.

5. CONCLUSION

Given the collective magnitude of these distinct and broader challenges to risk aggregation for crewed and uncrewed vessels, we argue that aggregated risk values should currently be framed as a decision-support tool to present overall risk, not as stand-alone for RIDM; aggregated risk can be used to inform and contextualise an overall risk, not replace detailed risk assessments. In addition, the challenges, limitations and uncertainties must be clearly documented to mitigate the risks of RIDM, and the highlighted recommendations for further research should be advanced to support effective risk aggregation application for crewed and uncrewed vessels.

Holistically, we identify that risk aggregation inherently operates as a bottom-up process, combining single risks to construct an overall 'bigger' risk picture. However, we argue that an effective risk aggregation strategy must be guided top-down by policy to ensure consistency, validity, and relevance for RIDM and to ensure the aforementioned challenges are adequately addressed. Bottom-up harmonisation is impractical; practitioners and assessors at lower system or platform levels lack authority to set cross-project methods or scales for vessels. As such, risk aggregation must be governed by a top-down goal-based framework driven by the AP. Such a framework should be developed to establish reporting requirements, equivalence assumptions, and aggregation parameters to support RIDM.

Beyond aggregation for RIDM, such a framework could also enable risk apportionment across system functions. Figure 3 illustrates how this process integrates into a combined physical and digital Systems 'V' lifecycle, with risk apportionment during left-side system definition and risk aggregation during right-side verification. In the context of uncrewed and autonomous vessels, this lifecycle could extend to digital models and virtual testing environments (as shown by the upper inverse 'V').

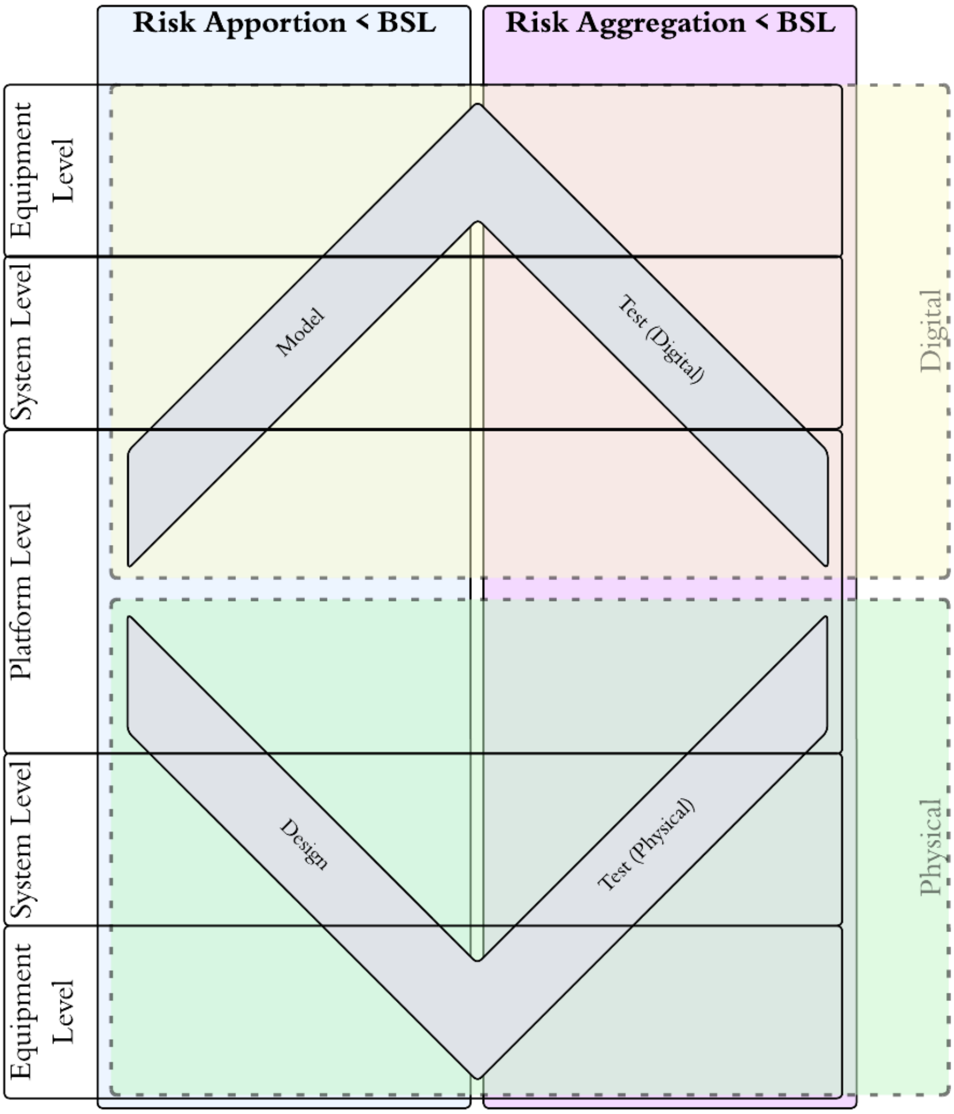

Figure 3: Digital and Physical Systems V Lifecycle Diagram Including Risk Apportionment and Risk Aggregation.

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