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Maritime safety: Prevention versus mitigation?

Romanas Puisa [a], James McNay [a,*], Jakub Montewka [b]

[a] University of Strathclyde, UK
[b] Gdynia Maritime University, Poland

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ABSTRACT

Consideration of risk treatment measures is an essential step of a risk assessment. The type of treatment, preventive or mitigative, is decided on an ad hoc basis, and there seems to be a preferential bias towards mitigation measures in the maritime domain. The paper poses the question of whether this bias is warranted. To this end, we analysed seven studies where the formal safety assessment (FSA) was applied to a variety of cargo and passenger ships. The analysis presents a qualitative review of the recommended RCOs and studies any correlation between the presented RCOs and any bias towards mitigation or prevention. The analysis concluded that any assertion that improving accident mitigation is more practical, i.e. cost-effective, than incident prevention is unwarranted. However, we also showed that the credibility of the FSA results is weak, making this conclusion rather preliminary. The results also show that the reviewed risk analyses expose a potential bias towards mitigation, and the paper discusses possible reasons for that.

1. Introduction

In 1735, Benjamin Franklin advised fire-threatened Philadelphians that "An ounce of prevention is worth a pound of cure" (Franklin, 1735). He voiced the age-old axiom (a.k.a. *prevention is better than cure*) that avoiding a fire, as any other adversity, is wiser than fighting it. This is also a common, textbook strategy in safety engineering when an inherently safe design is firstly sought, followed by the control of hazards, and only then by the mitigation of associated risks (Bahr, 2014; Hollnagel, 2016; Möller and Hansson, 2008). The strategy is referred to in many ways, some common references are: the order of hazard reduction (NASA, 1993), hierarchy of hazard (or risk) control (HSE, 1997), or the precedence of hazard mitigation strategies (MoD, 2017).

As axiomatic as this safety strategy could be, it is obviously conditional. In case of natural disasters, which one cannot escape and often predict, prevention is not an option and an adequate response is what saves lives. At the other extreme, aviation safety is all about prevention of crashes, given negligible likelihood of survival. The rail industry similarly puts much emphasis on collision avoidance, i.e. on preventive barriers (Holmberg, 2017, p. 49). However, there are many cases—somewhere in between these two extremes—where both hazards and their consequences are amenable. This is a playing field of maritime safety, and the above axiom should largely hold in the maritime domain. Yet, the larger part of risk control options evoked during risk analyses in the maritime domain are mitigative, as shown later in this paper. The preference towards mitigation seems to be the default position, which is predicated on the conjecture that mitigation should, on average, be more practical, i.e. cost-effective than prevention.

There is indeed some evidence that a preference toward mitigation can be justified. There is a general understanding that complexity of modern designs and operations makes incidents inevitable (Perrow, 2011), as confirmed by statistics (EMSA, 2017). By complexity we mean the designer's inability to apprehend all hazardous interactions that can materialise. Omissions of such interactions are referred to as design errors, which are hence rife in complex systems. Consequently, the operation of such systems is without no-surprises. Hence, one could reasonably assume that improving the emergency response should take precedence over, arguably, contingent effort on prevention. For instance, fire protection in machinery spaces has recently been transformed by high pressure water mist systems (Arvidson, 2014; Kaariainen, 2007; Liu and Kim, 1999) and new generations of fire alarm systems that use intelligent sensors (Bistrović and Komorčec, 2013). Flooding protection, which is conventionally achieved by maintaining the ship's watertight integrity by passive and active measures, has always been at the centre of maritime safety (Vassalos, 2014), not least when serious accidents revoke its importance (Book, 2012). A very recent advancement in this area is a new, much stricter damage stability regulation known as SOLAS 2020 as discussed by Cichowicz et al.

* Corresponding author at: 16 Richmond St, Glasgow G1 1XQ, UK.
E-mail address: jmcnay88@gmail.com (J. McNay).

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(2019). Efforts on improving effectiveness of the ultimate mitigative barrier, evacuation, have also been significant (Ha et al., 2012; Vanem and Skjong, 2006). As a matter of fact, the vast majority of large European research projects over the last decades, have solely focused on emergency response, e.g. large international research projects FLARE,[1] PALAEMON[2] and SAFEPASS[3] just started in 2019.

On the other hand, the counter-evidence that supports the axiom is not difficult to find. There have been numerous studies of cost-effectiveness of prospective safety regulations that favour the axiom. One of them is the double-hull requirements of the Oil Pollution Act of 1990 which were introduced in the aftermath of the Exxon Valdez oil accident in 1989 (Rodriguez and Jaffe, 1990). The requirements were aimed at the environmental risk from collisions and groundings of oil tankers. The risk was treated by passive protective barriers in the form of structural changes to a ship's hull and subdivision. The requirements were perceived practical in treating the risk (Viertola and Storgård, 2013). However, they were later shown to be largely cost-ineffective (Scott Brown and Savage, 1996), and the most cost-effective measure to control risk of oil accidents would be to prevent a collision or grounding in the first place (Haapasaari et al., 2014). Further, one can also provide the following reason in favour of prevention. Incident avoidance aligns well with the business objectives. The occurrence of accidents, i.e. unwanted events resulting in losses, can bring irreparable damage to reputation of a shipping company. It can discourage people from choosing the operator for a long time, reduce market share, company value, and introduce new safety regulations with additional financial repercussions (Kristiansen, 2005). Moreover, even an incident with no serious consequences—perhaps apart from a few scratches on the hull—is already a dramatic experience for passengers. The contemporary society holds high expectations for safety and service quality (HSE, 2001), which is also how leisure and business services are marketed today. Hence poor incident avoidance, which would lead to frequent disappointments on the part of customers, is clearly damaging for the business.

The above discussion raises an interesting question, which is the motivation for this paper. The question is to what extent the above axiom, the safety strategy, holds in the maritime domain? In other words, what safety measures or risk control options (RCOs), preventive or mitigative, would dominate the risk analysis, and how these two groups of RCOs would compare with respect to cost-effectiveness? While it is not easy to quantify human emotion and preference towards prevention or mitigation, one can review the actions taken in risk analysis and verify whether focus is placed towards prevention or mitigation, and whether this is justifiable from a cost benefit perspective, which this paper aims to do. By answering these questions, we aim to improve knowledge on the state-of-the-art of risk analysis in the maritime sector.

The adopted approach is as follows. The paper studies a set of risk analyses where risk control options (RCOs) were proposed and reviews their preliminary assessment of cost-effectiveness. The risk analyses are obtained from reports on formal safety assessment (FSA) which were jointly compiled by industrial and academic consortia over the last 15 years. We then group RCOs into preventive and mitigative, and calculate their relative rates of cost-effectiveness. The rate is a ratio of cost-effective RCOs over all RCOs proposed. The rates and other figures are then used to answer the questions raised in the paper. To the best of our knowledge, this study is unique with respect to the research questions being addressed.

We recognise that the compared rates contain uncertainties, as discussed later, and only a fraction of RCOs make their way into regulations, typically preceding with further assessments and debates. However, since the FSA process is the formal method for identifying and analysing RCOs within the maritime domain (Goerlandt and Montewka, 2015), the results of FSA studies is good evidence of what risks are perceived important by stakeholders—normally they involve safety regulators or their representatives—and how they are deemed to be treated.

The paper is organised as follows. Section 2 explains how the cost-effectiveness of RCOs is currently determined in the maritime domain. Section 3 discusses data sources and how they were analysed to achieve the objective of the paper. Section 4 summarises the analysis results, whereas Section 5 provides a discussion on them. Section 6 highlights limitations of this paper, which is then concluded in Section 7.

2. Analysis practice of cost-effectiveness

In this section we provide a background for FSA and explain how cost-effectiveness of risk control measures is meant to be performed. We then discuss the issues with quantitative risk analysis implied by the FSA guidelines. These issues highlight the inherent uncertainties in FSA results which have an important bearing on the discussions in this paper.

In the aftermath of the Piper Alpha disaster in 1988 (Cullen, 1993), a review of the safety regime and practices was triggered towards a more systematic (scientific) and proactive approach for their development, in view of established practices—such as a quantitative risk assessment (QRA)—in nuclear, aeronautic and other industries. In 1993 the UK Maritime and Coastguard Agency (MCA) submitted a five-step procedure for safety analysis called Formal Safety Assessment (FSA) (IMO, 2015a), with the IMO adopting interim FSA guidelines and starting trials in 1997. FSA is generally accepted in the industry now. Initially intended for IMO committees and maritime administrations, it is now used by classification societies for development of classification rules (Kristiansen, 2005). The FSA guidelines outline a systematic process of assessing different risks and Risk Control Options (RCOs) or safety barriers (Hollnagel, 2008), and provide guidance on cost benefit analysis of RCOs (IMO, 2007, 2015a). The FSA process implies—albeit does not explicitly request it—the use of QRA within the probabilistic framework. This is because the quantification of risks is helpful in cost benefit analysis, i.e. determining if a proposed RCO is cost-effective with respect to a quantitative criterion, and the risk contributors are considered as predominantly stochastic. The latter is implied in Section 3 (principles of risk evaluation) of the FSA guidelines (IMO, 2015b).

Two measures of cost-effectiveness of RCOs are applied: gross cost of averting a fatality (GCAF) and net cost of averting a fatality (NCAF). They are expressed as the ratios of the cost (gross or net) incurred per ship lifetime after implementing an RCO to the corresponding reduction in the societal risk per ship lifetime[4]. For an RCO to be cost-effective its GCAF and NCAF must be below some upper limit. However, NCAF values should be used with care, for they can fall below the limit even though the reduction in risk is negligible. This can happen when the benefits of implementing an RCO outweigh the costs; such RCOs should not generally be considered as risk reduction measures, but merely as design improvements. The upper limit is determined based on the willingness-to-pay to avert a fatality, past decisions and the costs involved, consideration of societal indicators such as the life quality index (LQI), and other aspects (Skjong and Eknes, 2001; Skjong and Eknes, 2002). The limit is not static and might need to be updated before use. For instance, in 2007 the value was 3 M USD (e.g., FSA MSC 83/21/1). Ten years later, the value was adjusted to 7 M Euro (~7.7 M USD) (EMSA et al., 2016).

The application practice of FSA, however, has not been without difficulties (Kontovas and Psaraftis, 2009; Psaraftis, 2012; Puisa and Vassalos, 2012; Skjong and Wentworth, 2001; Yang et al., 2013). The

[1] https://flare-project.eu/.

[2] https://palaemonproject.eu/.

[3] http://www.safepass-project.eu/.

[4] GCAF = $\Delta C/\Delta R$, NCAF = $(\Delta C-\Delta B)/\Delta R$, where ΔC is the life-time cost associated with a proposed risk control measure (RCO), ΔB is the economic benefit from the introduction of RCO, and ΔR is the reduction in risk by RCO.

raised issues are related to the overreliance on historical data and expert opinion, confusion of frequencies for probabilities, uncertainties in both risk and financial components, shallow assessment of interactions between combined RCOs and their effect on the joint cost-effectiveness. A notable critique, which is attributed to QRA in general, is the slippery assumption of independence of basic events in fault trees, e.g. (Wikman et al., 2017). Should this assumption turn out to be false, it would open the way for common-cause failures (Rae et al., 2012). The assumption of independence can also lead to so-called *Titanic coincidence*[5] (Machol, 1975), when many low probability events are multiplied to estimate the top event probability. This results in a negligible probability of the top event, which is then discarded as impossible or cost-ineffective to attend to.

It is also worth noting that the FSA guidelines suggest to use the human reliability analysis to quantify human errors. A human action is typically classified as the human error in the aftermath of an incident or accident when that action is found to have been in breach of safety procedures. However, many examples demonstrate that violating safety procedures could be necessary to actually maintain safety, for safety procedures are never perfect (Besnard and Hollnagel, 2014). In other words, human error is a product of the hindsight bias and is a psychological construct but not an objective or technical one (Dekker, 2011; Woods et al., 1994, p. xvii). Hence, determining the frequency (and probability) of human errors, as suggested by the FSA guidelines (IMO, 2015b), becomes rather problematic. Further, people do their best, hardly behave randomly, and make decisions based on prevailing conditions (Dekker, 2014). This means that the same conditions will make people produce the same output fairly consistently. People are also good at adapting to new circumstances, as long as the changes to work conditions are predictable (not random) and there are sufficient opportunities (time) for learning (Kahneman and Klein, 2009). Thus, instead of the human error, the adequacy of work conditions should be the object of quantification. For instance, the intermittent or constant presence of excessive noise or temperature could be such conditions, e.g. (Montewka et al., 2017).

An analogous treatment is applicable to software, which is becoming ubiquitous on modern marine systems. Software failure is also a misnomer, for software does not fail but does precisely as it is told in the specification (Leveson, 1995). In other words, for the same input, the software will always produce the same output. Consequently, assigning a probability to this deterministic behaviour is ill-advised, and the change of out-of-range input—for which the system design should normally be prepared—may be quantified instead. In contrast to human behaviour, software will never deviate from the specification. However, this often advantageous property can turn out to be hazardous when the specification appears to be wrong (Sarter et al., 1997).

The above glitches of the FSA make the comparison of RCOs against any quantitative criteria precarious. The fact that confidence bands are often not given in FSA results, and generally in QRA studies (Sormunen et al., 2015), does not help. Even when the corresponding analysis is undertaken, e.g. (Wikman et al., 2016), it is too simplistic to address the issues highlighted above. Therefore, the intended comparison of RCOs in this paper should not be strictly based on obtained numbers, so to speak, but also consider wider, possibly unquantifiable, knowledge of the system analysed (Askeland et al., 2017; Aven, 2013; Montewka et al., 2014). Section 3.2 explains how this knowledge was used for this purpose, while Section 5 provides a further discussion on the question of uncertainty.

[5] This is an ironic name, because the Titanic disaster was not, arguably, coincidental.

3. Method

3.1. Data sources

Over the last couple of decades, several studies have been performed to inform cost-effective improvements in maritime safety. The most consequential inquiries have come out of research projects funded by the European Commission and domestic funds. These have been industrial research projects, involving safety regulators such as class societies, flag states and IMO. Notable projects are SAFEDOR (Papanikolaou, 2009), FIRESAFE (Wikman et al., 2017) and FIRESAFE2 (Leroux et al., 2018). The SAFEDOR focused on both fire and flooding events across main types of cargo and passenger ships, whereas the latter two exclusively dealt with fires on passenger ro-ro (RoPax) ships.

These projects were initiated with the intention to impact maritime safety regulations. Therefore, we use the FSA studies that came out of these projects as a dataset for analysis in this paper. Note, the RCOs found in these studies are generic in the sense that they reflect generic accident scenarios and are supposed to apply to all ships in the given category. However, it does not rule out the possibility that for a specific ship in the category, given its unique design and operational circumstances, such an RCO can be impractical.

Table 1 lists specific reports from where the pertinent results of cost-effectiveness analysis were extracted. Specifically, from each data source the following information was obtained:

1. A list of RCOs against flooding and/or fire risks;
2. Categories of RCOs: preventive or mitigative;
3. GCAF and NCAF values for each RCO;
4. Used upper limits for GCAF/ NCAF;
5. A final list of RCOs found to be cost-effective and/or recommended for consideration.

Note, the information relevant to this paper corresponds to the second and fifth points only, as discussed in the following section.

3.2. Analysis

For a given ship type, GCAF and NCAF values for preventive and mitigative RCOs could be directly used to determine which category has

Table 1
Data sources.

Source	Reference*	Reference in paper
FSA – Liquefied Natural Gas (LNG) carriers	MSC 83/21/1, 3 July 2007	R1
FSA – Container vessels	MSC 83/21/2, 3 July 2007	R2
FSA – Crude Oil Tankers	MEPC 58/17/2, 4 July 2008	R3
FSA – Cruise ships	MSC 85/17/1, 21 July 2008	R4
FSA – RoPax ships	MSC 85/17/2, 21 July 2008	R5
FSA – Large passenger ships	NAV 51/10, 4 March 2005	R6
FIRESAFE II Combined Assessment for RoPax ships. This report presents the results of the combined assessment of cost effectiveness based on the results from the different parts previously considered separately in FIRESAFE and FIRESAFE II. Six sub-groups of ships are considered.	Version 1.1, December 2018	R7.1 - R7.6 (or R7 when to all)

* The reports can be found online (last accessed on 18/09/2019): http://www.safedor.org/resources/index.htm, http://www.emsa.europa.eu/firesafe.html.

higher cost-effectiveness. The quantitative comparison, however, would not be credible, for the number of RCOs is small and there is high uncertainty around the GCAF and NCAF values, as highlighted in Section 2. Therefore, instead of using the direct GCAF and NCAF values for comparison, we used the RCOs recommended for implementation by the FSA authors. The authors clearly went beyond numerical values, using wider knowledge when deciding on what RCOs were cost-effective as these do not always correlate directly with the GCAF or NCAF values. For instance, some GCAF values did not pass the threshold, but were highlighted as attractive alternatives for voluntary implementation by ship owners from a commercial point of view (NCAF < 0) or, because of a low GCAF value, can become cost-effective in the future. Also, the FSA studies acknowledge that some RCOs that were assessed to be cost-ineffective for a generic case, may turn out to be effective in many cases when specific ships or trades are considered.

The obtained RCOs were then split into two categories of preventive and mitigative measures. Then we used proportions of cost-effective RCOs (i.e. CE rates) in each category for comparison between the categories. The two RCO categories are distinct and fairly independent but yet belong to the same wider system of safety management. The idea of comparing datasets in terms of proportions comes from statistics (Campbell, 2007). Typically, the proportions correspond to some kind of success rate. For example, two school classes are compared in terms of their performance at an exam by using the pass rates. The rate would simply be calculated as the ratio between the number of kids who passed the exam to the total number of kids in that class.

In the following we provide an example analysis for Report R1. The analysis is analogous for all reports and hence only analysis results are provided in the section below. Thus, Report R1 evaluates possible risk control options (RCOs) for Liquefied Natural Gas (LNG) carriers (Table 2). The study proposed 17 RCOs:

- Collision, grounding and contact prevention (flooding prevention): implement risk-based maintenance (propulsion, steering, navigational, cargo handling system), implement a restriction on crew schedule to avoid fatigue of crew, increase use of simulator training, introduce a redundant propulsion system (two shaft line), improve navigational safety (ECDIS, track control system, AIS integrated with radar, improved bridge design).
- Collision, grounding and contact mitigation (flooding mitigation): increase double hull width, increase double bottom depth, increase hull strength.
- Fire and explosion prevention: perform a periodic thermal image scanning of engine-room, use strain gauges for measuring stresses onboard, and redundant radar sounding for filling level check.

Among the proposed RCOs, only three were directly related to accident mitigation (3/17), the rest were preventive measures (14/17). The analysis showed that all RCOs related to navigational safety and collision and grounding avoidance were exceptionally cost-effective. The rest of the RCOs were found to be cost-ineffective by GCAF values, although several of them—such as RCO#1 on the risk-based maintenance of propulsion and steering systems shown in Table 2—were recommended for voluntary implementation for commercial benefits due to negative NCAF values. In summary, the CE rate among preventive RCOs was 7/14, whereas of mitigative options was 0/3. Thus, for LNG carriers, preventing accidents might be more cost-effective.

Table 2
List of proposed RCOs in data source R1.

#	Risk control option	Type *	GCAF ** (10^6)	Recommended?
1	Implement risk-based maintenance of propulsion system	FLP	57.2	Y
2	Implement risk-based maintenance of steering system	FLP	7.4	Y
3	Implement risk-based maintenance of navigational system	FLP	2.21	Y
4	Implement risk-based maintenance of cargo handling system	FLP	159	
5	Implement a restriction on crew schedule to avoid fatigue of crew	FLP	159	
6	Increase use of simulator training	FLP	12	
7	Introduce a redundant propulsion system (two shaft line)	FLP	60.8	
8	Improve navigational safety: ECDIS	FLP	3.1	Y
9	Improve navigational safety: track control system	FLP	0.4	Y
10	Improve navigational safety: AIS integrated with radar	FLP	0.06	Y
11	Improve navigational safety: improved bridge design	FLP	2.3	Y
12	Increase double hull width	FLM	74.3	
13	Increase double bottom depth	FLM	59.5	
14	Increase hull strength	FLM	60	
15	Perform a periodic thermal image scanning of engine-room	FRP	28	
16	Use strain gauges for measuring stresses onboard	FRP	394.1	
17	Redundant radar sounding for filling level check	FRP	236	

* Type: FLP – flooding prevention, FLM – flooding mitigation, FRP – fire prevention, FRM – fire mitigation (unused in this table but present in other sources).

** GCAF units are cost (in USD) per fatality averted.

4. Results

Table 3 summarises the data sources in terms of variables used in the analysis, whereas Fig. 1 shows a bar chart of CE rates across all seven reports; the median value is also shown for guidance. The median CE rate indicates that preventive measures would typically be more cost-effective. However, the qualitative difference is what matters most. The larger number of preventive measures were more cost-effective than mitigative measures (e.g., in R1 none of mitigative RCOs were considered feasible), even though the number of mitigative RCOs across all reports was marginally larger (Fig. 2). Further, one can observe that in 10 out of 12 cases, preventive measures have higher or virtually the same cost-effectiveness (Fig. 1).

From Table 3 we can see that the total number of RCOs range between 7 and 24 between the reports. The majority of reports contain a higher total number of mitigative RCOs (8/12), however the majority of reports produce a more favourable CE rate for preventative RCOs (8/12, with one report resulting in a tie). Only 3/12 reports produced a higher CE rate for the proposed mitigative RCOs.

During the analysis we also compared the actual numerical values of NCAF and GCAF, although this comparison is not presented in this paper. This is done intentionally due to the indicated numerical uncertainties in the values, and so that we could keep the overall analysis as qualitative as possible. We noticed, however, that preventive measures in relation to training, procedures and other 'soft' factors had considerably higher cost-effectiveness than so called 'hard' factors such as component redundancy and other significant changes to the ship (e.g., in R6). This is primarily due to lower cost of implementation, but not necessarily due to high potential in reducing risk.

5. Discussion

The paper posed the question as to what extent the axiom of *prevention is better than cure* holds in the maritime domain? In other words, what safety measures or risk control options (RCOs), preventive or

Table 3
Summary of FSA results and corresponding CE rates.

Report #	No. of preventive RCOs	No. of mitigative RCOs	No. of CE preventive RCOs	No. of CE mitigative RCOs	CE rate preventive	CE rate mitigative	Preventive more cost effective than mitigative (Y/N)
1	14	3	7	0	1/2	0	Y
2	11	6	2	1	2/11	1/6	Y
3	6	1	5	1	5/6	1	N
4	4	6	4	5	1	5/6	Y
5	3	7	2	4	2/3	4/7	Y
6	17	7	12	5	12/17	5/7	N
7.1	6	12	4	6	2/3	1/2	Y
7.2	6	12	4	4	2/3	1/3	Y
7.3	6	14	5	10	5/6	5/7	Y
7.4	6	15	5	10	5/6	2/3	Y
7.5	6	12	5	11	5/6	11/12	N
7.6	6	12	5	10	5/6	5/6	–

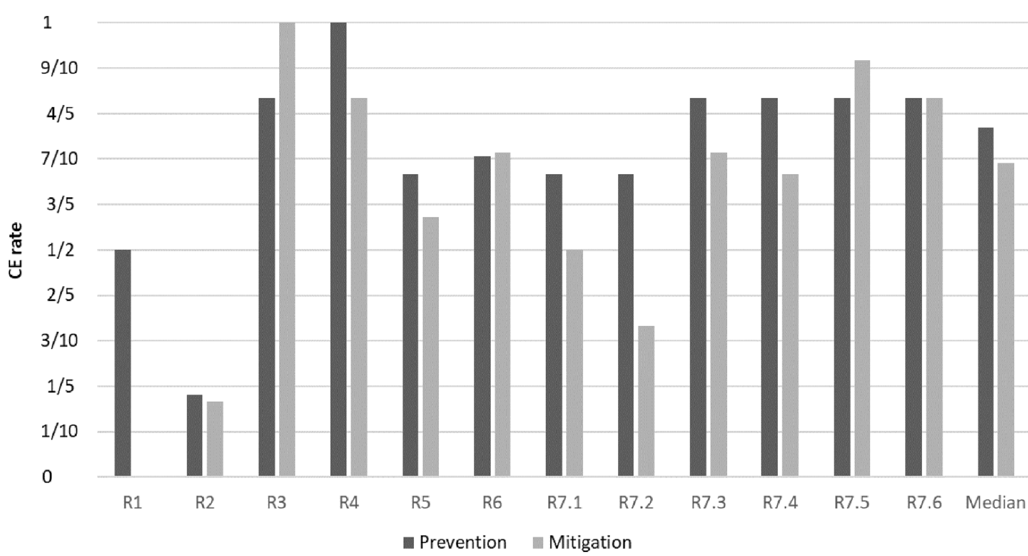

Fig. 1. CE rate per data source.

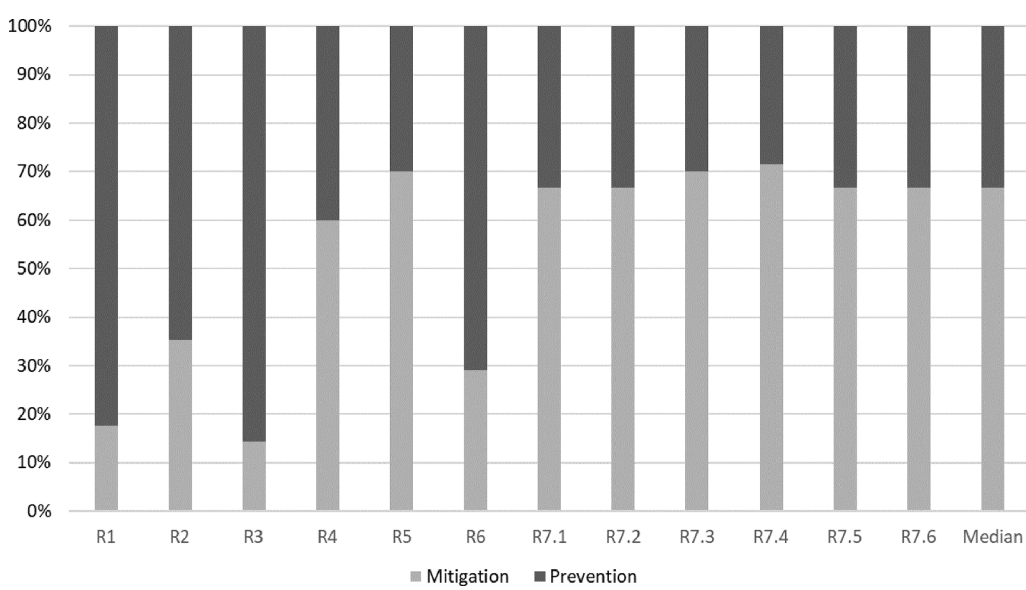

Fig. 2. Proportion of preventive and mitigative RCOs per data source.

mitigative, would dominate the risk analysis, and how these two groups of RCOs would compare with respect to implementation based on cost-effectiveness?

The results show that mitigative RCOs tend to dominate the risk analyses (cf. Fig. 2), although preventative RCOs lean towards higher CE or approval rates (cf. Fig. 1). Thus, improving incident prevention can be as cost-effective, if not more, than investing in accident mitigation. In other words, any assertion that improving accident mitigation is more cost-effective than its prevention is unwarranted, as far as the reviewed FSA studies are concerned. This observation, however, is much dependent on the analysis and interpretation of cost-effectiveness within the data sources, as highlighted in Section 2.

The analysis of the FSA studies was also helpful to observe the spectrum of risk control options (safety barriers) considered in the maritime domain. Fig. 3 illustrates the analysis results on a bow-tie or barrier diagram (Duijm, 2009). The illustration adds a safety focus in the merchant shipping to the original representation (Holmberg, 2017). It shows that both incident prevention and mitigation are similarly important for risk control in the shipping industry. This echoes the earlier study by (McNay et al., 2019), where the authors compared the prescribed and actual scopes of fire safety control. In other words, the two categories of safety barriers, prevention and mitigation, are equally essential for implementing the principle of defence-in-depth (Fleming and Silady, 2002). The principle is essentially deterministic, strictly demanding to have a barrier. In this case, both preventive and mitigative barriers are required, and weakness of one barrier cannot be compensated by making another one stronger (Holmberg, 2017).

Although maritime safety aims to focus on both prevention and mitigation, there is indeed a bias towards the latter. The rationale for this bias was highlighted in the introductory section and it can also be seen in the analysis results – there are generally more mitigative RCOs (Fig. 2). As pointed out by Yang et al. "some consequences such as collisions and groundings have been considered as initiating events in FSA studies, which results in the focus of RCOs shifting from risk prevention to risk mitigation. The development of 'higher level' events (i.e. root causes) leading to the occurrence of consequences should be emphasised in FSA studies, particularly in the establishment of casualty databases with more detailed root cause information" (Yang et al., 2013). Indeed, the reviewed risk analyses would not normally deal with pre-incident events. As Yang et al. mention, the paucity of or difficult access to causal data to draw probabilities or models from could be one reason. However, this explanation may not hold water in view of extensive research in this area, e.g. (Fowler and Sørgård, 2000; Montewka et al., 2010; Puisa et al., 2018; Puisa et al., 2019).

A more likely reason for forgoing pre-incident events in risk analysis is that many of those events are simply unquantifiable or unmeasurable (Townsend, 2016), the property that applies to many important aspects in life. To paraphrase Albert Einstein, what is important is not necessarily measurable, and what is measurable may not be important. We engineers are fixated on numbers and tend to discount things that cannot be measured. Additionally, we tend to think that those social aspects that prevail in incident prevention are outside our engineering purview. However, we forget that safety engineering is not a horizontal but a vertical discipline, covering social and technical aspects together, but not in isolation (Rasmussen, 1997). Therefore, in addition to further research in pre-incident events, there is need to widen our education to overcome such psychological barriers.

6. Limitations

Six out of seven data sources were at least ten years old. However, given the fundamental challenges associated with QRA and its application (cf. Sections 2 and 5), it is likely that more recent studies would have resulted in similar outcomes. This is partly supported by the EMSA studies (ref. R7), where the authors essentially replicated the same scope of analysis and were faced with the same uncertainties.

Risks to environmental and property damage, which were considered in some of the used data sources, were assumed to be outside the scope of this paper, which primarily focuses on fire and flooding.

The primary limitation is the inherent uncertainty of FSA results. As previously discussed, this paper relied on the expert judgment of the FSA authors without having direct access to those experts to query the decision-making process. It was deemed, however, that basing the cost effectiveness on their decision making was more reliable than basing it solely on the uncertain GCAF and NCAF values as discussed in Section 3.2.

7. Conclusions

The paper has sought to answer the question as to what extent the axiom of *prevention is better than cure* holds in the maritime domain, and if the argument that mitigation is more practical, i.e. cost-effective, is warranted. To this end, we analysed seven FSA studies tasked to arrive at risk control options along with their cost-effectiveness with respect to risk reduction. All of these studies were aimed to inform future safety regulations and, potentially, safety practices within the industry.

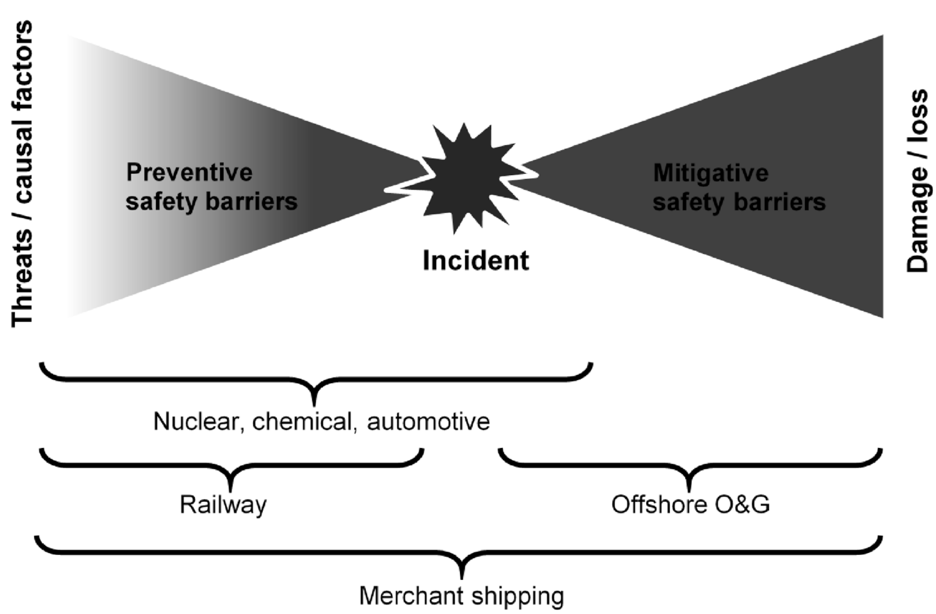

Fig. 3. Prime focus* of risk control in various industries (*the actual scope of risk control would cover, with varying degree of detail, both prevention and mitigation in all industries).

We have concluded that any assertion that improving accident mitigation is more cost-effective than incident prevention is unwarranted, when the results of the FSA studies are considered. We have, however, shown that the credibility of the FSA results is weak, making this conclusion rather hypothetical. Hence, more research is necessary to be able to determine and compare cost-effectiveness of risk control options (safety barriers) with high confidence.

The analysis of the FSA studies has also shown that both barrier categories, preventive and mitigative, have attracted comparable attention, although a potential bias towards mitigation exists. This means that although both barrier categories are equally essential for effective defence-in-depth, the scope of risk analysis should be widened to further consider pre-incident events. In other words, risk analysis should cover the socio-technical system within correctly drawn boundaries (Checkland, 1981).

References

Arvidson, M., 2014. Large-scale water spray and water mist fire suppression system tests for the protection of Ro–Ro cargo decks on ships. Fire Technol. 50, 589–610.

Askeland, T., Flage, R., Aven, T., 2017. Moving beyond probabilities – Strength of knowledge characterisations applied to security. Reliab. Eng. Syst. Saf. 159, 196–205.

Aven, T., 2013. A conceptual framework for linking risk and the elements of the data–information–knowledge–wisdom (DIKW) hierarchy. Reliab. Eng. Syst. Saf. 111, 30–36.

Bahr, N.J., 2014. System safety engineering and risk assessment: a practical approach. CRC Press.

Besnard, D., Hollnagel, E., 2014. I want to believe: some myths about the management of industrial safety. Cogn. Technol. Work 16, 13–23.

Bistrović, Kezić, Komorčec, 2013. Historical Development of Fire Detection System Technology on Ships., https://hrcak.srce.hr/112621.

Book, C., 2012. "The EU ignored years of expert warnings on cruise ship safety", The Daily Telegraph.

Campbell, I., 2007. Chi-squared and Fisher-Irwin tests of two-by-two tables with small sample recommendations. Stat. Med. 26, 3661–3675.

Checkland, P., 1981. Systems thinking, systems practice. J. Wiley.

Cichowicz, J., Olufsen, O., GL, D., Vassalos, D., 2019. Ro-Ro passenger ships–from Stockholm Agreement to SOLAS2020. In: Proceedings of the 17th International Ship Stability Workshop. Aalto University.

Cullen, L.W.D., 1993. The public inquiry into the Piper Alpha disaster. Drilling Contractor; (United States) 49.

Dekker, S., 2011. The criminalization of human error in aviation and healthcare: A review. Saf. Sci. 49, 121–127.

Dekker, S., 2014. The field guide to understanding'human error'. Ashgate Publishing Ltd.

Duijm, N.J., 2009. Safety-barrier diagrams as a safety management tool. Reliab. Eng. Syst. Saf. 94, 332–341.

EMSA, 2017. Annual Overview of Marine Caualties and Incidents 2017. European Maritime Safety Agency.

EMSA, Sweden, S.T.R.I.o., Veritas, B., AB, S.R., 2016. Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE), Appendix: Sensitivity and Uncertainty Analysis.

Fleming, K.N., Silady, F.A., 2002. A risk informed defense-in-depth framework for existing and advanced reactors. Reliab. Eng. Syst. Saf. 78, 205–225.

Fowler, T.G., Sørgård, E., 2000. Modeling ship transportation risk. Risk Anal. 20, 225–244.

Goerlandt, F., Montewka, J., 2015. Maritime transportation risk analysis: review and analysis in light of some foundational issues. Reliab. Eng. Syst. Saf. 138, 115–134.

Ha, S., Ku, N.-K., Roh, M.-I., Lee, K.-Y., 2012. Cell-based evacuation simulation considering human behavior in a passenger ship. Ocean Eng. 53, 138–152.

Haapasaari, P.E., Dahlbo, K., Aps, R., Brunila, O.-P., Fransas, A., Goerlandt, F., Hänninen, M., Jönsson, A., Laurila-Pant, M., Lehikoinen, A., 2014. Minimizing risks of maritime oil transport by holistic safety strategies (MIMIC) Final report.

Hollnagel, 2008. Risk+barriers=safety? Saf. Sci., vol. 46, pp. 221-229.

Hollnagel, E., 2016. Barriers and accident prevention. Routledge.

Holmberg, J.E., 2017. Defense-in-Depth. Handbook of Safety Principles 42–62.

HSE, 1997. Successful health and safety management. Health and Safety. Executive.

HSE, 2001. Reducing risks, protecting people. HSE decision-making process, Health and Safety Executive, Norwich.

IMO, 2007. MSC 83/INF.2 Formal Safety Assessment Consolidated text of MSC/Circ, 1023-MEPC/Circ.392. International Maritime Organisation.

IMO, 2015a. Rev.1 Revised Guidelines for formal safety assessment (FSA) for use in the IMO rule making process. International Maritime Organisation. MSC-MEPC.2/Circ, 12/.

IMO, 2015b. Revised Guidelines for Formal Safety Assessment (FSA) for Use in The IMO Rule-Making Process MSC-MEPC.2/Circ, 12/Rev.1)..

Kaariainen, J.S., 2007. High Pressure Water Mist Fire Protection Systems, ASME Turbo Expo 2007: Power for Land, Sea, and Air. American Society of Mechanical Engineers, pp. 723-731.

Kahneman, D., Klein, G., 2009. Conditions for intuitive expertise: a failure to disagree. Am. Psychol. 64, 515.

Kontovas, C.A., Psaraftis, H.N., 2009. Formal safety assessment: a critical review. Mar. Technol. 46, 45–59.

Kristiansen, S., 2005. Maritime transportation: safety management and risk analysis.

Leroux, J., Evegren, F., Gustin, L., Ukaj, K., Vicard, B., 2018. FIRESAFE II. Combined Assessment, Version 1.1 ed. European Maritime Safety Agency (EMSA).

Leveson, N.G., 1995. Safeware. Addison Wesley, System Safety and Computers.

Liu, Z., Kim, A.K., 1999. A review of water mist fire suppression systems—fundamental studies. J. Fire. Prot. Eng. 10, 32–50.

Machol, R., 1975. Principles of Operations Research—10. The Titanic Coincidence. Interfaces 5, 53–54.

McNay, J., Puisa, R., Vassalos, D., 2019. Analysis of effectiveness of fire safety in machinery spaces. Fire Saf. J. 108, 102859.

MoD, 2017. Defence Standard 00-56. Safety Management Requirements for Defence Systems. Part 1: Requirements. Ministry of Defence.

Möller, N., Hansson, S.O., 2008. Principles of engineering safety: Risk and uncertainty reduction. Reliab. Eng. Syst. Saf. 93, 798–805.

Montewka, J., Goerlandt, F., Innes-Jones, G., Owen, D., Hifi, Y., Puisa, R., 2017. Enhancing human performance in ship operations by modifying global design factors at the design stage. Reliab. Eng. Syst. Saf. 159, 283–300.

Montewka, J., Goerlandt, F., Kujala, P., 2014. On a systematic perspective on risk for formal safety assessment (FSA). Reliab. Eng. Syst. Saf. 127, 77–85.

Montewka, J., Hinz, T., Kujala, P., Matusiak, J., 2010. Probability modelling of vessel collisions. Reliab. Eng. Syst. Saf. 95, 573–589.

NASA, 1993. Safety Policy and Requirements Document. NHB 1700.1 (V1-B). NASA, Washington, DC.

Papanikolaou, A., 2009. Risk-based ship design: Methods, tools and applications. Springer Science & Business Media.

Perrow, C., 2011. Normal accidents: Living with high risk technologies-Updated edition. Princeton University Press.

Psaraftis, H.N., 2012. Formal safety assessment: an updated review. J. Mar. Sci. Technol. 17, 390–402.

Puisa, R., Lin, L., Bolbot, V., Vassalos, D., 2018. Unravelling causal factors of maritime incidents and accidents. Saf. Sci. 110, 124–141.

Puisa, R., Vassalos, D., 2012. Robust analysis of cost-effectiveness in formal safety assessment. J. Mar. Sci. Technol. 17, 370–381.

Puisa, R., Williams, S., Vassalos, D., 2019. Towards an explanation of why onboard fires happen: The case of an engine room fire on the cruise ship "Le Boreal". Appl. Ocean Res. 88, 223–232.

Rae, A., McDermid, J., Alexander, R., 2012. The science and superstition of quantitative risk assessment. J. Syst. Saf. 48, 28.

Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Saf. Sci. 27, 183–213.

Rodriguez, A.J., Jaffe, P.A., 1990. The Oil Pollution Act of 1990. Tul. Mar. LJ 15, 1.

Sarter, N.B., Woods, D.D., Billings, C.E., 1997. Automation surprises. Handbook Human Fact. Ergon. 2, 1926–1943.

Scott Brown, R., Savage, I., 1996. The economics of double-hulled tankers. Maritime Policy Manage. 23, 167–175.

Skjong, R., Eknes, M., 2001. Economic activity and societal risk acceptance, Proc. ESREL.

Skjong, R., Eknes, M.L., 2002. Societal risk and societal benefits. Risk, Decis. Policy 7, 57–67.

Safety of Life at Sea (SOLAS), 2020. International Maritime Organisation (IMO), ISBN 9789280116908.

Skjong, R., Wentworth, B.H., 2001. Expert judgment and risk perception, The Eleventh International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.

Sormunen, O.-V.E., Goerlandt, F., Häkkinen, J., Posti, A., Hänninen, M., Montewka, J., Ståhlberg, K., Kujala, P., 2015. Uncertainty in maritime risk analysis: Extended case study on chemical tanker collisions. Proc. Inst. Mech. Eng., Part M: J. Eng. Maritime Environ. 229, 303–320.

Townsend, A.S., 2016. Safety can't be measured: An evidence-based approach to improving risk reduction. Routledge.

Vanem, E., Skjong, R., 2006. Designing for safety in passenger ships utilizing advanced evacuation analyses—A risk based approach. Saf. Sci. 44, 111–135.

Vassalos, D., 2014. Damage stability and survivability–'nailing'passenger ship safety problems. Ships Offshore Struct. 9, 237–256.

Viertola, J., Storgård, J., 2013. Overview on the Cost-effectiveness of Maritime Safety Policy Instruments. University of Turku, The Centre For Maritime Studies.

Wikman, J., Evegren, F., Rahm, M., Leroux, J., Breuillard, A., Kjellberg, M., Gustin, L., Efraimsson, F., 2016. Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE). Sensitivity and Uncertainty Analyses. EMSA, Appendix.

Wikman, J., Evegren, F., Rahm, M., Leroux, J., Breuillard, A., Kjellberg, M., Gustin, L., Efraimsson, F., 2017. Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE). Eur. Maritime Saf. Agency.

Woods, D.D., Johannesen, L.J., Cook, R.I., Sarter, N.B., 1994. Behind human error: Cognitive systems, computers and hindsight. Dayton Univ Research Inst (Urdi) OH.

Yang, Z., Wang, J., Li, K., 2013. Maritime safety analysis in retrospect. Maritime Policy Manage. 40, 261–277.

Further reading

Akyildiz, H., 2015. Formal Safety Assessment of a Fishing Vessel. Gidb Magazinr 1, 31–46.

Akyildiz, H., Mentes, A., Helvacioglu, I.H., 2012. Formal Safety Assessment of Cargo Ships at Coasts and Open Seas of Turkey. In: ASME 2012 31st International

Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers Digital Collection, pp. 175-183.
Beer, J., 2011. The true significance of common cause failures in accidents. University of York, York.
Franklin, B., 1735. On Protection of Towns from Fire, The Pennsylvania Gazette.
Goerlandt, F., Hänninen, M., Ståhlberg, K., Montewka, J., Kujala, P., 2011. 25. Simplified Risk Analysis of Tanker Collisions in the Gulf of Finland. Miscellaneous Problems in Maritime Navigation, Transport and Shipping: Marine Navigation and Safety of Sea. Transportation 181.
Guarin, L., Konovessis, D., Vassalos, D., 2009. Safety level of damaged RoPax ships: risk modelling and cost-effectiveness analysis. Ocean Eng. 36, 941–951.
IMO, 2018. International Safety Management Code (ISM Code) with guidelines for its implementation. IMO, London.
Leveson, N.G., 2011. Applying systems thinking to analyze and learn from events. Saf. Sci. 49, 55–64.
Lois, P., Wang, J., Wall, A., Ruxton, T., 2004. Formal safety assessment of cruise ships. Tour. Manage. 25, 93–109.
Wu, B., Yan, X., Wang, Y., Soares, C.G., 2016. Selection of maritime safety control options for NUC ships using a hybrid group decision-making approach. Saf. Sci. 88, 108–122.