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CONSORTIUM OF EU PROJECT FAROS

Final Report

Public summary of the project

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This report summarises key results of EU project FAROS (2012 – 2015). The objective of this report is to structure and summarise significant project results that may inform decision-making for ship designers, operators, and regulators, as well as other stakeholders. The document specifically summarises knowledge obtained through experiments on virtual machinery spaces and bridge simulators, risk modelling and application for risk assessment of ship concepts. It provides recommendations and further steps to achieve improvement or implementation of the project results. The project website contains detailed technical reports accessible by the general public.

Disclaimer

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1 Executive summary

The ultimate project objective has been the quantification and integration of the human error (human factors) into risk-based, concept ship design. It is a design process where risk is to be systematically reduced along with improvements in other conventional performance characteristics.

In the course of implementation, the project could not avoid the challenges currently pertinent to the maritime domain. One such challenge was related to the paucity of statistical data on the detailed realisation of human error in reported **m**aritime **a**ccidents, **i**ncidents, and **n**ear-misse**s** (MAINS). It was also found that little quantitative knowledge is available in the literature (incl. design standards) about the notoriously detrimental effect of noise, ship motions, vibration, deck layout and other Global Design Factors (GDFs) on human performance. Particularly, knowledge about the failure in cognitive performance is scant. The consortium calls for decisive actions to establish proper reporting of MAINS and promote basic research on fundamentals of human performance in maritime settings to bridge this knowledge gap.

Nevertheless, the FAROS consortium offered solutions to some of these challenges. A theoretical framework was proposed and implemented to link GDFs to the human reliability, although the framework still suffered from the data paucity problem described above. This framework, however, allowed the development of a novel Human Reliability (HR) model and integrating it within risk models. The HR models are innovative, featuring new concepts (e.g., safe behaviour, attention management) that are well justified by scientific and experimental evidence. They reflect and amalgamate the state-of-the-art knowledge available about the human performance and its link to the occupational environment, i.e. GDFs. Therefore they have a wide spectrum of application.

The risk modelling focused on personal (individual) and societal (collision, grounding, and fire) risk contributions. Each risk model represents a combination of hazard probability and consequences. The HR models were part of hazard probabilities, assuming that failure in HR increases chances of unfavourable events. The risk models were then applied in the risk-based design process to achieve and demonstrate the improvements in design.

However when applied, the risk models showed low sensitivity—principally due to the data paucity problem—to certain GDFs when applying typical design modifications at the concept design stage. This was in particular significant for tanker ships, which have quite simple deck layouts and much less crew than on large passenger ships. Nevertheless, significant design improvements were achieved and recommendations made in relation to human factors in concept design. Thus, optimisation of tankers improved economic and environmental performance of the baseline designs by 90% (when considering through life operation) and 11% (when considering air emissions), respectively. And optimisation of RoPax ships reduced the total risk, improved economic and environmental performance by up to 67%, 3%, and 4%, respectively.

The results of the risk models led to the realisation that those parts of risk models that link human performance to GDFs, i.e. the HR models, should be decoupled from risk and used separately for human reliability analysis (HRA) during normal ship operations. Then the ship design process would simply have an extra design objective aimed to improve HR by optimising GDFs. However, a full demonstration of this process was beyond the scope of FAROS.

In addition to these activities, the project conducted a series of experiments to learn about the link between GDFs and human performance. The experiments with seafarers were conducted on bridge simulators and machinery spaces simulated in virtual reality, studying the effect of noise and ship motions on navigational performance, and the effect of deck layout on safe execution of engineering tasks. It was concluded that the deck layout can have impact on crew safety, whereas noise on the ship's bridge may affect the navigational task performance. It is suggested that the use of watertight doors (WTD) has to be reduced to the minimum to avoid personal injuries or jeopardy to ship's damaged stability. This can be achieved by reducing the number of WTD or crew tasks that require using them and enhancing damage stability calculations with open WTD scenarios. As for noise, the noise level on the ship bridge has to be reduced as low as practicable to facilitate crew performance during demanding tasks.

The project results and activities have been disseminated through public workshops, conference, journal and magazine publications, leaflets, and a promotional film available on-line.

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2 Guide to concepts and terminology

Global Design Factors (GDFs): specific ship design factors that are manipulated in design and are assumed to influence crew performance, potentially contributing to the unwanted outcomes of collision, grounding, fire and personal injury on board. These performance-shaping factors, known within FAROS as Global Design Factors, are listed below [1]:

- Ship Motion (i.e. motion-induced sickness (MIS) and motion induced interruption (MII))
- Noise
- Full body vibration
- Deck layout, equipment arrangement and accessibility (DLEAA) [2]

Unsafe behaviour is one that generates the opportunity for an incident in combination with the presence of contextual factors. The contextual factors can be described as the circumstances that exist at the time the negative outcome (personal injury) occurs [3].

Individual risk: The risk of death, injury and ill health as experienced by an individual at a given location, e.g. a crew member or passenger on board the ship, or belonging to third parties that could be affected by a ship accident. Usually IR is taken to be the risk of death and is determined for the maximally exposed individual. Individual Risk is person and location specific (MSC 83/INF.2). Individual risk is relative (see **Risk is relative**).

Personal risk: The term is used interchangeably with the individual risk with no reference to individual risk perception.

Societal risk: Average risk, in terms of fatalities, experienced by a whole group of people (e.g. crew, port employees, or society at large) exposed to an accident scenario. Usually Societal Risk is taken to be the risk of death and is typically expressed as FN-diagrams or Potential Loss of Life (PLL) (refer to section 2). Societal Risk is determined for all exposed, even if only once a year. Societal Risk is not person and location specific (MSC 83/INF.2). In FAROS, societal risk comprised such hazards as fire and flooding caused by either a ship-to-ship collision or ship grounding. The societal risk combines the frequency (or probability) of a hazard and its consequences in terms of loss of life (MSC 83/INF.2). Societal risk is relative (see **Risk is relative**).

Total risk: The aggregated level of *risk contributions* from various hazards: fire, flooding, occupational accidents during normal operation, etc. The total risk is relative (see **Risk is relative**).

Risk contribution: An integral part of the total risk and it is linked to a specific hazard such as fire, flooding, occupational accident etc. A risk contribution is relative (see **Risk is relative**).

Risk is relative: throughout this text, the referred and displayed risk values are not absolute but always relative to some baseline design. This is due to the fact that no complete design information is available at concept design and the absolute risk value cannot be calculated confidently.

EEDI: Energy Efficiency Design Index, as per IMO MEPC 65/4/4.

NPV: Net Present Value.

3 Introduction and project objectives

Over the last decades, the reliability of onboard technology has increased dramatically. However, human reliability has not been improving at the same pace and, consequently, has become the primary cause of maritime accidents. There are two basic, complimentary approaches to human error: person and system approaches. The person approach focuses on the errors of individuals, blaming them for forgetfulness, inattention, or moral weakness. The FAROS project adopted the system approach which concentrates on the conditions under which individuals work and tries to build defences to avert errors or mitigate their effects. Human errors are seen as consequences rather than causes, with their origins rooted in ship design on both meso (i.e., deck layout, arrangement of equipment and accessibility) and macro levels (i.e., hull and structural arrangement determining levels of ship motions, whole body vibration, and noise).

Design related factors that affect human performance are referred to in FAROS as global design factors (GDFs) or performance shaping factors. Based on the existing literature and anecdotal evidence, GDFs are assumed to potentially contribute to risks associated with such hazards as collision, grounding, fire and personal injuries (occupational accidents). Specific performance-shaping factors used in FAROS are: ship Motion (motion-induced sickness (MIS) and motion induced interruption (MII)), noise, full body vibration, deck layout, and equipment arrangement and accessibility (DLEAA).

The concept of maritime risk adopted includes its two contributions: societal risk and individual (or personal) risk, as defined in the guidelines on Formal Safety Assessment by IMO. Societal risk is the average risk, in terms of fatalities, experienced by a whole group of people (e.g. crew, port employees, or society at large) exposed to an accident scenario. Societal risk is taken to be the risk of death and is typically expressed as Potential Loss of Life (PLL). Societal Risk is determined for the all exposed, even if only once a year. Societal risk is not person and location specific. In FAROS, societal risk comprised such hazards as fire and flooding caused by either a ship-to-ship collision or ship grounding. The societal risk combines the frequency (or probability) of a hazard and its consequences in terms of loss of life. Individual risk is the risk of death, injury and ill health as experienced by an individual at a given location, e.g. a crew member or passenger on board the ship, or belonging to third parties that could be affected by a ship accident. Usually IR is taken to be the risk of death and is determined for the maximally exposed individual. Individual risk is person and location specific.

The project's ultimate objective has been to improve the conditions under which crew works by improving human reliability (HR) and mitigating consequences of its degradation. This objective was achieved through quantification and integration of HR into risk-based ship design by means of risk models. The risk was then calculated along with other more conventional performance measures and used to rank design alternatives based on the multi-disciplinary performance.

The technical research programme was structured into four work-packages (WPs) focusing on individual areas essential to achieve the ultimate objective. Specific objectives in the WPs were:

- Comprehensive literature review on human (crew) performance affected by ship motions, noise, whole body vibration, deck layout and arrangement of equipment and accessibility. The review involved the examination of scientific literature and current design rules and standards.
- Experiments conducted on bridge simulators and machinery spaces simulated in Virtual Reality. The former experiments were aimed to address the navigational human errors, whereas the latter addressed the errors leading to occupational accidents and safety the vessel as a whole (i.e. the interaction between deck layout and safe performance of crew tasks).
- Development of individual and societal risk models with the human error integrated. The risk models were used in risk-based design to discriminate different design alternatives on the compartment and ship levels, and may also be used in cost-benefit assessment of risk control measures.
- Risk-based design of crude oil tanker and Ro-Ro passenger ships. This WP used the knowledge generated and tools developed in the preceding WPs to arrive at design improvements. Specifically, the risk levels of the baseline designs were to be improved cost effectively, ensuring safety for crew members and the entire ship.
- The non-technical objectives included project dissemination activities, preparation of an exploitation plan, and submission of main project results to International Maritime Organisation (IMO) to inform the process of rule-making.

The following sections address all these objectives in detail. The final section recaps and concludes the report.

4 Summary of results

4.1 Comprehensive literature review

Current design rules and international standards specify maximum allowable limits on noise, vibration and motion levels on-board vessels [4–6]. These limits assume that exposure above these levels would have detrimental effect on both physiological and cognitive performance of crew members. The extensive literature review showed that some design standards and requirements are indeed linked to physiological functions, for example, walking and how GDF exposure impacts the probability of being knocked off your feet and sea sickness [4]. Therefore we can say, with some certainty, that some basic physiological performance of crew members can be improved by the adoption of the some content of design standards.

However, no evidence was found to support the assumption that safety critical cognitive functions (working memory, comprehending and producing language, calculating, reasoning, problem solving etc.) were considered when maximum allowable limits on noise, vibration and motion levels were defined, although such cognitive functions have been found to be linked to the human error in maritime accidents [7,8]. These limits seem arbitrary in this respect and hence would not necessarily have a positive effect on the performance of safety critical vessel tasks. This observation is further reinforced by the fact that maximum limits on noise and whole body vibration significantly vary from class to class (e.g., noise limits in the wheelhouse range from 55dB acc. ABS to 65 dB acc. LR) [5]. As highlighted by the bridge simulation experiments performed within the project (see Section 4.5), evidence can be developed to validate the limits set through the use of appropriate experimental techniques.

Probabilistic risk analysis has been one of the cornerstones of the project implementation. This analysis allows dealing with uncertainty about frequencies of accidents, their consequences and other related aspects. However, one has to have sufficient knowledge, ideally in terms of quantitative data, about the hazards in question and their preconditions. The consortium found that there is detrimental lack of detailed statistical data about maritime accidents, the data that would also describe the role of human factors in particular. To rectify this situation, a typical practice today is to borrow the data from other industries (e.g., OREDA database from the offshore industry or NARA from the nuclear power industry), which is generally inappropriate.

Recommendations

As the FAROS deliverables contain a comprehensive summary of the available literature on the cognitive effects of GDF exposure, they provide an opportunity to begin a review of industry design standards for noise, whole body vibration and ship motion. Funding further research is necessary to ensure that appropriate limits can be set for the marine (and other) industries to minimise harm and maximise human performance.

Regarding the data paucity problem:

- Detailed reporting of accidents, incidents, and near misses has to be significantly improved and the reported data are made appropriate for risk analysis. The underreporting and poor reporting is a well-known issue (MSC 93/15/2).
- Basic research focusing on factors shaping cognitive human performance in the maritime domain has to be undertaken. This is necessary to advance the incomplete knowledge and enable to upgrade the design and other tools that apply it.

4.2 Effect of GDFs on human performance

In FAROS, the main challenge was that data on the specific GDF effects of ship motion (with the exception of Motion Induced Interruption[1]), noise, vibration and DLEAA on human performance are sparse. Furthermore, in many (but not all) cases these data was generated under very specific, often non-marine, conditions, raising as yet unanswered questions about their applicability to the maritime domain. However, the data that exists in the literature shows that there is certainly evidence for GDFs having some effect on human performance. The direct effects of GDF exposure on human performance tend to be weak, whereas secondary effects acting through another mechanism (e.g. fatigue, Motion Induced Sickness – MIS) tend to be stronger and more pervasive (see Figure 1 as an example describing the effects of exposure to ship motion). In addition, a given level of exposure to GDFs of a certain intensity or duration may not affect all individuals equally; for example, while a given frequency and amplitude of ship motion may be generally MIS-inducing, individuals experiences may range from significant nausea to no negative effects whatsoever, depending on their underlying susceptibility to MIS and the degree to which they have acclimatised.

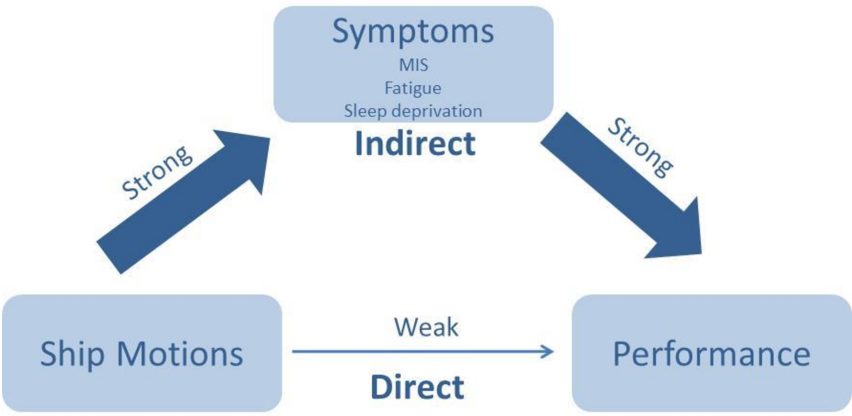


Figure 1: Relationship of ship motion to human performance (Colwell 2005).

Moreover, with the possible exception of secondary effects on human performance caused by fatigue (attributable to sleep disruption), a holistic view could not readily be derived from the individual study findings than provided inputs into the project.

The project found evidence that the effects of the GDFs could be represented as stressors acting people's attention management system. The approach that emerged combines the principles of the Dynamic Adaptability Model (DAM [16]), the Cognitive Control Model (CCM [17]), and the Malleable Attentional Resources Theory (MART [18]). Taken together, these theories describe a mechanism that accounts for the impact of what Hancock & Warm [16] describe as a 'trinity of stress' on human performance, based on the principles of attention management. When stressors overwhelm the

[1] MII is well understood and is a physical phenomenon related to loss of balance motor control events due to ship motion. While ship motion can affect task performance through MII, it does in the same way as DLEAA by increasing task demands (i.e. making the task more difficult) but does not affect the underlying cognitive capabilities of the human.

attention management system's ability to adapt, attention may be inappropriately or ineffectively directed, and contributing to the generation of errors and subsequent unwanted outcomes.

Where statistically significant results were generated in the experiments regarding the effects of exposure to noise on navigational performance, they could be interpreted using the model of attention management above.

Recommendations

Attention management may be a useful way to understand how the many characteristics of vessel design (e.g., the GDFs investigated within FAROS) interact with human performance and serve to enhance or degrade human performance by acting as stressors that may exceed individual's abilities to adapt. A great deal more research is required to validate the integrated attention management based CCM, DAM and MART models. Further work is also required to establish its utility of this approach when applied to human performance in the marine environment and extending the experimental work begun in the FAROS project.

4.3 Development of risk models

The accumulated knowledge about the factors affecting crew performance allowed developing risk models, for RoPax and tanker ships, with the human error in mind. The individual risk model [3] linked GDFs with probabilities of injury and death (
Figure 2). This unique model introduces the generic Human Reliability model, which is then used in other risk models, and focuses on such incident types as slips, trips, falls, falls from height, and hit by moving objects, and considers unsafe behaviour as the main antecedent condition of accidents.

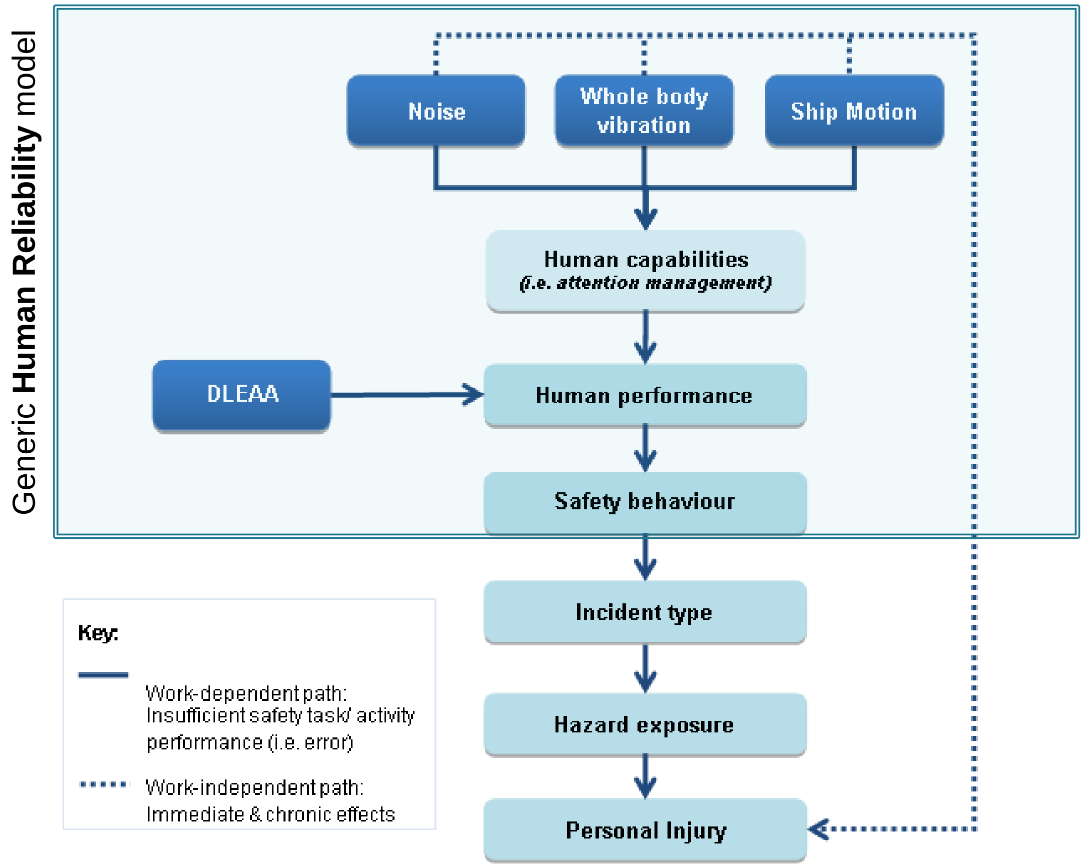


Figure 2: Work-dependent and work-independent causal paths describing the effect of GDF on human performance and safety behaviour, and the occurrence of personal injury (adopted from [3]).

The collision and grounding risk model [9] comprises probability of collision/grounding event and its consequences. The model is based on the most recent casualty statistics and expert estimates of incident encounters on preselected routes. The consequence part of the model is underpinned by recent research work on damage stability.

The work on the fire risk model [10] was focused on fire inception probability in different onboard spaces. The development was based on causality statistics, fire accident investigation reports, empirical data elicited from marine engineers (Figure 3 and Figure 4), etc. The work resulted in probabilistic ignition models for engine rooms, galley, cabins, electrical fault caused ignitions, etc. The risk models were then integrated into the overall risk model that deals hazards emerging in both normal and emergency situations. This makes the risk assessment comprehensive and useful at the concept design stage where distinct design alternatives are assessed on the ship level.

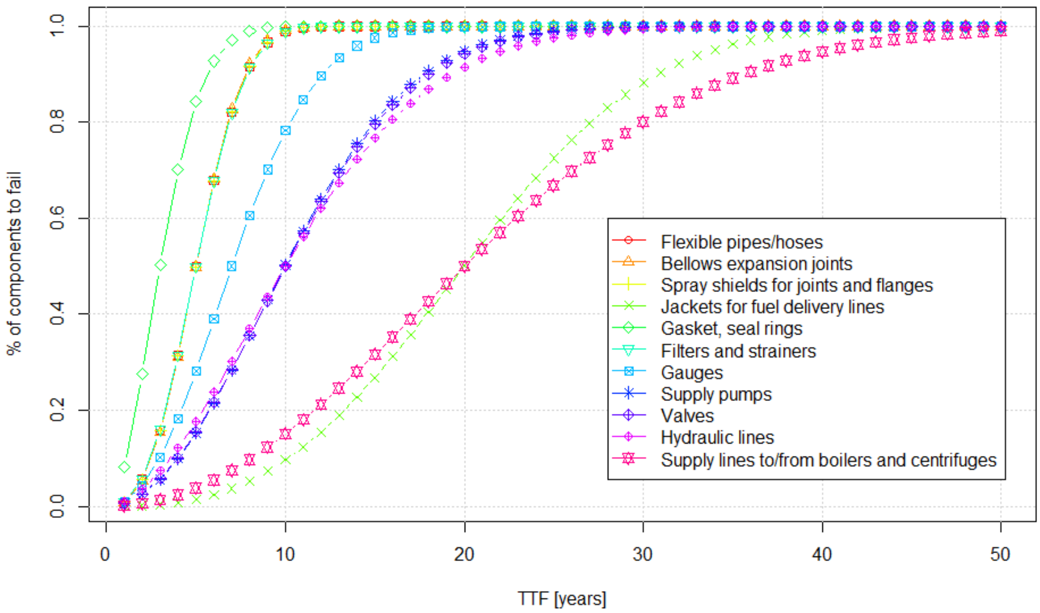


Figure 3: Cumulative probability distributions for Time to Failure (TTF) for components liable to leaking flammable oil (4 strokes machinery).

Figure 4: Periodicity of the damage / leak probability of any component group (4 strokes machinery). The peak period is around 8 years.

4.4 Experiments in virtual machinery spaces with marine engineers

Nineteen Engineers participated in a series of short scenarios using CAVE and head-mounted display virtual reality (VR) platforms [11] (earlier report [12]). The experiments were designed to investigate the effect of deck layout of RoPax ships on personal (crew members only) and societal risks. The personal risk was associated with personal injuries by watertight (WT) doors and other hazardous objectives during normal operation (Figure 5). The societal risk was associate with the possibility of open WT doors – as a result of misuse of SOLAS regulations II-1/22 (paragraph 4) which permits open WT doors under special circumstances – during emergency situations such as water ingress following a collision or grounding event. The open WT doors during such emergency situations jeopardise ship's damage stability and often results in shorter time to capsize and greater life loss.

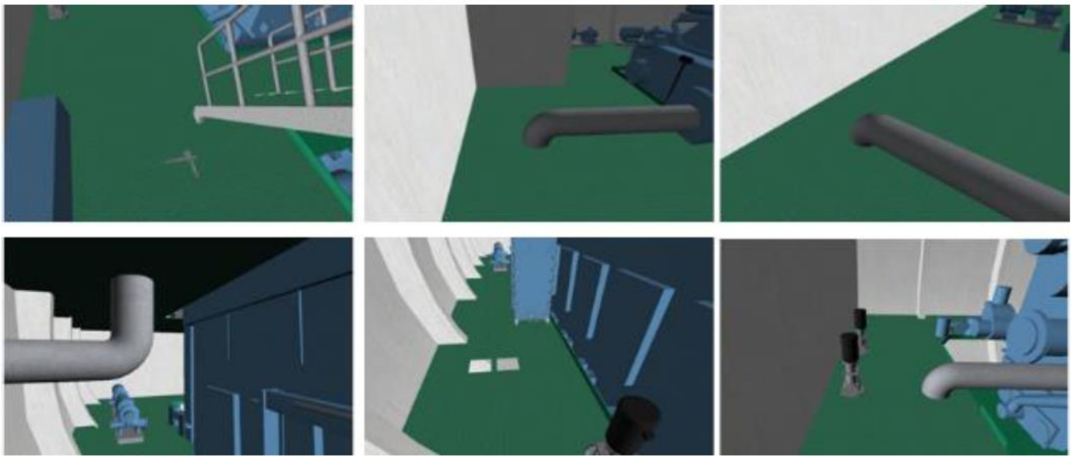


Figure 5: Simulated hazards: 8 hazards in the engine room, 4 pipes (3 on the floor and one overhead), two missing plates on the floor and two tools lying on the floor.

Naturalistic scenarios were trialled in relation to watertight doors, compartment layout around machinery spaces and passage width in the engine room, in conditions of low and high time pressure. The key findings are:

- It was hypothesised that the frequency of doors crossing would be inversely related to the number of doors closed. This prediction was confirmed by the results of the analysis, which also showed that a reduced number of doors is associated with a lower risk of a single door being left open, particularly during routine operations. This indicate that societal risks deriving from unsafe behaviours related to closure of WT doors can be reduced by optimising deck layout in order to minimise the frequency of doors to be crossed.
- It was further hypothesised that participants would pass through doors that were less fully opened to a greater degree when configurations resulted in higher frequency door crossings, particularly when doors were in automatic door closure mode. These predictions were confirmed by the results of the statistical analyses, which showed that the doors in spaces that are crossed very frequently are more likely to be passed when the door is not fully opened, and that unsafe crossing are more likely with automatic than with manual doors. Therefore, mariner personal safety may be increased by designing of Main Engine room and auxiliary machinery rooms in a way that is conducive to low frequency door crossings.
- Low frequency door crossing scenarios were also predicted to be associated with a faster navigation time to complete the tasks. This hypothesis was also fully supported by the experimental results, which showed that low frequency door crossing scenarios are indeed associated with faster navigation time to complete the task, even when the time taken to operate the doors is removed from total route time. This confirm previous findings from WP4 [12] indicating that the time saving would be mainly due to a reduced walking distance in the low doors frequency deck design.

- It was hypothesized that unsafe behaviours would be observed more frequently in high time pressure conditions that in low time pressure ones. The results of the WTD scenarios suggest that behaviours concerning personal and societal safety might be differently influenced by time pressure. On the one hand, and conversely to what we had predicted, it was found that the percentage of doors left open was *lower* in high time pressure scenarios than in low time pressure ones. It is possible that this effect might be due to an increased risk perception triggered by the description of the high time pressure scenario, which in turn might have prompted participants to pay more attention to safety procedures. On the other hand, in high time pressure scenarios a higher frequency of unsafe crossing was observed.
- Finally, it was hypothesised that increased space in the engine room would be associated with reduced proximity to hazardous objects and with a faster navigation time around the space where objects have been noticed. The first part of the hypothesis was fully supported by the patterns and by the results of the statistical analysis, which showed generic linear relationships between increased passage width and reduced collisions as well as increased proximity to hazardous objects. There was no evidence, however, to support the prediction that route time would be influenced by passage width.

<u>Recommendations</u>

In summary and as far as safety is concerned, the above findings state that the layout of machinery spaces has to be designed in the context of anticipated tasks within and between the affected spaces. Although it alludes to the existing regulations such as Regulation 13 of SOLAS (Chapter II-1 Part B-2), MSC/Circ.834 [13], etc., the conducted parametric study has confirmed the sensitivity of specific design parameters to personal and societal risks.

Therefore, the risks can be reduced by arranging machinery compartments to:

- Reduce the frequency of crossing watertight doors (i.e., reduce the number of WTD or crew tasks that require to use them, or both),
- Shorten the walking distance between commonly used compartments (e.g., position the frequently accessed spaces vertically rather than horizontally across different WT compartments, move such spaces closer to each other), and
- Increase the passage width in areas close to potentially hazardous objects.

4.5 Experiments on bridge simulators with deck officers

Experiments were conducted at the bridge simulator located in HSW Warnemünde to investigate the effects of noise and ship motion on navigation performance [14] (earlier studies in [15]) associating it with the probability of collision or grounding and hence the societal risk.

The first set of experiments yielded no significant effects of noise or of ship motion [15]. However, the experimental manipulation of ship motion in the simulator was limited to visual presentation of wave patterns given that the floor in the simulator is fixed. For the second set of experiments, therefore, it was decided to manipulate noise further given that it could be simulated more realistically than could vessel motion [14].

The primary objective of the second experiment was to assess the effect of noise on human performance in a simulated navigation task, as measured by the passing distance to a target ship or a grounding risk, deviation from the required track, and speed of reaction to on-board alarms within High Risk Events (such as rudder failure and radar failure) occurring during a simulated voyage.

The experiment demonstrated that the effects of noise were marginal but occasionally statistically significant. In all cases where there was an effect of noise, it had the effect of impairing mariner performance. Mariners' overall performance of the navigation task, as measured by instructor ratings, was impaired by noise. Mariners' performance of some tasks related to the High Risk events (e.g. reducing engine speed in response to a rudder failure) was significantly impaired under conditions of noise, as measured by slower responses and responses of less good quality. Finally it was observed that during the early scenarios within the sequence, noise was having a significant adverse effect on navigation performance, as measured by the distance from the target vessel or grounding risk. These findings suggest that mariners may cope quite well with extraneous noise when faced with less complex tasks, but that noise may impair their response to more difficult and/or surprising situations.

Recommendations

The maximum noise level for navigation spaces defined in Resolution MSC.337(91) [6] has been supported. However, considering the effect of stressors on (team) decision making other factors together with the existing noise might combine exceeding a limit for optimal decision making. Therefore it is recommended that the maximum noise level for navigation spaces is kept as low as possible.

Demanding scenarios with adverse external factors (noise, vibration etc.) were found useful by the mariners and are recommended to become a compulsory element in bridge resource management training.

The developed evaluation system using (semi-)automatic scoring was found applicable to the scenarios used. It is recommended to extend this scoring using weighted average and normalised values across different training scenarios to compare performances of mariners in a manner that is instructor and site independent.

4.6 Utility of probabilistic approaches to modelling human factors

The development of the risk models in FAROS was based on a probabilistic approach, specifically using Bayesian Belief networks (BBN) to represent causal relationships between factors affecting the risk. These factors were modelled as random variables (i.e. nodes in BBN) representing GDFs, the effect of GDFs on mariners' behaviour and human error. Human Reliability Analysis (HRA) techniques, specifically HEART and NARA, were used to quantify the probability of human error. HRA techniques come from the nuclear industry and allow to integrate human performance into probabilistic risk assessment. Main features of HEART and NARA are as follows:

- A database with human error probabilities (HEPs) for different type of tasks performed by humans; HEPs provided baseline probability values in the BBN when no effect of GDF was present.
- A table listing human Performance Shaping Factors (PSFs) that can increase, or decrease, the probability of human error. PSFs were used to represent GDFs by selecting the most closest (according to its definition) PSFs from the table. The baseline probabilities where then modified (normally increased) to reflect the presence of PSFs. In this way, it was possible to represent and quantify the effect of GDFs on normal (baseline) human performance.

The crux of the probabilistic modelling was the quantification of "insufficient human performance". Because, in our understanding, this is the essential factor in the causal chain towards personal and societal risks onboard. Once this random variable had been modelled, the further factors down the causal chain (e.g. personal injury and its type) were relatively easy to implement.

Whilst already listed as an option in IMO guidelines on Formal Safety Assessment (MSC 83/INF.2), the joint use of HRA techniques and BBN in FAROS is a promising approach for the maritime industry. The obtained risk models can be considered as the foundation for further modelling attempts, which are likely to be most beneficial if performed at a lower level of granularity.

Although some cases of the human error were modelled taking advantage of the existing databases (HEART, NARA etc.), the overall modelling work was significantly impaired by the lack of scientific and industry data that would have been useful in the project. Appropriate data on the nature of whole body vibration effects on human performance and accident analyses identifying the role of human factors are examples. Probabilistic approaches to risk modelling require that relationships between factors can be represented numerically as a probability. In FAROS we found that the body of knowledge we needed to populate probabilistic input to the project was incomplete in terms of depth or breadth, absent, or inappropriate to convert to probabilities. While modelling techniques are available to handle uncertainty, the issue in FAROS was one of meta-uncertainty (aka deep uncertainty [19]), i.e. we know we have uncertainty in the models, but we do not know how much.

If probabilistic approaches modelling complex human (and other) interactions are to have utility in the marine domain, significantly more scientific research is required, better data about factors affecting risk needs to be captured, and better analyses need to be performed to allow specific questions about the relationship between human performance and outcomes to be answered.

Recommendations

Industry-wide systematic, detailed reporting of accidents, incidents, near misses etc. has to be implemented. If the notorious issue of underreporting [20,21] is properly addressed, one can expect a significant reduction in maritime risk. In addition, reports from research, accident investigation and other undertakings various that contain qualitative and quantitative information should be made public, and found in centralised locations, whenever possible.

Vulnerability analysis: Before the issue of deep uncertainty is resolved, the use of probabilistic approaches with subjectively assumed or borrowed probabilities from other domains (e.g. nuclear, offshore) may mislead the decision making. An alternative approach in this situation is to use some simulation models of crew members performing specific tasks under various operational conditions. For example, the existing, agent-based, evacuation software (e.g. [22]), which is already applied to advanced evacuation analysis according to IMO guidelines MSC.1/Circ.1238, can be tailored for this purpose. The software would then be run over all plausible scenarios (as many as available computation resources allow) to identify specific conditions when the misfortune (e.g., unsafe action potentially leading to personal injury) definitely happens. This kind of analysis is referred to as a vulnerability analysis [23–25] and could be used for making robust safety policies under deep uncertainty.

Design criteria for minimal personal risk: Inference analysis with the personal risk model, pointed out specific input values for motions, noise, vibration and deck layout that lead to minimal risk value [3]. To achieve this effect, the following values should be attained at once:

- Heave frequency has to be within 0.5 – 0.7 Hz
- Heave acceleration RMS has not exceed 0.981 m/s2
- Lateral acceleration RMS has not exceed 1.177 m/s2
- Whole body vibration has not exceed 2 Hz
- Noise has not exceed 30 dB
- Effect of deck layout has to be negligible (explained in [3])

The above values can be used for ranking design alternatives at a design stage where there is enough design information to calculate the above values. The latter can also be done based on the risk models developed in FAROS, if the outcome is limited to the probability of an accident. Evaluation of further consequences may only increase the uncertainty of the models, due to the limited amount of design and operational information that a designer has at this stage of ship design process.

4.7 Risk-based design of tanker ships

The objectives of this design exercise were:

- Integration of the developed human factors risk models into risk-based concept design. The integration also involved other conventional performance assessment tools relevant to concept design.
- Optimisation of baseline tanker designs based on their risk, economy and environmental impact, with optimisation objectives being minimal total risk, maximal NPV and minimal EEDI, subject to various constraints.

The work involved two oil tanker baselines of Aframax and VLCC size. Detailed design specifications were provided by project partner, design office, Naval Architecture Progress [26]. The ships were assumed to operate on the route between Port Rashid (UAE) and Chiba (Japan). Design s|peeds and required annual number of trips were assumed to be known.

The re-design, or optimisation, process involved modifications to internal arrangements - to affect personal, flooding and fire risk contributions - and the hull shape, which changed the ship's behaviour in waves and consequently affected probability of grounding and collision. Additionally, the number of crew and payload capacity was subject to alteration. Such a comprehensive design exploration was aimed to investigate the benefits of the developments in the project, specifically the risk models and economic evaluation, and the degree of cost effective reduction in risk.

A total of 11 topological variants were developed from each of the two tanker baselines, and these are summarised in Table 1. For each of the 12 options (including the baseline), a total of 5 numerical variants in dimensions were examined. The topological options included radical changes such as relocating the superstructure and machinery to amidships and the use of Flettner rotors for wind-assisted propulsion, as shown in Figure 6.

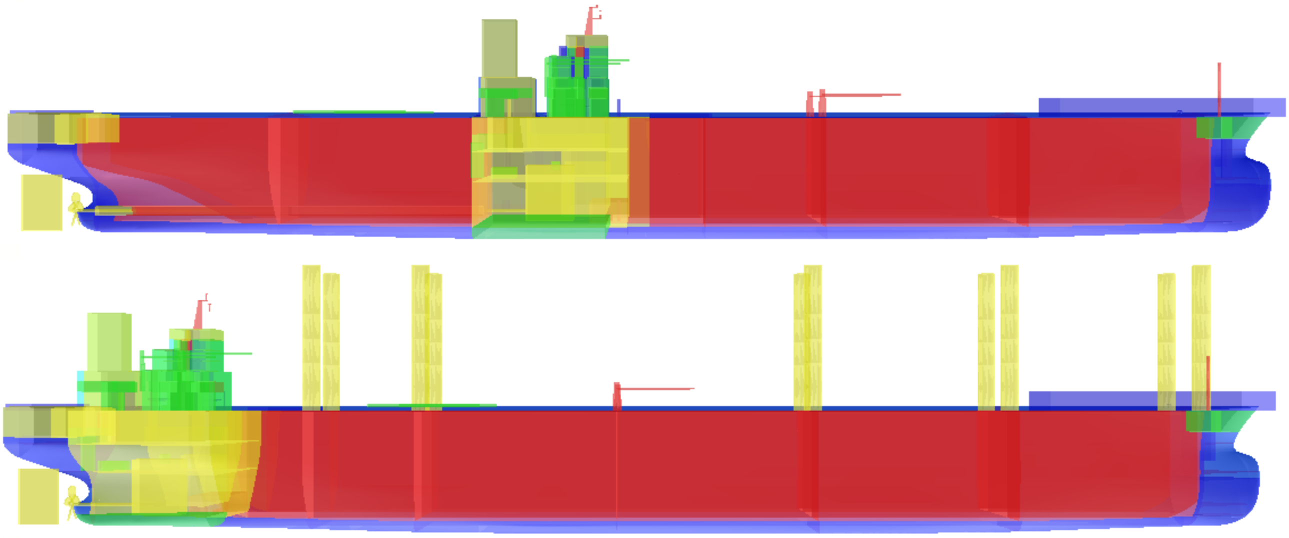


Figure 6: Radical tanker topological variants including amidships machinery (top) and Fletter rotor assistance (bottom)

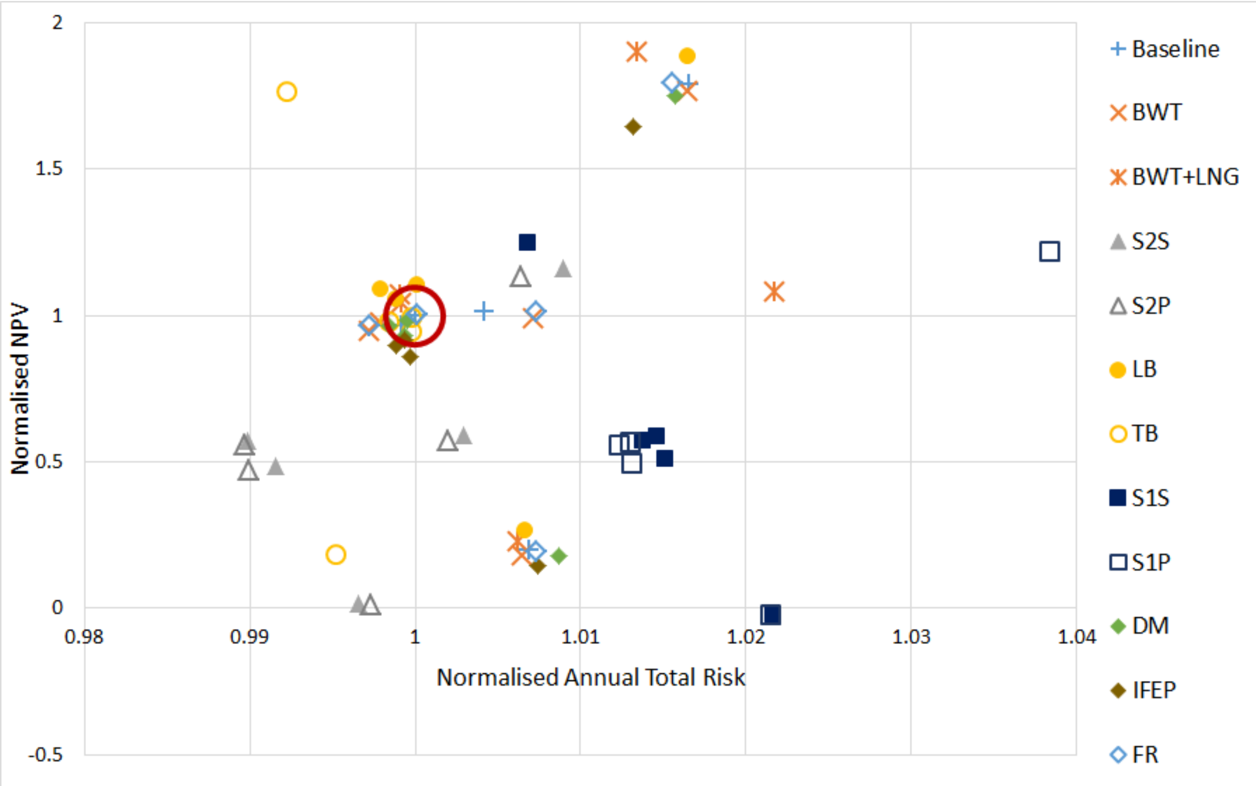
The main results and recommendations of this design exercise are summarised as follows.

Improved economic and environmental performance: Some design modifications produced significant benefits in both economic and environmental performance, compared to the baseline cargo ship designs, showing that for approximately equal risk, benefits can be achieved in other optimisation areas. The economic analysis showed that by assuming larger cargo availability, larger vessels have improved economic performance, as do alternative fuels (LNG) and the use of wind assistance (Flettner Rotors). These three options also improved the environmental performance, as measured by the EEDI. However, the larger ships suffered from increased environmental risk (in terms of oil outflow) due to larger cargo tanks, unless additional cargo subdivision was included. In terms of safety, it was assumed that future LNG fuelled ships will have demonstrated equivalent levels of risk to diesel fuelled vessels, mainly through the location of fuel tanks and detail design of ship systems. The cost implications of dedicated spaces to contain and protect LNG fuel storage were included in the calculations of overall ship costs, as these were based on the ships as modelled. Potential increases in UPC due to additional machinery systems may not have been fully captured, however, due to sparse and unreliable data, particularly when considering future mass-market systems.

Risk reduction potential in the concept design of tanker ships: Overall, the FAROS project succeeded in demonstrating the integration of some aspects of human factors into design, but as noted above, the FAROS project has revealed that integrating a *complete* assessment of human factors into a probabilistic ship design approach is difficult. This is primarily due to issues specific to the human factors domain (see Section 4.6), however, there are also considerations relating to the specific application to tanker ships. The most notable issue affecting tanker ships is that their layout is highly constrained by the desire to provide the largest possible tankage on a given displacement, with the subsequent compression of almost all working spaces into a small part of the vessel.

Sensitivity of risk models: Due to the tanker-specific issues described above, the risk variation amongst the tanker design options was insignificant, as shown in *Figure 7 and Figure 8 (see also* Table 1*).* The figures compare the NPV and total annual risk for each of the VLCC and Aframax variants, respectively, in both normal and worst-case sea conditions. These results have been normalised against the baseline design, which is highlighted by a large circle. A desirable design would have the highest NPV and lowest risk, so would be towards the upper left of these figures. For the both ship types, we can see that the majority of the options have lower NPVs than the baseline, and that most have higher risk. Those variants with significantly higher NPVs were always those with longer hullforms, allowing for greater cargo capacity. For the VLCC options, using LNG fuel and Flettner Rotors (to reduce propulsion fuel use) improved NPV slightly without changes to the hullform.

A significant conclusion that can readily be seen in the figures is that there was little scope to reduce risk by adopting any of the design options investigated – with a maximum of 3.5% reduction for an Aframax in the worst case sea conditions (which would rarely be encountered). Rather, most of the options produce small increases in risk. However, as the majority of the options lie within +/- 1% of the baseline, it could also be concluded that such changes to ship design could be considered as risk neutral, with the primary consideration being economics.



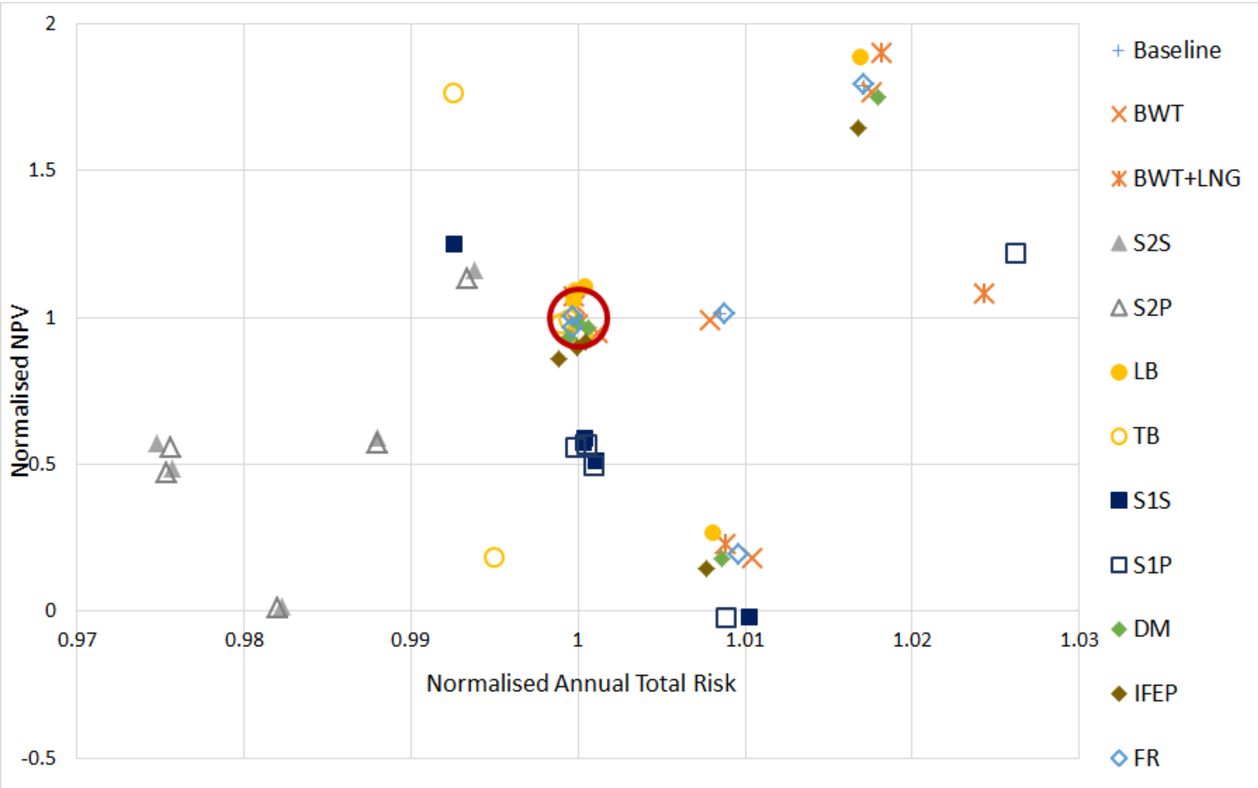
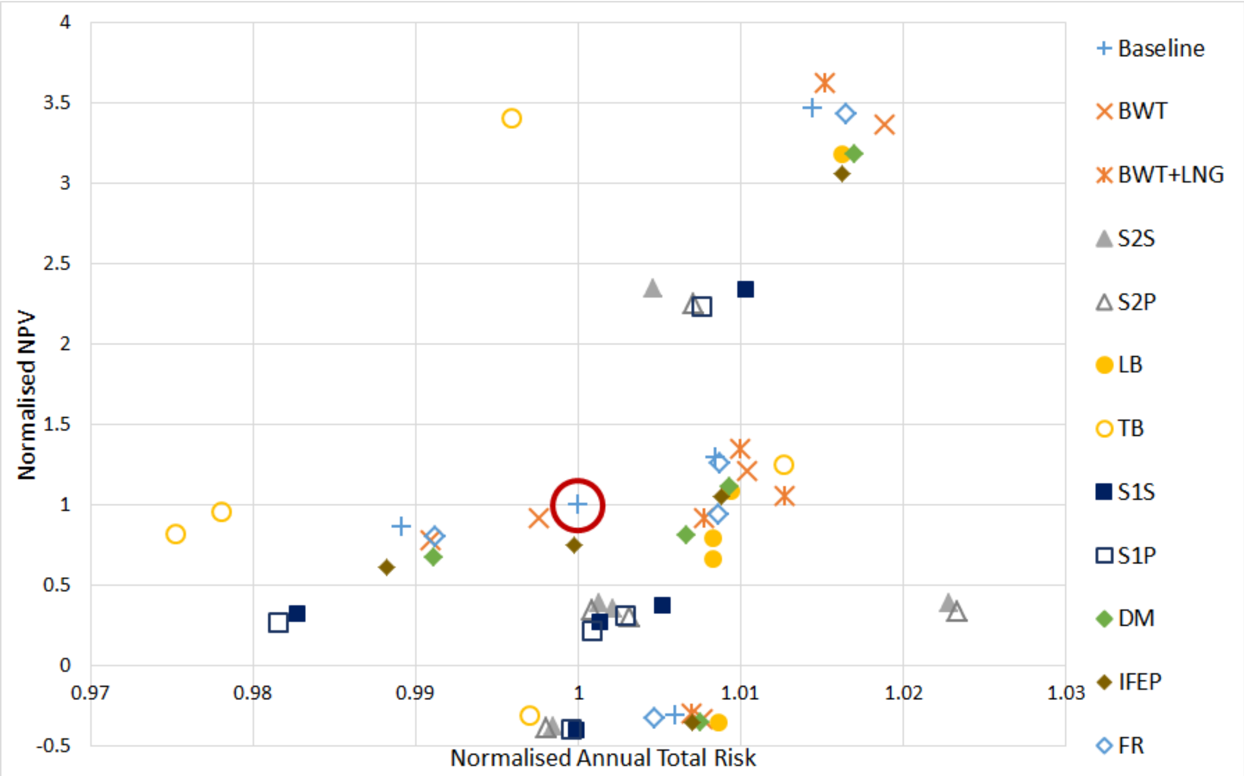


Figure 7: Normalised NPV against normalised total risk for all VLCC variants in average (top) and worst (bottom) sea conditions



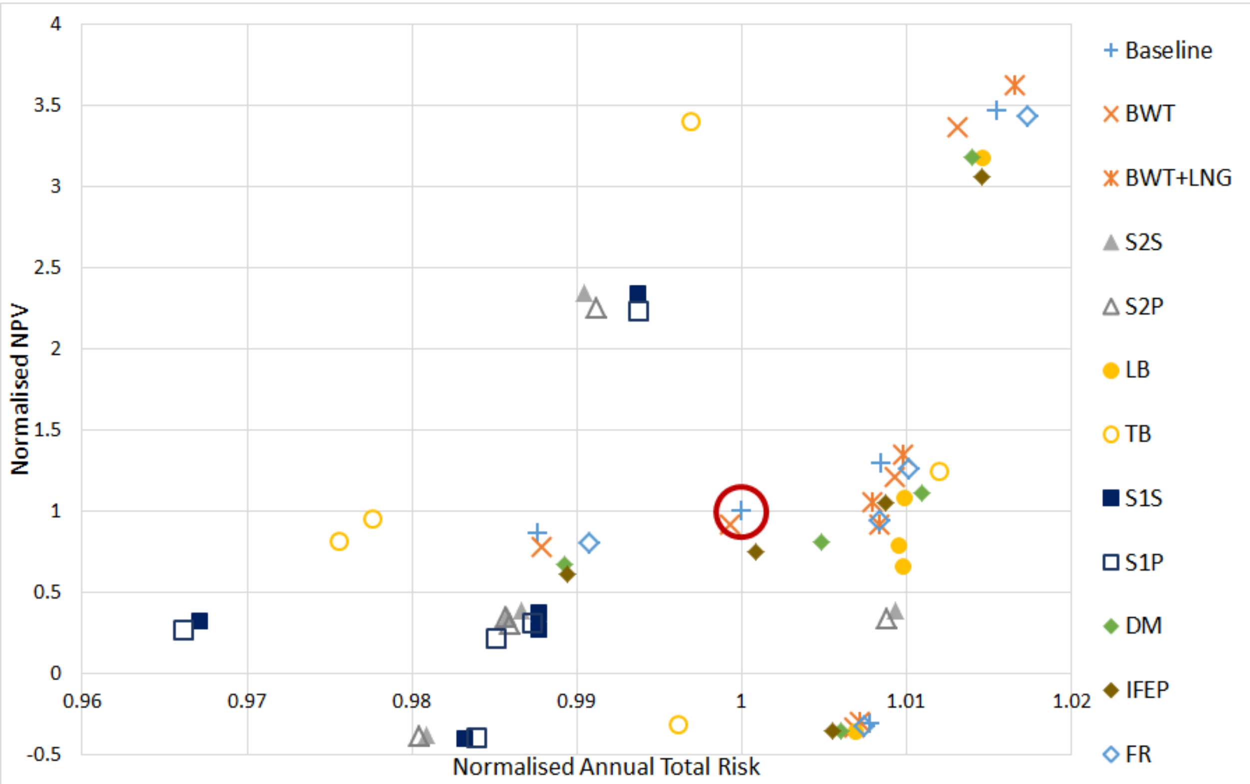


Figure 8: Normalised NPV against normalised total risk for all Aframax variants in average (top) and worst (bottom) sea conditions

Table 1: Explanation of abbreviations used in Figure 7 and Figure 8

Abbreviation	Design Variant Description
Baseline	Baseline VLCC/Aframax vessel variant
BWT	Variants with Ballast Water Treatment (BWT) units
BWT+LNG	Variants with BWT units and LNG capable propulsion systems
S2S	Variants with working spaces shifted forward by two watertight compartments, mechanical transmission
S2P	Variants with working spaces shifted forward by two watertight compartments, electrical transmission
LB	VLCC variant with one longitudinal watertight bulkhead removed; Aframax vessel variant with one longitudinal watertight bulkhead added
TB	Variants with one transverse watertight bulkhead added
S1S	Variants with working spaces shifted forward by one watertight compartment, mechanical transmission
S1P	Variants with working spaces shifted forward by one watertight compartment, electrical transmission
DM	Variants with duplicated propulsion machinery
IFEP	Variants with Integrated Full Electric Propulsion (IFEP) systems
FR	Variants with Flettner rotors for wind assisted propulsion

Recommendations

Sensitivity of risk models: The scope of the risk models has to be expanded to include, for example, other working spaces such as pump rooms, auxiliary machinery spaces, cargo holds, etc. This may increase sensitivity and utility of the risk models to design changes at the concept design stage.

Shift to the detailed design stages: The sensitivity of the current risk models would be much greater at later design stages (e.g. detailed design) for tanker ships, as extra occupational details become available as design progresses. This is primarily due to the properties of the developed risk models, specifically the qualitative, expert judgement-based assessment of deck layouts that can take into account various levels of detail and assess their impact on risk. Hence, the recommendation is to apply the developed risk models at later design stages as well.

Include other ship types: A similar recommendation would be the expansion of research to consider other cargo vessels such as container ships, with particular consideration of cargo loading and unloading operations, and also the more radical topologies such as wind assistance that were considered in the FAROS project. Given that these are likely to see increased use in cargo ships due to emissions regulation, the assessment of additional technologies, such as kites and sails, will be important. Similarly, it may be the case that VR experiments simulating spaces unique to cargo ships may produce more applicable results than those in the FAROS project, which modelled Ro-Ro machinery spaces.

4.8 Risk-based design of RoPax ships

The objectives of this design exercise were:

- Integration of the developed risk models in risk-based concept design (i.e. human factors in design). The integration also involved other conventional performance assessment tools relevant to concept design.
- Optimisation of baseline designs based on their risk, economy and environmental impact, with optimisation objectives being minimal total risk, maximal NPV, minimal EEDI, subject to various constraints.

The work involved two RoPax baselines (1,925 and 5,746 DWT) of which specifications were provided by project partner, design office, Naval Architecture Progress [26]. The small RoPax was assumed to operate in the North Sea, connecting Holland and UK, whereas the big RoPax was to operate in the Baltic Sea, connecting Estonia and Sweden. Design speeds and required annual number of trips were assumed to be known.

The re-design, or optimisation, process involved modifications to internal arrangements—to affect personal, flooding and fire risk contributions—and the hull shape, which changed ship's behaviour in waves and consequently affected probability of grounding and collision (Figure 9 to Figure 10). Additionally, the number of passengers, crew and payload capacity was subject to alteration. Such a comprehensive design exploration was aimed to investigate the benefits of the developments in the project, namely the risk models and economic evaluation, and the degree of cost effective reduction in risk.

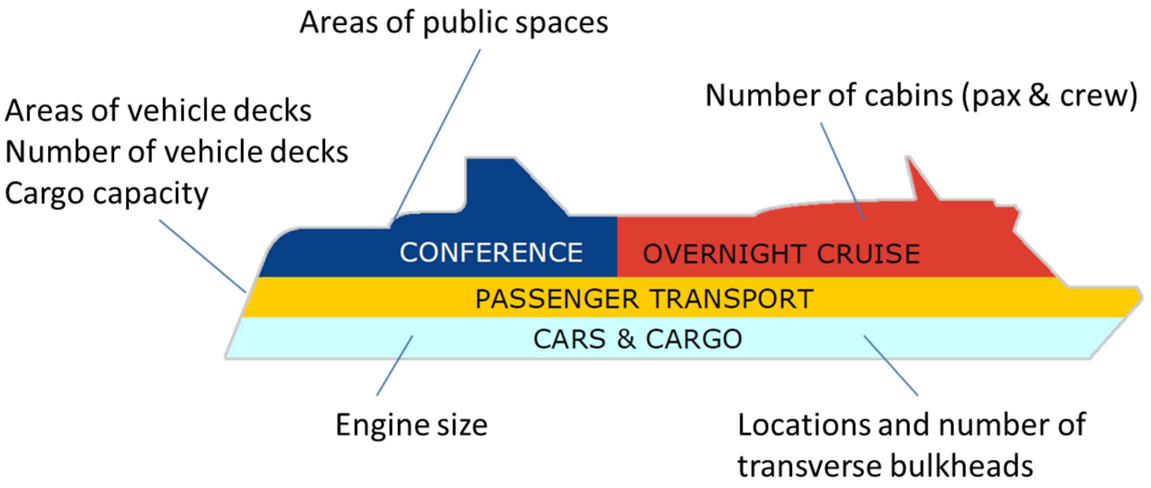


Figure 9: Ship design aspects subjected to variation.

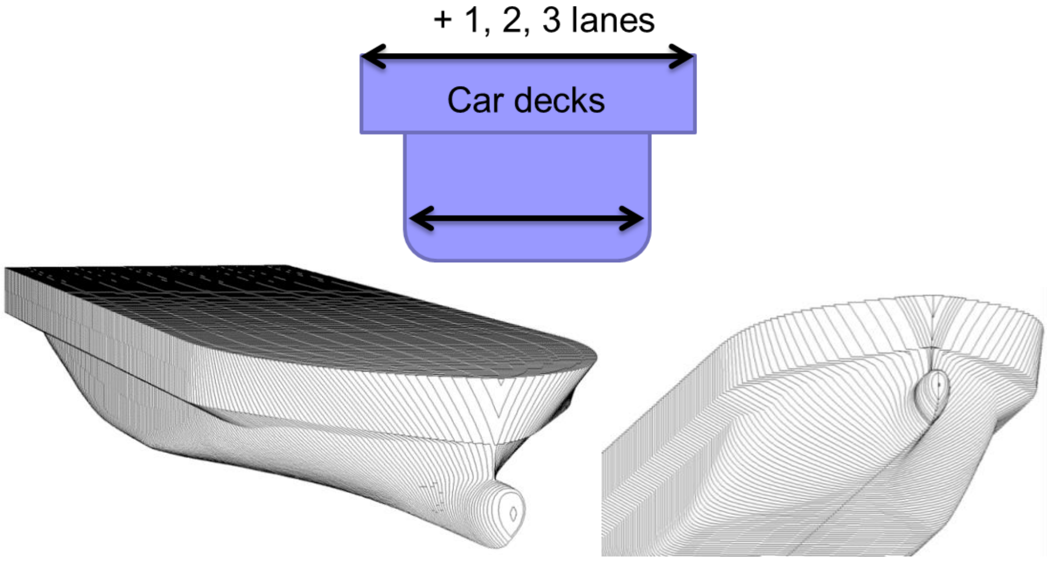


Figure 10: UFO hull shape (used for the large RoPax only).

The following graphs show the high-level results for the small RoPax. The results for the large RoPax are analogous and hence omitted. Specifically, Figure 11 shows all generated design variations with respect to their total risk, NPV and EEDI. The rest of graphs show differences between the three selected, cost effective design alternatives.

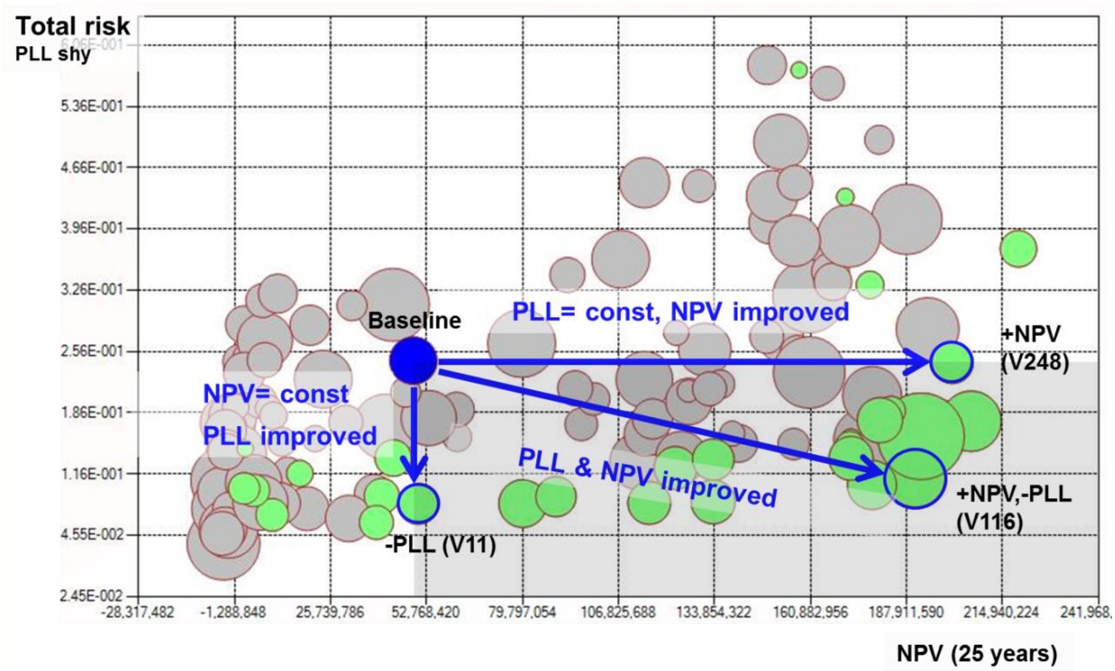


Figure 11: Alternative design variations to the baseline (blue-shaded circle) with respect to total risk (PLL per ship year), NPV and EEDI (corresponds to the circle's size). The green circles indicate dominant variations, i.e. Pareto efficient. Three cost efficient alternatives are selected: (-PLL) – mainly improvement in risk only, (+NPV, -PLL) - improvement in both NPV and PLL, and (+NPV) – improvement in NPV only. The results are shown for the small RoPax.

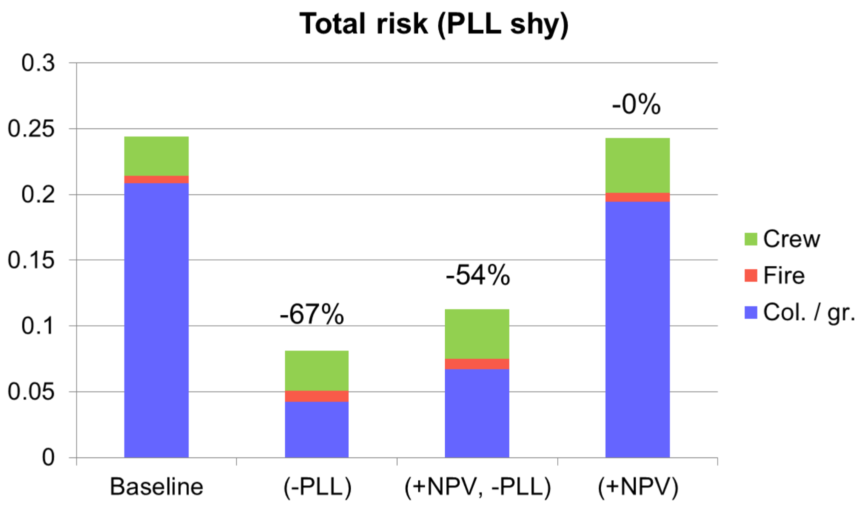


Figure 12: Comparison of total contributions to total risk between the baseline and the three alternatives (see Figure 11). The results are shown for the small RoPax.

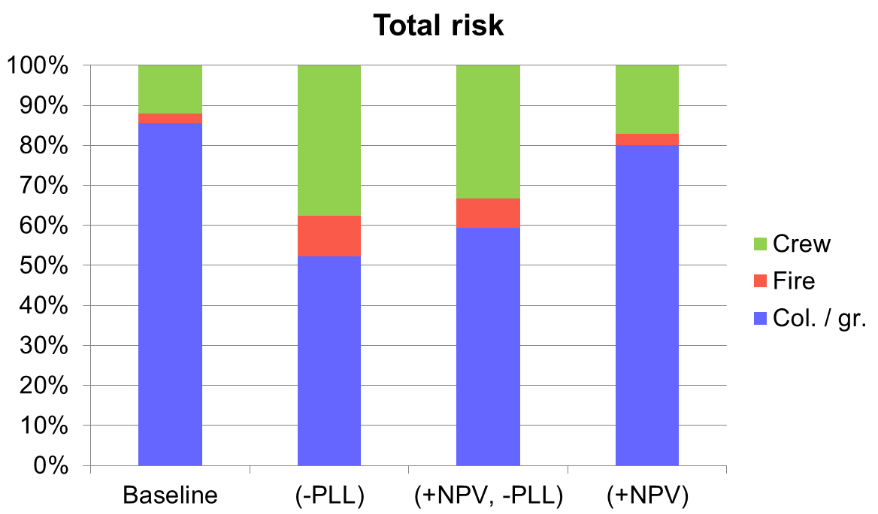


Figure 13: Comparison of percentage contributions to total risk between the baseline and the three alternatives (see Figure 11). The results are shown for the small RoPax.

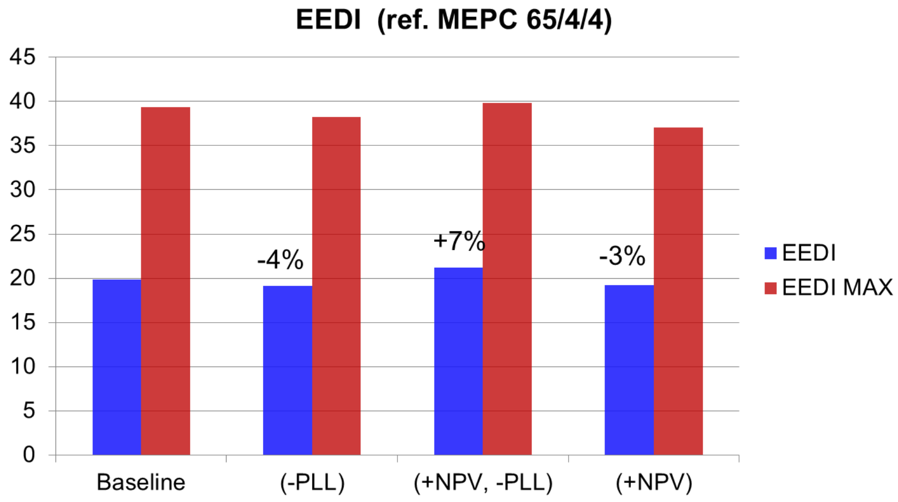


Figure 14: Comparison of absolute EEDI values between the baseline and the three alternatives (see Figure 11). The results are shown for the small RoPax and they are far to exceeding the threshold.

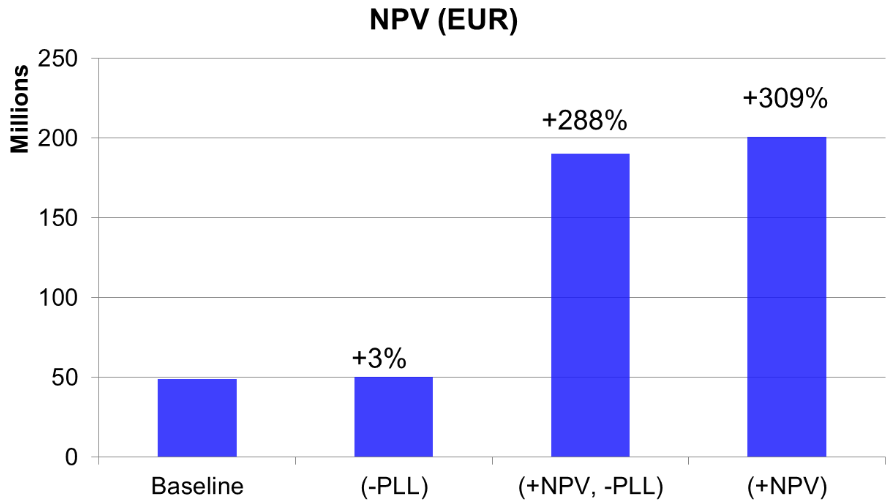


Figure 15: Comparison of absolute NPV values between the baseline and the three alternatives (see Figure 11). The results are shown for the small RoPax.

The summary of the main results is given as follows.

Cost effectiveness risk reduction: The presence of multi-disciplinary performance information—risk, economy and environmental impact—for each design variation, enabled to make cost effective design choices in terms of risk reduction. As Figure 11 shows, the design variations that fall within the IV quadrant (grey-shaded) represent cost effective design improvements. Formally, a design modification is cost effectiveness if either of the two conditions is satisfied:

CE condition 1[2]*:*

$$\text{Risk} \leq \text{Baseline risk}$$
$$\text{Net economic benefit} > \text{Baseline net economic benefit}$$

CE condition 2:

$$\text{Risk} < \text{Baseline risk}$$
$$\text{Net economic benefit} \geq \text{Baseline net economic benefit}$$

It is important to compare the adopted conditions of cost effectiveness to the cost benefit analysis described in the formal assessment guidelines (FSA) by IMO (MSC 83/INF.2). Compared to the current IMO approach (example critique is found in [27]), the adopted method:

- Is not based on the predefined cost of averting a fatality (CAF), or any other point criterion for that matter. Hence, it is immune to inaccuracies (uncertainties) in CAF values and other application and semantic issues associated with the CAF criteria.
- Automatically assesses combinations of multiple risk control measures (design modifications) regardless the level of dependency between them.
- Is more robust, transparent and communicable.

The most cost effective design variation, shown in Figure 11 to Figure 15, is coded as (+NPV, -PLL). This variation has a lower risk level and better economic performance than the baseline design, whereas the new EEDI value stays below the threshold.

Significant reduction in risk: Amongst optimised design alternatives, the total risk was reduced by 67%, while at the same improving economic and environmental performance (variation coded (-PLL) in Figure 11 to Figure 15).

The main reduction in the total risk resulted from a significant decrease in collision and grounding risk contributions, primarily due to improved damage stability. Other risk contributions (i.e. individual crew, fire) were higher in the optimised designs due to primarily bigger number of people onboard which outweighed the positive effect of lower ship motions and noise on the risk.

Risk drivers*[3] *at concept design: The total risk was primarily driven by (1) ship's damage stability, (2) number of people onboard (POB), and (3) by cargo capacity (although marginally). Further analysing separate risk contributions, societal and personal risk contributions were found to be also driven by the number of crew.

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[2] Here the risk can correspond to the total risk or a risk contribution.
[3] By risk drivers we refer to dominant parameters which tend to significantly change the risk level.

Although the significant reduction in risk was achieved (see above), the developed risk models exhibited relatively low sensitivity to other factors affecting human performance along with corresponding design modifications. As a result, the effects of such factors as the sizes and location of compartments and equipment that influence ergonomics, or ship motions and noise that affect crew attention management became negligible.

However, there are other aspects of human factors which are relevant to concept design but were not taken into account during the risk modelling. Specifically, the developed risk models ignored the effect of watertight doors (WTDs), which can already be planned at concept design, on the chance of occupational accidents (e.g., limb injuries of crew members) or on ship's damage stability, and consequently on the societal risk, should the ship experience flooding with open WTDs. These chances were investigated in the virtual experiments (Section 4.4), but were disregarded due to lack of sufficient quantitative data that would allow confidently defining probabilities of injuries or open WTs.

We believe that the future integration of the effect of WTDs into risk models will significantly increase their utility at concept design. However, relevant research undertakings are necessary to materialise this.

Recommendations

Total risk representation at concept design and robust damage stability: Based on the design study, it is suggested to ignore some aspects of integrated human factors in the risk models at concept design. Other aspects of human factors still appear in the calculations, as explained in the text below.

Specifically, in future applications at concept design, the total risk as PLL can only be linked to the ship's damage stability and approximated by the following conservative formula:

$$\mathrm{PLL} = (1 - A') \cdot \mathrm{POB}$$

where *A*' is the modified (see below) probabilistic subdivision index (SOLAS chapter II-1, MSC 82/24/Add.1), i.e. probability of surviving any plausible flooding scenario. The formula is an abridged form of its original version and it does not aim to predict PLL as its prototype does. Its aim is to provide ship designers with simple but yet sufficient way of balancing risk with economic and environmental performance indicators as shown in Figure 11. The formula contains the parameters readily available to ship designers.

In the formula, the subdivision index is modified to cater for possibility of open WTDs during flooding accidents. It is recommended to rank WTDs according their probability of being open during flooding accidents and perform the damage stability calculations with at least one WTD open. The open WTD might reduce the subdivision index below its minimal threshold and incite the designer to search for design improvements that rectify the potential loss of stability. Consequently, the ship design will become more robust to the flooding hazard.

At this stage of knowledge, we recommend to estimate the probability of WTD to be open during a flooding accident as the frequency of WTD use over a single voyage. This implies that the crew task analysis should also become part of concept design.

Reduction in crew: The reduction of crew onboard would mitigate occupational accidents, reduce opportunities for flooding scenarios exacerbated due to open WTDs, and lower manning costs. It may prove a cost-effective risk reduction measure, provided the cost of alternative solutions that replaces the vacated crew does not exceed the reduction in manning cost, and these solutions do not undermine ship's safety.

Such alternative solutions should aim to eliminate the need to use WTDs which are typically used by crew during routine inspection and overhauls of various machinery systems. It can, for example, be achieved through significantly increased reliability of machinery components.

5 Overall conclusions

The significant project results summarised in this report are intended to inform decision-making for ship designers, operators, and regulators, as well as other stakeholders. The findings can already be used to enhance the training of crew members, upgrade internal safety procedures as a part of continuous improvement under the International Safety Management (ISM) Code, implement revisions and changes to plan approval processes, and improve ship design practices.

The presented knowledge has been obtained through experiments in virtual machinery spaces and bridge simulators, risk modelling and its application risk based design of tanker and RoPax ships. These results have also been supplemented with recommendations and further steps to achieve improvement or implementation of the project results. The following conclusions are drawn from the presented material (refer to the individual sections for details):

- A theoretical framework has been proposed and tested to link GDFs to the human reliability (degradation of which leads to human error).
- Human error-based (or human reliability-based) risk models have been developed for the main maritime hazards (collision, grounding, fire and personal injuries) to be then used in risk-based ship design.
- Little quantitative knowledge is available about the effect of GDFs on human performance and human reliability. In the FAROS project, a detrimental effect was confirmed to exist but its magnitude and variability need to be investigated further.
- Reporting of accidents, incidents, and near misses has to be significantly improved (underreporting to be eradicated) and structured appropriately to be used as input in risk analysis.
- Following the results on the use of watertight doors, their frequency of use should be reduced to the minimum (but still within the regulatory frame) to avoid

personal injuries or jeopardy to ship's damage stability. The frequency of crossing watertight doors could be reduced by reducing the number of WTD, by reducing crew asks that require to use them, or both.

- Moreover, individual risk in machinery compartments can be reduced by shortening the walking distance between commonly used compartments (e.g., position the frequently accessed spaces vertically rather than horizontally across different WT compartments, move such spaces closer to each other) and by increasing the passage width in areas close to potentially hazardous objects.
- Noise level on the ship bridge should be reduced as low as practicable to avoid impact on crew performance during demanding tasks.
- Noise and vibration limits used in the existing design rules would benefit from being reviewed to make sure they do not provide opportunity to significantly undermine cognitive, safety critical functions of crew members.
- In the case of concept design of tanker ships, further research is necessary to improve our knowledge of human factors and their influence on human performance on board those vessels
- Optimisation of tanker designs improved economic and environmental performance of the baseline designs by 90% (when considering through life operation) and 11% (when considering air emissions), respectively.
- The experiments in virtual reality in RoPax ships have confirmed the evidence that crew are tempted to leave watertight doors open under certain scenarios considered in the experiments, depending on tasks performed and deck layout aspects such as the number of WT doors to pass through. At concept design of RoPax ships, it would be beneficial that damage stability calculations could accommodate the possibility of open watertight doors.
- Optimisation of RoPax ships reduced the total risk and improved economic and environmental performance by 67%, 3%, and 4% respectively.

Concerning the low sensitivity of the risk models to GDFs, it should not be considered in any way as an underdevelopment. More time and resources may have helped to make the risk models more comprehensive, but it would have not improved their quality which reflects the state-of-the-art in knowledge on human performance. On this basis, the consortium concludes that no radical change can be expected to risks associated with maritime operations unless detailed reporting of accidents, incidents, and near misses is significantly improved and basic research focusing on factors shaping cognitive human performance in the maritime domain is undertaken.

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