Marine Technology

Proceedings of the Second FAROS Public Workshop, 30th September 2014, Espoo, Finland

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Aalto University

SCIENCE + TECHNOLOGY

SEMINAR PROCEEDINGS

Aalto University publication series
SCIENCE + TECHNOLOGY 14/2014

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Aalto University publication series
SCIENCE + **TECHNOLOGY** 14/2014

ISBN 978-952-60-5873-3
ISBN 978-952-60-5872-6 (pdf)
ISSN-L 1799-4896
ISSN 1799-4896 (printed)
ISSN 1799-490X (pdf)
http://urn.fi/URN:ISBN:978-952-60-5872-6

http://www.faros-project.eu

Graphic design: Rachel Pawling

Unigrafia Oy
Helsinki 2014

Finland

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 314817

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Printed matter

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Introduction to the Proceedings of the Second FAROS Public Workshop

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The ultimate technical objective of the FAROS project is to quantify and integrate the human error—which is found to be responsible for some 90% of maritime accidents—into risk-based ship design. Risk-based design is a design process supported by systematic risk assessment so that all significant design decisions are risk-informed. The FAROS project focuses on the concept design stage and adopts a system approach to the human error problem. The basic assumptions of the system approach are that the crew are fallible and errors are to be expected. Such 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). Hence the broader operational aim of the project is to improve the conditions under which the crew works, thereby reducing the occurrence of human error and mitigating its consequences.

Since October 2012 when the project kicked-off, much of valuable work has been in done towards the project objectives. In summary, the key technical deliverables of the first project period are:

- Comprehensive literature review on human (crew) performance affected by ship motions, noise, whole body vibration, deck layout and arrangement of equipment and accessibility. The summary report is publically available on the project website.
- High-level, scientifically backed framework that enables quantification of affected human performance and consequently human error.
- Results of experiments on bridge simulators and engine room simulated in Virtual Reality.
- Personal and societal risk models with the human error integrated. The risk models can be used in risk-based design, cost-benefit analysis of risk control options, inference of prescriptive design guidelines, etc.
- Parametric models of oil tanker and RoPax ships to be optimised for low overall risk, high economic performance and energy efficiency.

The project findings and deliverables 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.

Project FAROS organises a public workshop near the end of each project year. In total three public events are planned for. This way the consortium publicises project results obtained over each year of research and development.

This year, we are meeting in Dipoli Congress Centre in Otanemi, Espoo, just outside Helsinki for the 2nd workshop. During the event delegates are invited to confer about the findings summarised above and learn about the research results at first hand. The event also serves as a good networking opportunity with the audience comprising representatives from shipyards, ship operators, design offices, various consultancies, class societies and other regulators.

I would like to thank the local organising committee members Prof. Pentti Kujala, Dr. Jakub Montewka, and Seppo Kivimaa from AALTO University and VTT, as well as consortium partners Jose Gonzalez Celis (Lloyds Register) and Dr. Rachel Pawling (UCL) for gathering the material and compiling the proceedings.

I would like also take this opportunity to promote the project website, www.project-faros.eu, where detailed descriptions of the majority of project findings can be found in public reports. I also invite you to include the project into your professional network on LinkedIn (http://www.linkedin.com/company/3194994), to stay up to speed with the progress.

Dr Romanas Puisa,

Project Coordinator

Ultra Light Arctic Ship Design – Critical Cause and Effect in Basic Processes and ULIVES Project dd 2008-2012.

Veikko Hintsanen, Master Mariner,EMLog Project Manager of EU Martec "ULIVES" multinational ship design project yy 2008-2012

Executive Summary

Laffcomp is a privately owned start-up company, which was founded October 2007. The company operates in ultra-light fresh water vessel design and development for Finnish and European transport areas and river traffic.

The company has been in co-operation with the German engineering company SMK and the Fraunhofer Institute, also from Germany ; since 2007.

Laffcomp's innovation project is based somewhat on the "Blue Ocean" idea. Not less due to the fact that the design bases differs so much from conventional Arctic ship Design. In conventional Arctic ship design You need not to take into similar consideration and analyses of the weight issues, operational safety (simultaneous ballasting operations /draft etc..) due to weight reducing of the hull fi. design weight from 6000 tons of steel down to target of 600 tons hull weigh with the about same length of the vessel.

Laffcomp plans to bring a new product to a new market place; Bioship ULIVES type vessels

The ultra-light fresh water vessel's most important features are ultra-light hull structure and ability to operate in icy inland water areas without conventional berths. conditions, while minimizing waves in operation.

Laffcomp's case can be translated into Porter's terms as well (Porter, 2000). The value innovators achieve sustainable competitive advantage through strategic positioning: performing different activities from rivals or similar activities in different ways.

The main objectives of the design of the vessel were

- Replacing road transfers with water transfers according to EU traffic strategy
- Reduction in fuel costs / transferred tonnage
- Reduction in CO2

- Reduction of total manufacturing costs of the vessel (especially in series production).
- Radical reduction in the weight of the vessel (compared to conventionally manufactured steel vessels).
- Increase of transfer capacity without increasing operational depth of the vessel.
- Safe operation in shallow waters with minimum manning even when mooring/unmooring the vessel every two hours.

The design was successful not only in terms of operational view but also in terms of safety processes of the vessel and the number of personnel in operations.

The best evidence of the successful design was the State research report 37/737/2009, in which there were up to 7 items of innovation during the design processes; to reduce effort and make safer human work when operating daily in several locks, with repeated vessel mooring, loading & discharging. The innovations make year round 24/7 operation safe and possible with minimum manning in shallow rivers, channels with locks and icy waters.

The state research centre proposed, on the basis of innovative ideas and feasibility studies performed, Finnish Government innovation support to Laffcomp ship construction up to 800,000 Euros, following to EU rules and legislation.

In addition to the massive design work described above, LCA /LCC studies was performed with Lappeenranta University for the vessels' life cycle, consumption and emissions compared to trucking in Keitele-Päijänne cargo operations: The result showed that the ship is a competitive alternative to trucking and ready for construction.

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The opportunities and challenges for bringing sophisticated modelling and analysis into the formative stages of design development, and design optimisation of ship concept.

Antonios Mantouvalos, Naval Architecture Progress (NAP), Greece

George Pratikakis, Naval Architecture Progress (NAP), Greece

Naval Architecture Progress (NAP) has for years applied naval architecture knowledge into the design and modification of many ship types. Currently NAP is in the process of adopting an integrated ship design and optimisation system in order to benefit the better service quality to our customers.

Many opportunities arise:

1. More complex ship types can be designed.
2. Reduce carbon footprint (Because it is becoming a currency on its own and has environmental impacts).
3. Increase crew and passenger comfort and safety.
4. Perform research studies.

Many challenges arise:

1. Train NAP staff to use sophisticated modelling and analysis tools.
2. Using a Personal Computer or Server to run the tools.
3. Persuade customers it is worth paying extra in order to search for an altogether better solution.
4. Choose the right tool for our portfolio of ship types.

NAP carries out 10-20 design studies every year for many different types of ships (such as bulbous bow modification after collision to achieve better performance). Currently being partners in EU projects gives us state-of-the-art know-how of products and services available within the EU where we can get better support. NAP is looking forward to adopting sophisticated modelling and analysis tools in the initial design process to reduce design time.

The next stage for NAP is to include the Human Factor (HF) in the design in order to optimise it further. By adopting new and state-of-the-art techniques we believe we can better service our clients' needs while at the same time offering the best possible quality of service, and all this in a cost-effective manner.

Modelling information flow on ship bridges as cooperative socio-technical systems

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Ship bridges as socio-technical systems

In CASCADe, the European FP7-Project "Model-based Cooperative and Adaptive Ship-based Context Aware Design", the ship bridge is seen as a cooperative socio-technical system. This system consists of the ship bridge as a technical system and control centre of the ship that communicates with other ships, the shipping company or VTS stations. Furthermore, we have crew members and human-machine interaction on the bridge as cooperative decision making is involved. For maritime safety, the ability of ship's personnel to co-ordinate activities and work as an effective team is vital during emergency situations or even during routine sea passages and port approaches. While watch keeping for example, a task with high visual workload, attention has to be paid to numerous additional instruments which can lead to visual overload and to "human-out-of-the-loop" situations. Thus, bridge design should also involve cognitive capacities of humans and nature of the tasks at hand.

The development of ship bridge systems, workstations, displays and controls on the one hand and procedures on the other hand is characterized by being non-harmonious and far from guaranteed to be of optimal design for the actual users of them. Existing regulations for system and procedure design are disconnected and defined on a level which is not informative for bridge design. Research has shown clearly, that in many cases, accidents and incidents were caused by human error, e.g. due to non-optimal design of the human-machine interaction leading to degraded situation awareness (e.g. Tang et al 2013).

CASCADe addresses the study and design of bridges as an integrated whole to improve overall safety and resilience on ship bridges. We use the cooperative system design methodology to develop an Adaptive Bridge System to permanently or semi-permanently adapt the information content, distribution and presentation on user interfaces. This holistic cooperative system perspective allows detecting and solving potential conflicts, i.e. inconsistencies and redundancies of information presented on screens leading to human errors, already during design time. The human-centred design methodology hereby supports the analysis of crew performance at early development stages and leads to a bridge system development that considers human errors by improving the information flow between crew and machines on the bridge.

Human-centred design methodology

We develop, demonstrate and evaluate a new methodology enabling the design of a highly Adaptive Bridge System (ABS) from a cooperative system perspective. The methodology integrates techniques and tools for harmonization of system development, procedure development and human factors fostering a holistic and affordable human-centred approach to ship bridge design. Based on task analysis and optimal situation awareness distribution of seafarers, it should help to provide the most important information, in the most effective way at the most useful time. Besides the Physical Simulation Platform of the ABS, a bridge simulator, we develop a functionally equivalent Virtual Simulation Platform that is purely based on computational models of the human and machine agents, i.e. individual seafarers or automated bridge systems. By using models of virtual seafarers that mimic task execution and the human-machine cooperation of real seafarers, the Virtual Simulation Platform allows us to evaluate bridge designs and information flow at early development stages. In addition to experiments with real seafarers on the Physical Simulation Platform, the Virtual Simulation Platform facilitates simulating many more scenarios and the investigation of extreme scenarios, sometimes impossible or too costly on a Physical Simulation Platform.

The methodological approach is shown in Figure 1: the bridge system is analysed as a cooperative socio-technical system. In selected test scenarios we identify all participating human and machine agents, such as Master, OOW, ECDIS or Radar, the resources as well as the human or machine agent´s procedures to fulfil an ongoing task such as port approaching or collision avoidance. The aim is to study and optimize the way in which these different agents perform and share tasks e.g. according to procedures. The socio-technical bridge system as a whole is analysed in terms of how it has to assess situations e.g. with an incoming ship on a collision course, associated sub-tasks have to be distributed to currently available agents, human and machine, and a decision has to be made as to who will perform them based on currently available resources.

The analysed scenarios are studied and implemented on the Virtual and Physical Simulation Platform (c.f. Figure 1). By using the Physical Simulation Platform, a bridge simulator and mock-ups to test different ship bridge designs, we can evaluate new design ideas together with seafarers. The test scenarios are conceptually relevant to the two key ideas in CASCADe, i.e. the cooperative system perspective, and ‘adaptiveness’, in particular at the level of user interfaces. Furthermore, it is necessary for scenarios to involve human-machine cooperation and allow design improvements in terms of adaptive user interfaces. During evaluation of new design ideas, we asked seafarers and pilots to perform tasks while using also the equipment of the ABS.

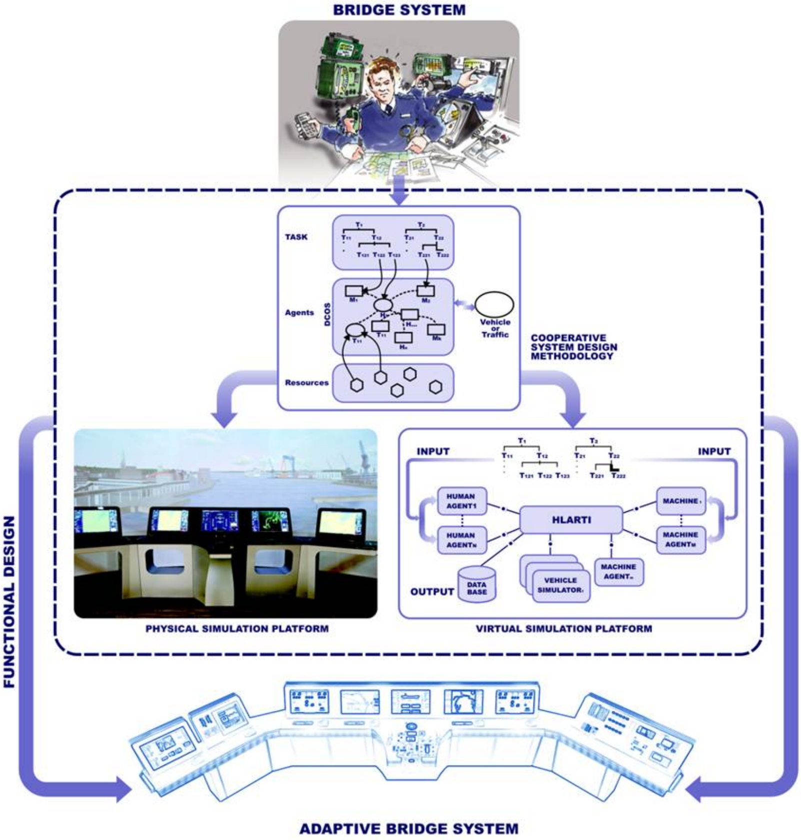

Figure 1: Human-centred design methodology

The Virtual Simulation Platform (VSP) is used to simulate all necessary components of a ship´s bridge in the selected target scenarios. The VSP is a virtual and functionally equivalent replica of the Physical Simulation Platform, i.e. it is purely based on computational models of the involved human/machine agents and varying bridge designs of the ABS (c.f. Figure 1). It enables the analysis of the cooperative bridge system purely based on models, in particular executable task models and cognitive models which mimic decision making and situation awareness processes of real human seafarers. According to the new bridge design ideas, especially new user interfaces or workstations, developed on the Physical Simulation Platform can functionally be realised on the VSP. During simulation runs, the cognitive models are interacting with the represented user interfaces and workstations to evaluate task performance of the system at early development stages. Therefore the VSP realizes the ship bridge components and agents as a cooperative socio-technical system. Agents, whether human or machine, are the main information processors and cooperatively achieve the tasks assigned to the bridge system as a whole. Thus, the platform allows a very careful evaluation of the Adaptive Bridge System to research solutions for adaptation which provide benefits (e.g. increase situation awareness) that outweigh their costs (e.g. cognitive disruption). All elements of the VSP provide interfaces based on the High Level Architecture Standard (HLA) for integrated and distributed simulation defined under IEEE Standard 1516.

Hereby, CASCADe addresses the effect of human performance that has to be considered in future bridge designs, as there remains a disconnect between the guidelines for system design and the guidelines for procedure design. This can only be achieved by treating the equipment, the mariners and the tasks as an integrated whole. Our approach allows adapting the information content, distribution and presentation of the whole cooperative system to the current situation, relevant procedures and the needs of the individual seafarer.

Simulation and evaluation of information flow on ship bridges

To improve overall safety and resilience on ship bridges, our methodology brings together the capabilities of humans, the nature of seafarers´ tasks and ship bridge design. In our target scenarios we especially focus on information overload and decreased situation awareness that can lead to “human-out-of-the-loop” situations. In a first step we learned about the way seafarers interact with each other and with bridge technology during simulator observations and surveys with seafarers. We derived hypotheses concerning how the bridge, as a cooperative system, processes information. This also allowed us to set up a first version of the Virtual Simulation Platform with task models of virtual seafarers and representations of bridge components to study the system´s information flow. By testing various scenarios and actual ship bridge designs in our VSP, we are able to evaluate how well a design supports seafarers in completing an on-going task and/or situation, already at the design phase. Furthermore, we can test the new bridge design ideas on the Physical Simulation Platform. By involving seafarers that perform certain tasks of scenarios, we are able to answer analysis questions in terms of the optimal distribution of information and the optimal level of cooperation between system components. Thus, varied approaches are applied to test whether necessary information is provided in the most effective way and how to measure the improvements made by the project.

Seafarers´ opinions

By conducting surveys, focus groups and observations of seafarers, the purpose was to build up a conceptualisation of the bridge from the end-users perspective, with a particular focus on identifying those areas where there are currently problems and therefore scope for improvement. In our target scenarios, we also brought in new user interfaces of the Adaptive Bridge System designs that support information exchange and communication. The participating seafarers were invited to provide feedback on design ideas being developed in the project. From this a picture emerged concerning where it might be most beneficial for CASCADe to focus. This can be seen as a ‘seafarers-eye-view’ of the bridge; an identification of areas for improvement based on the direct experience of seafarers. In a broad sense, the most promising area for potential innovation appeared to be around communication.

By using the Physical Simulation Platform, a bridge simulator and mock-ups to test different ship bridge designs, we are able to evaluate new designs together with seafarers. It was possible to gain valuable feedback that could be fed into the design process for the first mock-up. For example, seafarers were concerned about information over-load on the displays and about the over-reliance on technology by new seafarers. The participants were generally reluctant to encourage seafarers to use electronic aids at the expense of old fashioned and reliable watch keeping techniques (see also Sub-Committee on Safety of Navigation 2009).

Seafarers´ task simulation

To set up scenarios on the Virtual Simulation Platform, we developed hypotheses concerning how the bridge, as a cooperative system, processes information. Once the human and machine agents and tasks were described in the selected scenarios of CASCADe, the Virtual Simulation Platform enabled us to simulate the ship bridge as a cooperative system. This process involved the development of executable task models e.g. of the participating human agents, including cognitive capabilities of humans, the representation of all necessary information displays as well as traditional and/or new bridge designs to be used in the selected scenarios.

As such, the VSP allows evaluating whether the various bridge design ideas provide appropriate information to seafarers and/or support the seafarers to obtain task-specific optimal situation awareness (c.f. Sobiech et al 2014). Besides some generic questions on socio-technical information exchange, our analysis questions are task-dependent as seafarers require specific information in order to achieve certain goals or tasks e.g.:

- How much effort is needed to gather all necessary information?
- What kind of information do the seafarers consider as important/critical in the scenario?
- Has information presentation matched the information needs of the seafarers at all times during the scenario? Is further communication necessary?
- How well does the current understanding of a given situation from a seafarer’s perspective match reality?

On our VSP we do not focus on low-level cognitive actions of seafarers. Basically, we analyse and model *what* information a seafarer needs to obtain in order to execute a certain task and *how much effort* is needed to get this information in terms of e.g. location on the bridge or system mode. However, to achieve these goals, certain behaviours need to be implemented within the Virtual Simulation Platform, e.g. actions to change the modes of displays, gaze actions, communication or movements of the human agents to gather information.

In the scenarios selected within CASCADe, we are now able to evaluate different functional and actual ship bridge design solutions concerning their ability to provide necessary information to seafarers and support the seafarers to obtain task-specific optimal situation awareness. In comparison to the Physical Simulation Platform, this can be done already during very early design stages and with more extreme scenarios.

Thus, the VSP allows model-based simulations and rapid prototyping of different design solutions for existing and new workstations without the need to implement actual workstations and displays in a first step. In our approach symbolic representations of workstations can be used to simulate where the information is provided, i.e. the areas of interest presenting specific information and can be rearranged amongst the different applications, modes and areas of interest to better fit the end user´s requirements.

Conclusion

In the framework of the project CASCADe we propose an approach to human-centred bridge study and design based on surveys with seafarers and simulator studies. Currently, we are evaluating new design ideas for improved information processing on ship bridges as socio-technical systems with seafarers on a physical mock-up and with task models on a virtually and functionally equivalent replica of the mock-up. The results of the project will contribute to the improvement of safety in maritime transport through: a new Adaptive Bridge System that will recognise, prevent and recover from human errors by increasing cooperation between crew and machines on the bridge and a new human-centred design methodology supporting the analysis of information flow at early development stages.

Acknowledgement

This research has been performed with support from the EU FP7 project CASCADe, GA No.: 314352. Any contents herein are from the author and do not necessarily reflect the views of the European Commission. The author would like to thank our partners in CASCADe and especially the participating seafarers.

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Dr. Cilli Sobiech is Project Manager of the FP7 project CASCADe at OFFIS, an application-oriented research institute for IT. She is specialised in the application of agent-based simulations to different fields of safety-related research and domains. CASCADe involves seven partners from five European countries such as ship bridge manufacturers, shipping companies, psychologists, ergonomists and computer scientists.

Understanding the impact of ship design on human performance

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The FAROS project preselected a number of ship design factors that were thought to influence crew performance and could contribute to the unwanted outcomes of collision, grounding, fire and personal injury on board. These performance-shaping factors, known within FAROS as Global Design Factors (GDFs), are listed below:

- Ship Motion (i.e. motion-induced sickness (MIS) and motion induced interruption (MII))
- Noise
- Vibration
- Deck layout, equipment arrangement and accessibility (DLEAA)

The objective of this paper is to describe the theoretical frameworks that have emerged from the scientific literature that facilitated the development of the human performance component of risk models. This represents an evidence-based approach based on what is known about human performance when exposed to GDFs. This paper covers the following:

- The challenges in defining the link between GDF exposure and human performance from the scientific literature
- An overview of viable frameworks that have emerged from the scientific literature describing the effects of exposure to the GDFs to support human performance risk model development
- An approach to human performance risk model validation in FAROS

Challenges Linking GDF Exposure to Unwanted Outcomes

The scientific literature of most interest to FAROS describes the effects of GDF exposure on individual cognitive capabilities associated with task performance and human error. Humans contribute to the risk of the unwanted outcomes in FAROS at task level, i.e. an unwanted outcome may be fully or partially dependent on whether human performance on safety critical tasks is sufficient or insufficient[1].

In FAROS, the main challenge is that data on the specific GDF effects of ship motion (with the exception of MII[2]), noise, vibration and DLEAA on human performance are sparse. Furthermore, in many (but not all) cases this data has been generated under very specific, often non-marine, conditions. The data that exists shows that there is certainly evidence for GDFs having some effect on human performance. However, the direct effects of GDF exposure on human performance tend to be weak, whereas secondary effects acting through another mechanism (e.g. fatigue, MIS) tend to be stronger and more pervasive (see **Figure 2** 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.

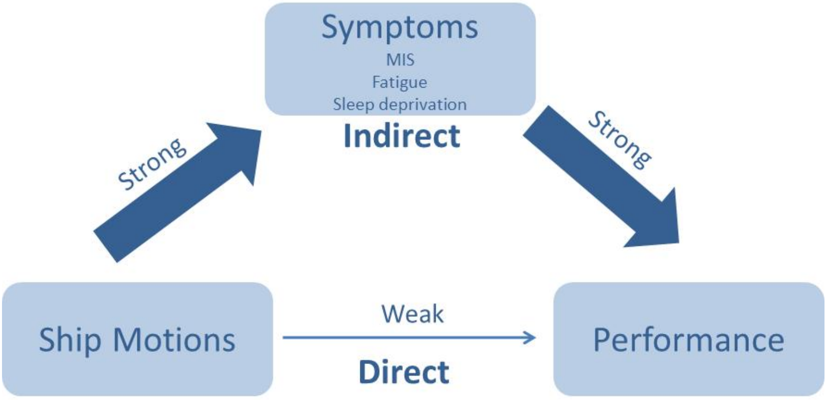

Figure 2: Relationship of ship motion to human performance (Colwell 2005).

Moreover, with the possible exception of secondary effects on human performance caused by fatigue (attributable to sleep disruption), a holistic view cannot readily be derived from the individual findings. As such it is inappropriate to extrapolate these data to crew performance in the marine environment in general. The marine simulator and virtual reality experiments performed within WP4 of FAROS are designed to address some of these issues.

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[1] Task performance in conceived to have two levels within FAROS:

Sufficient: Timely and correct (but not necessarily optimal) performance

Insufficient: Includes, but is not limited to error. However, within FAROS we are only interested in erroneous performance

[2] MII is well understood (see Baitis, Holcombe, Conwell, Crossland, Colwell, Pattison & Strong, 1995; Crossland & Rich, 2000) 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.

However, until this experimental output is available, the FAROS approach must be guided by the relevant theoretical models available in the scientific literature.

Ship Motion, Noise, Vibration GDF Exposure & Human Performance

The literature on the effects of exposure to ship motion, noise and vibration GDFs has directed us towards an approach that provides a workable framework for human performance risk modelling and accounts for both strong and weak effects. It is based on three related theories described in the GDF literature.

The approach that emerged combines the principles of the Dynamic Adaptability Model (DAM – Hancock & Warm, 1989), the Cognitive Control Model (CCM – Hockey, 1997), and the Malleable Attentional Resources Theory (MART - Young & Stanton, 2002). Taken together, these theories describe a mechanism that accounts for the impact of what Hancock & Warm (1989) describe as a 'trinity of stress' on human performance, based on the principles of attention management.

Under the DAM paradigm, GDFs are seen as types of physical stressor that affect human capabilities associated with maintaining a desired level of task performance either directly or indirectly (e.g. via fatigue). When exposed to GDFs, CCM describes humans compensating through the effortful direction more cognitive resources at the task, typically at the cost of performance in other areas. Despite the sophisticated (and potentially subconscious) strategies humans have at their disposal, there is a limit to how much an individual can compensate without experiencing degradation in primary or secondary task performance.

In addition, the extent to which human can compensate for task demands is not fixed. MART describes this compensatory capability changing as a function of task demands and associated arousal an individual experiences (See **Figure 3**) – attentional resources available vary as a function of load. When humans are in a state of under-load (i.e. bored) their pool of attentional resources is relatively small and will increase proportionately with the demands placed on them. However, there is a limit to how much the pool of attentional resources can grow. When task demands exceed the pool of attentional resources available (either transiently or when the upper attentional resource limit is exceeded), performance can breakdown and errors may be made.

Generally, task performance is only expected to degrade and become insufficient when compensatory mechanisms have failed. However, the literature does not allow prediction of how and when (chronologically) an operator would fail, under what conditions of GDF exposure, and what the specific effect on behaviour (i.e. type of error) would be.

These theories encapsulate the idea of the 'adaptive human performer', whereby humans are active agents in their world and are capable of adapting to environments when motivated to do so, such as required by (safety critical) task completion (Teichner, 1968, Hockey, 1997).

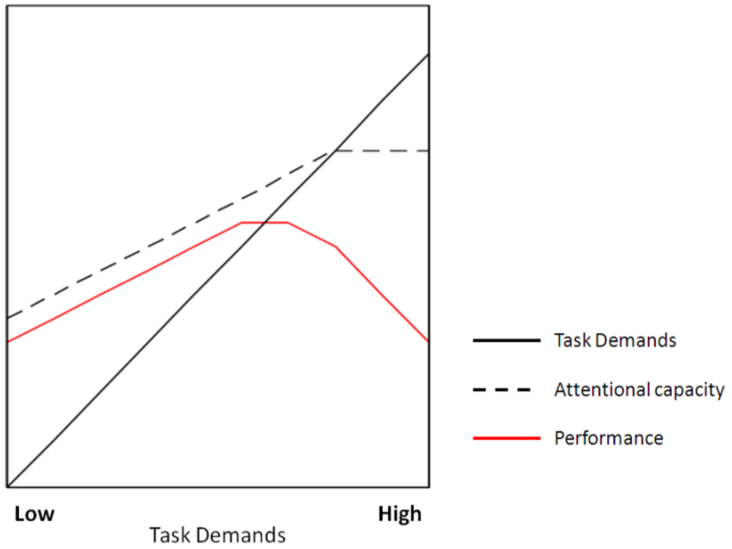

Figure 3: The proposed model of Malleable Attentional Resources Theory according to the correlation between task demand and performance (adapted from Young and Stanton, 2002).

In terms of risk modelling, an approach based on attention management theory allows representation of the effect of GDF exposure as a stressor that sits either above or below the threshold of attentional capacity for any given task. If the stressor exceeds the attentional capacity then a negative effect is expected, whereas no negative effect on human performance would result if the stressor can be managed within the available attentional capacity. This is a simple but flexible approach that takes into account the variable attentional resource pool that changes as a function of task demands described by MART.

Deck Layout Equipment Arrangements & Accessibility (DLEAA) GDF Exposure & Human Performance

The mechanism that underpins DLEAA effects on human performance is qualitatively different to that of the other GDFs. Again, there is lack of empirical literature on the effects of DLEAA or the general physical design of a work environment upon crew performance on-board ships. Unlike the other GDFs, the arrangement of spaces and equipment does not directly affect an individual’s underlying cognitive capabilities. Rather, features of DLEAA affect human performance through changing the task demands themselves (making tasks easier or more difficult). Changes in DLEAA would typically leave an individual’s underlying cognitive capability to do a given task unchanged.

However, an understanding of the general principles of user-centred design would suggest that DLEAA presents challenges to seafarers with regard to the difficulty (i.e. task demands) and safety with which a vessel can be traversed and work can be undertaken. Within FAROS, it only appears reasonable to consider DLEAA as a causal factor related to the unwanted outcome of personal injury.

Literature on DLEAA shows effects may be found due to the following design characteristics on board:

- Room geometry
- Space allocation
- Location of areas (i.e. segregation / co-location)
- Accessibility / circulation

DLEAA parameters such as room geometry, size, space, location and access can act as performance shaping factors that may impact performance of the task undertaken. Evidence from maritime studies suggest that restrictions to movement due to confined space & obstructions, physical expenditure of effort due to the distance traversed and overcoming impaired access, and task interruptions due to the separation of functional areas may be the predominant features of a design that contribute to performance and risks to personal safety.

Psychological studies have explored the effects of task interruption and the application of memory in recovering from interruption. Tasks that straddle segregated functional areas on board are effectively interrupted each time the individual moves between each area. This affects the ability of seafarers to retain and use information when having to move between work spaces. Specifically, moving between segregated areas may be especially problematic to engineers as it can impact their overall awareness of the operational status of the room and the efficiency with which they can perform engineering tasks (Wagner, 2008).

It is recognised that suboptimal ship design seen in the location of walkways and functional areas may reinforce unwanted seafarer behaviour by encouraging the taking of shortcuts to save time. By violating rules associated with route selection between areas, crew may pose risks to themselves either by passing through hazardous areas, or pose a risk to the vessel where their behaviour may compromise its safety (e.g. by leaving watertight doors open).

It could be argued that the rule violation examples given above are a result of expediency and a strategy to save time and effort. A time pressure workload model (Pickup & Wilson, 2002) could provide a simplistic way of identifying circumstances when there is a high propensity for taking short-cuts. Time pressure workload models determine the time taken to complete a scenario as a proportion of the time available. In circumstances when this nears or exceeds 100%, it could be speculated that people may take shortcuts in order to save time and alleviate their workload. Models incorporating the effects of self-imposed or external pressure on safe behaviours could be applied to determine the likelihood of violations when there is a need to traverse from one area of the vessel to another.

Integrating the theory in to the FAROS Risk Models

In principle, representing ship motion, noise and vibration GDFs as stressors interacting with an individual's attention management capabilities may provide a viable, evidence-based mechanism that describes the impact on human performance for integration into the risk models. Similarly, representing the effects of DLEAA in terms of time pressure on route selection may provide an effective, defensible way to represent its effects on unwanted outcomes.

However, a gap existed in the definition of probabilities describing the likelihood of failure given the task demands generated by exposure to the GDFs. Due the limitations in data on the effects of GDF exposure on human performance, such values are not available in the scientific literature. Hence, probabilistic representation of the human performance component in the risk model was potentially problematic.

A solution was found in Human Reliability Analysis (HRA) techniques. While HRA techniques do not typically cover the specific GDFs or the maritime environment, the human error probabilities generated by HRA allow sensible bounds to be determined and compared against FAROS risk model output. While HRA cannot provide the specific human error probabilities for nodes with the Bayesian Belief Network, it can provide an approximation of human error probability based on tasks that are analogous to those found in marine operations that may lead to the unwanted consequences within the scope of FAROS. While imperfect, and stretching the application of HRA tools, this approach allowed the calibration of probabilities in the risk models against established generic human error probability values.

Conclusion

The task posed by FAROS is extremely challenging due to the paucity of data on the GDF effects of GDF exposure on human performance. The specific nature of the threat of GDF exposure presents to the generation of collision, grounding, fire and personal injury, while certainly present, is neither known nor predictable based on available data in current scientific literature.

In terms of probabilistic modelling, this is a source of both structural uncertainty and probabilistic uncertainty. Chen and Pollino (2012) note both types of uncertainty provide challenges for the Bayesian Belief Network (BBN) approach to risk modelling within FAROS. However, these challenges can be managed through the development of viable causal frameworks and the calibration of probabilities through HRA techniques. The frameworks represent human performance in a way that allows a link between GDFs and the unwanted outcomes in FAROS to be modelled and HRA techniques will allow validation of the output of human performance sub-model output.

Despite the challenges FAROS has presented, the pragmatic, evidence-based theoretical frameworks identified to underpin risk model development here are generalizable to other areas seeking to link specific performance-shaping factors (i.e. GDFs) to specific outcomes in operational settings.

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Results of the Physical and Virtual Reality Experiments

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Introduction

Two sets of experiments were carried out in bridge simulator (at HSW Warnemunde) and virtual reality environments (at CIS Galicia). Their purpose was to inform the risk models as these developed, and to test specific hypotheses. The bridge simulator experiments involved 24 master mariners undertaking navigation tasks, whilst the virtual reality experiments involved 12 ships' Engineers undertaking tasks involving movement around a simulated engine room environment. Each set of experiments will be described in turn.

Physical experiments

Members of the consortium from Wismar University and the Unversity of Strathclyde together developed 40 minute long navigation scenarios for tanker (VLCC 'Lagena') and RoPax ('Mecklenburg-Vorpommern') vessels which were designed to have a high degree of realism, in terms of being located in appropriate sea areas (Baltic sea, Dover Channel, Singapore strait), using appropriate motion characteristics for each type of vessel, appropriate configurations of bridges for the two types of vessel, and with realistic tasks for the mariners to undertake (grounding avoidance in the case of the tanker vessel and collision avoidance in the case of the Ropax vessel). These scenarios were each conducted at a simulated time of 8am. This time was selected during the pilot testing phase of the experiments as being associated with the optimal lighting conditions to maximise the visual effect of waves in order to maximize the chances of inducing motion sickness. An example scenario is shown below:

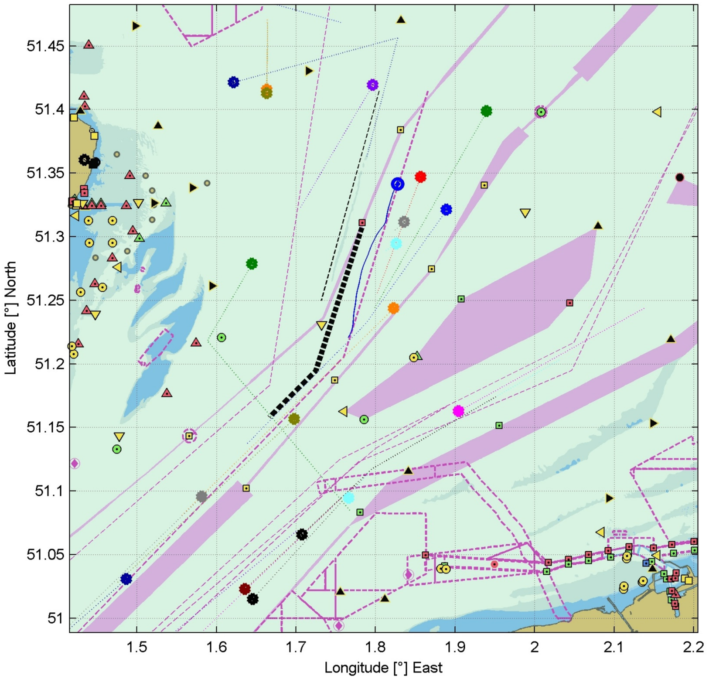


Figure 1 Example Tanker Scenario: Dover Strait Westbound (loaded): Black dashed line depicts grounding limit line.

In order to make the scenarios as realistic as possible, HSW scheduled various events such as external communications and alarms in the lead up to a critical scenario involving a potential threat of collision with a selected target vessel or a potential grounding at a selected part of the route. Mariners were instructed to maintain a constant speed of the ship to ensure that the timings of the events would coincide with the planned timing of events within the scenarios.

The scenarios and simulated vessels were combined with different environmental conditions (sea state, motion and noise) for benchmarking the risk models for grounding and collision. Four conditions were therefore created:

N0 – baseline condition, low noise (61 dB RoPax, 65 dB tanker) low sea motion (sea state 2 on the Jonswap spectrum)

N1 – intermediate noise condition (70 dB RoPax, 76 dB tanker), low sea motion (sea state 2 on the Jonswap spectrum)

N2 – loudest noise condition (80 dB RoPax, 85 dB tanker), low sea motion (sea state 2 on the Jonswap spectrum)

M – low noise (61 dB Ropax, 65 dB tanker) plus a greater degree of sea motion (sea state 7 on the Jonswap spectrum)

24 Mariners, 12 from Estonia experienced in the handling of passenger vessels and 12 mariners from Greece experienced in the handling of tanker vessels

were involved in the simulator test trials. The participants completed one set of 4 RoPax scenarios as described above after a full night of sleep and another set under restricted sleep conditions. Tanker scenarios were conducted in the full sleep condition only. Therefore, 12 scenarios were undertaken in total by each mariner. These lasted for 40 minutes each to allow five minutes for hand over and adequate time to allow a potentially threatening situation to develop. Collision and grounding threats occurred within a predefined epoch in the second half of the scenario. Whilst somewhat simplified and of short duration, the design of the scenarios was constrained in terms of time and resources and the requirement to have 40 minute scenarios that had to be standardised across GDF and fatigue variables. Ethical approval for the experiment was granted by the University of Strathclyde Ethics Committee. Twenty mariners participated in four scenarios each day at regular intervals for the full 12 sessions. Another two mariners completed only eight sessions on the first two days because they were not fully comfortable with engaging in the sleep deprivation stage.

Having read the participant information sheet and signed the consent form, participants were asked to complete a sleep diary a week before the testing week for a week to establish a baseline of sleeping patterns. This provided information on general sleep patterns, which would alert the researchers to any anomalies that may suggest an abnormal sleeping pattern but no anomalous cases were found on analysis of these, so the baseline data was not analysed further. Participants were asked to attend the simulator centre each day for a period of three consecutive days. After the simulator exercise, participants went to a separate room to complete the Motion Sickness Assessment Questionnaire (MSAQ; Gianaros, Muth, Mordkoff, Levine and Stern, 2001) and the Karolinska sleepiness scale (Akerstedt and Gilberg, 1990). Following this, participants were asked to complete a 10 minute long psychomotor vigilance task (PVT) (in which accuracy rates and reaction times for identification of an LED display were recorded).

Participants had been told at the beginning of scenarios to keep a safe distance from other vessels and from grounding limit lines of 1nm. Results were then measured in terms of the closest point of approach (CPA) to potential collision threats in metres; the frequency of crossing the safe limit threshold; the deviation from planned course at the point of CPA and at the end of the scenario as well as the time of the CPA. These measures were gained by computing the recorded simulator data using the SIMDAT 5.4 software analysis package from ISSIMS Gmbh (www.issims.gmbh.de).

The track deviation mean figures for tanker vessels do conform to the expected pattern of greater values for noise and motion conditions relative to baseline. There was a high rate of violation (22 mariners out 24 doing so across N0, N1 and N2 conditions and 23 doing so in the motion condition) of the safe grounding limit across all conditions, suggesting a high level of task difficulty. However, the overall effects of Global Design Factors are very small and statistically non-significant on either the Closest Point of Approach mean figures (in metres: N0 – 974.8, N1 – 822.0, N2 – 970.1, M – 942.4) or the track deviation figures at CPA (N0 – 401.6, N1 – 565.2, N2 – 686.6, M – 519.6) or at end point (N0 – 352.7, N1 – 493.8, N2 – 647.5, M – 455.8).

For RoPax vessels in the full sleep condition, the CPA data demonstrated the expected pattern (with the baseline or N0 condition being associated with the highest mean CPA value of 1406.4m, and the N1, N2 and M conditions having lower mean CPA values – 1376.2, 1183.0, and 1190.0 respectively). the ANOVA results demonstrated that these differences were not significant. Similarly, the main effects of track deviance were non-significant across conditions. Violations of the safe distance from a collision varied slightly across conditions (with the numbers of mariners violating the safe distance being 19 in N0, 21 in N1, 22 in N2 and 21 in M conditions). Again however this variation was not statistically significant.

When the analysis of the RoPax data was extended to include the sleep restricted condition, again no significant effect of GDFs was found, nor was there any significant sleep X GDF interaction. However, there was a significant main effect of sleep restriction, such that sleep restricted mariners exhibited significantly higher CPA values, suggesting that the mariners might have been attempting to compensate for the effect of fatigue on navigation performance by sailing at a greater distance from the collision threat than they did in the full sleep condition. It should be noted that the results from the Karolinska sleepiness scale indicated that mariners reported themselves to be significantly more sleepy in the restricted sleep conditions although again there was no effect of GDF on reported levels of sleepiness.

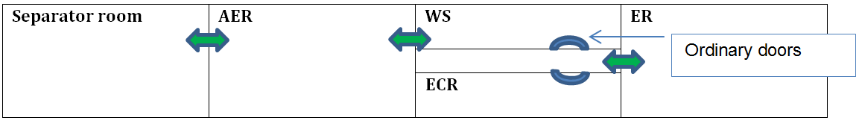
There was no significant overall effect of GDF on the numbers of mariners crossing the safe limit in both full sleep and restricted sleep conditions in the RoPax conditions, but the main effect of sleep restriction on numbers of mariners crossing the safe limit approached significance ($p = 0.06$) such that fewer mariners who had had restricted sleep violated the safe line limit compared to mariners who had slept fully, again suggesting the use of a compensatory strategy. In the vigilance (PVT) task, sleep restriction had no significant difference on performance on the number of lapses in attention on RoPax scenarios since the rate was generally very low but it did significantly slow reaction times in all conditions, indicating that sleep reduction not only made mariners feel more sleepy as the self-report data suggested but that their responses were also significantly slowed down as a function of sleep reduction. This may help to explain why they appeared to employ compensatory strategies when navigating.

In summary, there were no significant effects of global design factors (GDFs, i.e. noise and motion) across Tanker scenarios. In RoPax scenarios, again there were no significant effects of GDFs, but CPAs were significantly wider in the sleep restricted compared to full sleep condition. This may indicate the employment of a compensatory strategy when participants were tired, which paradoxically improved performance.

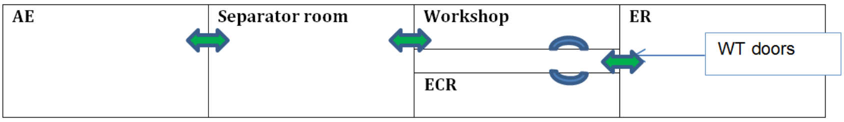
Virtual Reality Experiments

The virtual Reality experiments addressed two issues: crew members' use of watertight doors (specifically, the frequencies with which they closed or left open WTDs, and the frequency with which they made potentially unsafe crossings of WTD thresholds when the doors were partially open), and their movement around hazardous objects located within the room space within which they were operating.

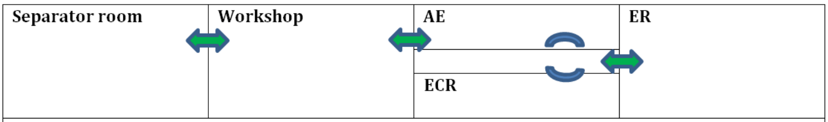
Twelve experienced Ropax Engineers were recruited. Factors manipulated in the WTD scenarios included compartment layout around the engine room (i.e., the relative locations of the control room and the workshop) with manually operated and automatic door closure WT door mechanisms. Three experimental scenarios were designed to investigate the effect of WT door crossing frequency as a function of compartment layout. These were conducted in a CAVE virtual reality platform, which is a visualization system consisting of 4 screens (3 walls and a floor) and provides an immersive environment where users are surrounded by virtual images. Special glasses provide high quality stereoscopic visualization and a tracking system attached to one pair of glasses provides a perspective adapted to the position of the research participant. Tasks were devised which required participants to move between an engine room, an auxiliary engine room, a workshop, a separator room, and a control room. Participants had to attend to numerical displays within each room, and to add up the 3-digit numbers displayed on these to yield a final 4-figure total. Three different arrangements of the rooms were devised in order to create situations involving a minimal (8) number of WTD crossings, an intermediate (14) or a maximum number (26) of WTD crossings (see Figure 2 below):



Engine compartment configuration Case 1(14 crossings: moderate)



Engine compartment configurations Case 2 (26 crossings: frequent)



Engine compartment configurations Case 3 (8 crossings: infrequent)

Figure 2: arrangements of Engine Room, Auxiliary Engine Room, Workshop, Engine Control Room, and Separator room in the three different scenarios, and the sequence of movements between compartments required in order to complete the assigned task.

The results, although demonstrating a very high door closure rate nevertheless provide some tentative support for the hypothesis that higher frequencies of encounters may be associated with a higher frequency of failure to close doors: although the majority of doors were closed, only 1 participant (9% of the sample) failed to close 100% of doors on the 8 crossing (low frequency) scenario but 3 participants (27% of the sample) left at least one door open during the exercise on 14 crossing (moderate frequency) and 26 crossing (high frequency) scenarios. These results are necessarily tentative due to the sample size, but could be argued to suggest that reducing the frequency of door crossings may be associated with fewer incidences of crew members failing to ensure that all doors are closed as they navigate round their route. Furthermore, reducing required door crossing frequencies and locating compartments that are most heavily commuted between close to each other appear to be associated with considerable time savings on task completion. Based on these conclusions, reducing the frequency of door crossings during the design stages of arranging engine room compartments may reduce societal and personal injury risks.

A further three experimental scenarios were conducted using a Head Mounted Display (HMD) platform. The aim of these experiments was to investigate the influence of engine room passage widths on both collisions with, and proximity to hazards. Essentially the question addressed here was the likelihood of crew members to use additional passing space when it was available.

Hazard scenarios were performed using a head mounted HMD display device that had a small display optic in front of each eye. It operates in communication with an Intersense IS-900 tracking system to translate the user head movements into the virtual simulations. The position and orientation of the head in relation to the virtual scene was recorded in addition to the collisions with hazards and proximity to them.

An engine room hazard simulation was devised with three different widths of passageways. Passing distances have been computed from the mean width (0.84m) found from a sample of 100 RoPax vessels by project partners, Naval Architecture Project (NAP) who provided this data from their internal database. This constituted the moderate passage width used in the experiments. The maximum width was derived from taking one standard deviation above the mean (1.15m) and the minimum width was one standard deviation (0.52m) below the mean passage widths found on the tank top of 200m RoPax vessels. The minimum passage width found across the sample of vessels was 0.38m and the largest was 2.05m, and therefore the values adopted for the experiment fell within these limits.

Hazards included floor pipes and tools lying around, presenting a trip hazard, an overhead pipe presenting a head injury hazard, and missing floor plates, which presented the danger of falling through an aperture in the floor (Figure 3). Participants navigated the route in both directions leading to 16 observations of behaviour around hazards for each participant.

It was hypothesised that increased space would be associated with reduced proximity to hazardous objects and with a faster navigation time around the space where objects have been noticed. Accordingly, it was predicted that Case 1 (maximum passage width) would provide the optimal design of those presented.

Again results from hazard scenarios are tentative but the patterns were generally consistent across the sample. For example, the mean percentages of objects collided with was 58.2 in the simulation with the widest passageways, 68.9% in the simulation with the intermediate width passageways, and 85.3% in the narrowest passageways. The mean proximity to hazards was lowest in the case of wide passageways (0.09metres) intermediate in the medium width passageways (0.05m) and highest in the case of narrow passageways (0.02m), suggesting that if mariners are provided with extra

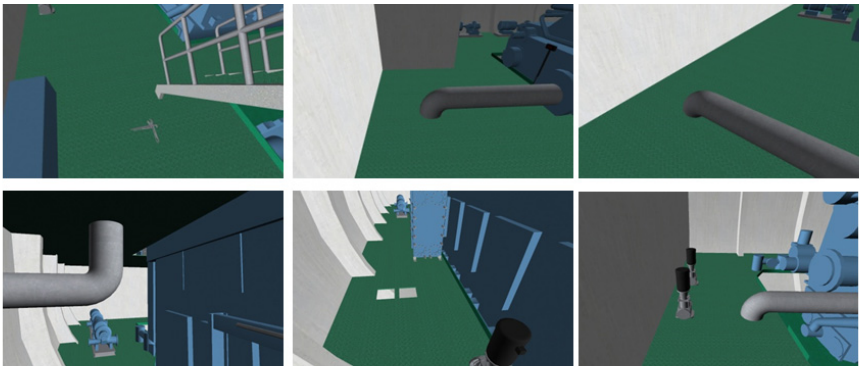


Figure 3 Hazards in HMD scenarios

space adjacent to a hazard they will use that space to create a greater distance between themselves and the hazard. The results therefore indicated that increasing engine room passageway widths in areas where hazardous objects are likely to be found may be likely to reduce proximity to and collisions with hazardous objects, thereby reducing personal risk.

Overall conclusions and outlook to next steps

Both the physical and the virtual experiments provided data that largely conformed to the predicted patterns but the variation involved across GDF conditions did not attain statistical significance in those cases where statistical analysis was possible. There are several possible reasons for this: for example, the length of time during which mariners were exposed to GDFs was very short; the mariners themselves may have, despite careful instruction to the contrary, been concerned that the outcome of their individual performance might be reported to their employers and therefore made extra effort at the tasks, hence for example the very high frequencies of closure of watertight doors in the various conditions of the WTD task; individual differences in approach to the tasks may have diluted the effects of GDFs given the small sample size; and so on. These considerations will inform the design of the experimental studies to be undertaken in Work Package 7.

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Risk models for crew injury and death on cargo and passenger ships

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One of the aims of FAROS project is to develop risk models that would suit the purpose of risk-based ship design process (RBD). The risk model described in this paper addresses the specific question about the effect of several performance-shaping factors, known as global design factors (GDF), on human performance and the subsequent probability of crew injury and death. The GDFs we are interested in are ship motion, noise, whole-body vibration (WBV) and Deck Layout, Equipment Arrangement and Access (DLEAA).

A pragmatic, evidence-based approach to human performance risk modelling emerged from the literature on the effects of exposure to the GDFs. This approach combines the principles of three theories; the Dynamic Adaptability Model (DAM – Hancock & Warm, 1989), the Cognitive Control Model (CCM – Hockey, 1997), and the Malleable Attentional Resources Theory (MART - Young & Stanton, 2002). Taken together these theories describe a mechanism that accounts for the impact of stressors on human performance, based on the principles of attention management. Regarding the effect of DLEAA, an approach was taken based on the assessment of vessel design characteristics and their potential effects on human performance.

This approach, in conjunction with expert knowledge and a review of personal injury accident data allowed us to develop a risk model that quantifies the effect of GDF on the probability of crew injury or death. The risk model for personal injury of the crew was designed to provide a predictive measure of risk of personal injury due to exposure of operators to GDFs during vessel operations. The model is intended for use as a means of comparative assessment of the personal injury risk posed by the GDFs associated with two or more vessel designs.

Personal Injury risk model development

In FAROS, a definition for personal injury of the crew was required that could reflect the potential effects of GDFs exposure leading to an unwanted outcome of injury or death of a crew member. We have defined personal injury as a physical injury of the body of a crew member as the result of an incident on board (excluding acts of violence and suicide). This personal injury ranges from minor abrasions causing temporary pain and inconvenience, to the permanent loss of limbs or other bodily function, disability and fatality.

Personal injury logical causal chain

Requisite to the development of the risk model is an understanding of the process through which exposure to GDFs can influence the occurrence of a personal injury. This necessitated the identification of a causal pathway that links the input (exposure to GDFs) with the output (crew injury and death) through the mediating agent of the crew member. The casual path from the exposure to GDFs, though human performance to the occurrence of a personal injury, is summarised in **Figure 4**. Two main paths connecting GDFs to a personal injury have been identified:

- The injury could result from a direct exposure to the GDF (e.g. hearing damage due to loud noise) and this is considered to be **work-independent** effect.
- GDFs can affect the ability of a crew to carry out their task in a safe manner which could result in an injury. Noise, vibrations and ship motions impact work performance through their effect on the perceptual, cognitive and physical capabilities of the crew, while the effect of the DLEAA (deck layout, equipment arrangements and access) is understood to be through the changes in the task demand (i.e. adds constraints). In this case the effect of the GDFs is considered to be **work-dependent**.

The personal injury risk model focuses on this work-dependent causal path.

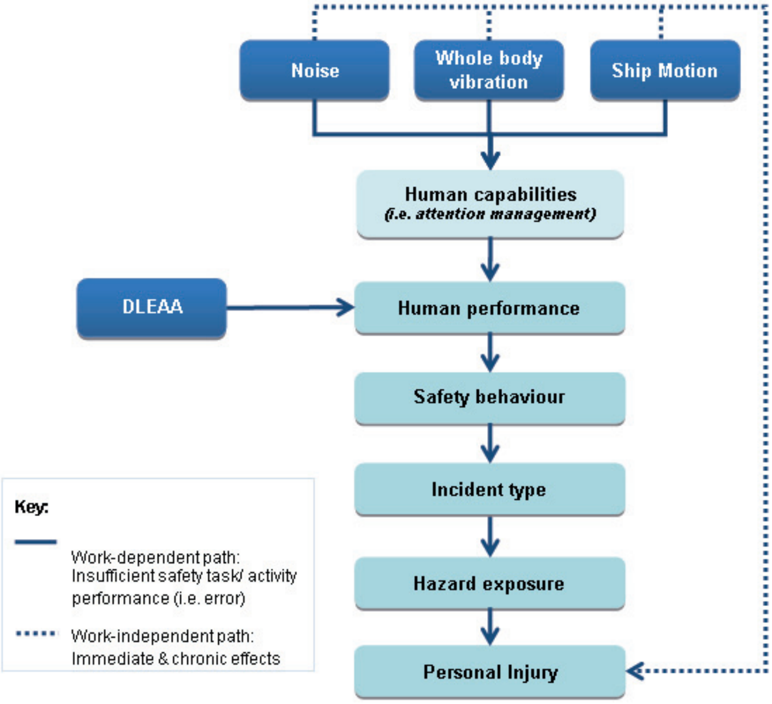

Figure 4: Work-dependent and work-independent causal paths describing the effect of GDF on human performance and safety behaviour, and the occurrence of personal injury.

The work-dependent causal path shows how GDF exposure affects human performance, which in turn influences the performance of safety behaviour. For the purposes of the personal injury risk model, we assume that human performance has two levels:

- Sufficient: Human performance which is timely and correct (but not necessarily optimal).
- Insufficient: Human performance which includes errors (but is not necessarily limited to them).

Safety behaviour performance can be unrelated to the specific task being performed and is linked to its intrinsic safety behaviour component (e.g. holding a banister while on stairs, using fall arrest equipment). However, insufficient safety behaviour performance alone does not determine whether or not an incident occurs (e.g. the act of not holding a handrail while walking down stairs does not mean you will always have an incident). Based on this, we have defined insufficient performance of a safety behaviour as 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.

The insufficient performance of safety behaviours creates the antecedent for the occurrence of a certain incident type (e.g. fall from height, hit by moving object) and then exposes the crew member to a hazard (kinetic, thermal, chemical, etc.). Finally, if the hazard exposure results in a level of energy transmitted to the individual that is sufficient to be injurious, then injury or fatality may occur. For example, an individual will be exposed to a greater amount of hazard (kinetic energy) if they were to trip whilst descending stairs in comparison to a trip whilst walking on level ground. It is much more likely that the former will expose the individual to a sufficient amount of kinetic energy to be injurious.

Review of personal injury accident data

To aid the development of the personal injury risk model, accident data was examined with the aim of identifying the causal and contributing factors to personal injuries of crew on-board vessels. Overall, there is a lack of consistent data on seafarer injuries and fatalities, especially of the type that can be used for the development of risk models. To better inform risk model development, a further qualitative analysis of accidents was then performed using reports from the MAIB (UK), BEAmer (France) and JTSB (Japan) records to gain a deeper understanding of the situational antecedents that contribute to personal injury outcomes. The most frequent and severe reported incident types, and focus of the FAROS personal injury risk model, are:

- Slips, trips and falls
- Falls from height
- Hit by moving (included dropped) object
- Manual handling (handling, lifting or carrying)
- Entering enclosed spaces

This information was used to develop conceptual models to assist the final risk model development.

Personal Injury risk model

The FAROS Generic Personal Injury Model (FGPIM) BBN (see **Figure 5**) was developed to reflect the work-dependent causal mechanism underlying personal injury defined above. The risk model was developed using Bayesian Belief Networks (BBNs), which are probabilistic tools being capable of representing background knowledge about the personal injury phenomena, the quantification of associated uncertainties, efficient reasoning and updating in light of new evidence. BBNs have already been used in the maritime context to model risk. In particular in the EU funded project SAFEDOR, where they were used for structural integrity and collisions and grounding. In FAROS, and based on the experience gained in SAFEDOR, the fire, collision and grounding risk models are also modelled with BBN.

Risk model structure

The structure of the BBN is essentially based on the causal chain for the impact of GDFs on the occurrence of Personal Injury explained above.

The generation of personal injury outcomes is ultimately determined by the sufficient or insufficient performance of safety behaviours for a single instance where safety behaviours are required (i.e. time is not modelled within the FGPIM). Insufficient performance of safety behaviours exposes an individual to hazards, and therefore the possibility of personal injury (green, dark yellow and red/white nodes). Three mechanisms combine to determine the whether a safety behaviour is successfully performed or not:

- GDF exposure results in degradation of a crew members attention management capability via a stressor effect (yellow node)
- GDF exposure directly influences task performance via a physical effect (red node)
- DLEAA characteristics affect the task demands associated with safety behaviour (blue node)

The output of the risk model quantified the probability associated with the outcomes to the crew in line with the definition of personal injury adopted by FAROS (i.e. Fatality, Injury, No injury), and as such, enables comparative assessment of ship designs.

Model inputs

Where possible, the input level values for each GDF (grey nodes) of ship motion, noise and WBV, and the probability of their effect have been determined from the literature review conducted earlier in the project. The data available rarely describe the effects probabilistically, therefore estimation was required to attribute the probability of GDF exposure having an effect of some kind.

To best represent the effects of ship motion, noise and WBV GDF exposure as described in the literature, a threshold of effect was set as a Boolean variable (purple nodes). GDF exposure was therefore represented either above or below the level of a stressor effect (with subsequent impact on attention management) or direct physical effects. In reality, the threshold of effect may be different for all individuals, but what is important from a human performance perspective is whether an individual experiences an effect.

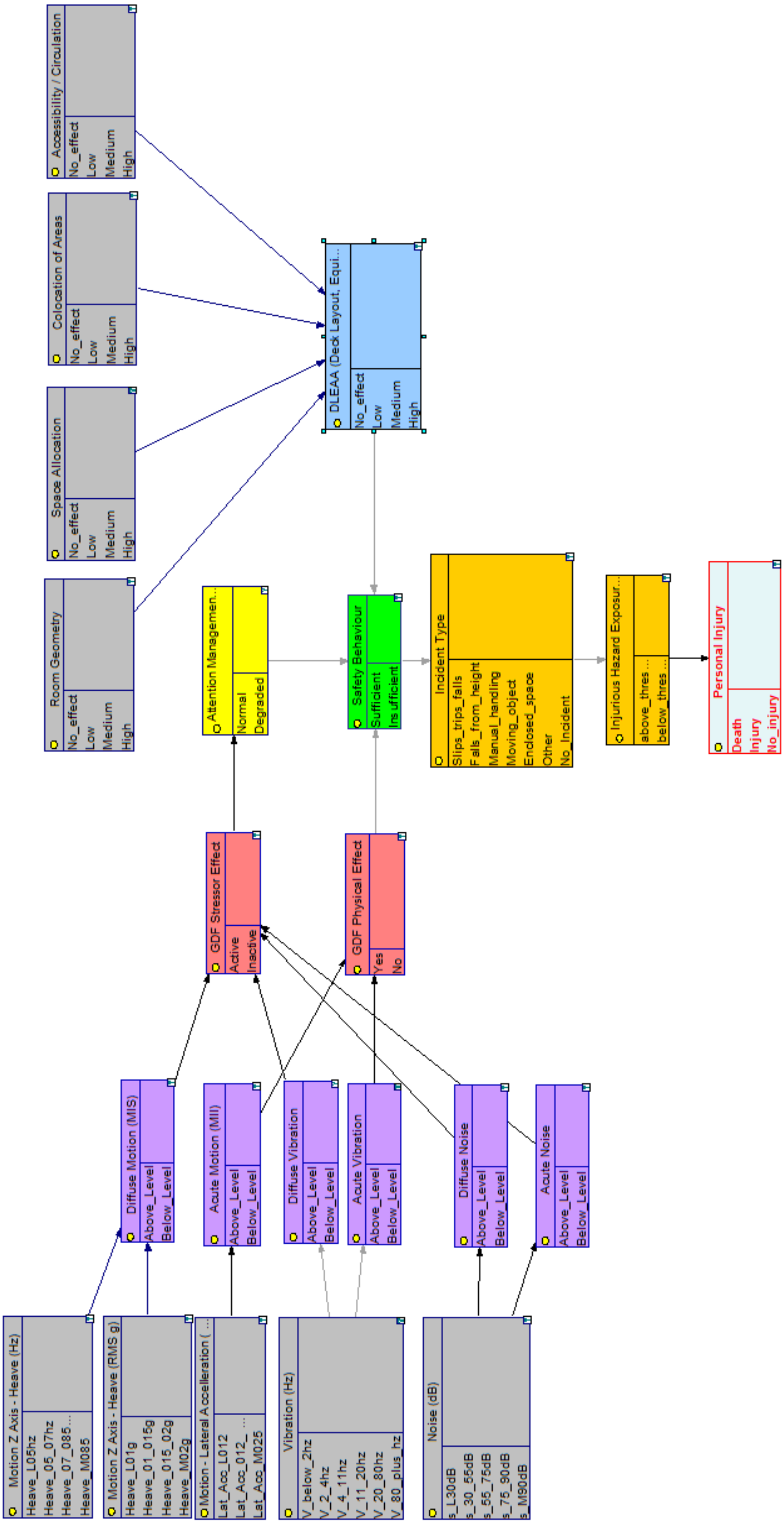

Figure 5: FAROS Generic Personal Injury Model (FGPIM) BBN.

The effects of DLEAA exposure (blue node) was also represented based on expert judgement of the DLEAA characteristics. Here, four levels (‘no effect’, ‘low’, ‘medium’ and ‘high’) have been defined to approximate the combination of potential effects resulting from the strength of DLEAA input parameters. The qualitative assessment of DLEAA characteristics used criteria based on an extensive literature review. The highest rated of the four characteristics was taken as the input level feeding into the rest of the model.

Integrating human reliability assessment in the risk model

During the risk model development, a gap existed in the definition of probabilities describing the likelihood of ‘insufficient’ safety behaviour performance given the demands generated by exposure to the GDFs. Limitations in data on the effects of GDFs on human performance means that such values are not available in the scientific literature.

A solution was found in Human Reliability Analysis (HRA) techniques. While HRA techniques do not typically cover the specific GDFs or the maritime context, the human error probabilities (HEPs) generated by HRA allow sensible bounds to be determined for FAROS risk model nodes. The integration of the HRA method HEART (Human Error Assessment & Reduction Technique; Williams, 1986) provided a means to determine the probability of insufficient safety behaviour represented as human error.

HEART was used to determine a baseline human error rate (Nominal Unreliability Value – NUV) to set the safety behaviour HEP unaffected by GDF exposure. One of the limitations of the application of HEART in this context was highlighted by the difficulty in selection of the task from the predefined list within HEART. The task selected represented safety behaviours associated with the incident types and defined the associated NUV. To limit the complexity of the model, a single generic task type was sought to represent all possible safety behaviours. The best fit was determined to be: *Task M – Miscellaneous tasks for which no description can be found (NUV = 0.03).*

This then allowed probabilistic estimation of the effect of GDF exposure on HEPs over the baseline error rate for the chosen task type. HEPs affected by GDFs were represented through the selection of appropriate Error Producing Conditions (EPCs) and associated Proportion of Affect (POA). EPCs from HEART best fitting the attention management and DLEAA paths were selected. The EPCs selected to represent the stressor effects on attention management capability and the effects of DLEAA are shown in Table 1. The potential strength of effect of the each EPC was set using the POA variable (see Table 1).

Table 1: Maximum POA Value Caps for EPCs associated with Attention Management and DLEAA paths.

GDF effect path	HEART EPC Ref	HEART EPC description	Max POA cap	Justification for max POA cap
Attention Management	EPC No. 8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information unintended action.	0.1 (low)	GDF effects on cognitive performance are generally weak.
DLEAA	EPC No. 5	No means of conveying spatial and functional information to operators in a form which they can readily assimilate.	0.1 (low)	Spaces on board vessels are not complex from a perceptual standpoint.
	EPC No. 6	A mismatch between an operator's model of the system and that imagined by a designer.	0.1 (low)	Design does not often incorporate a strong model for DLEAA. It provides options for access / movement reducing the possibility of a designer/operator model mismatch.
	EPC No. 12	A mismatch between perceived and real risk.	1 (high)	Risk perception is a key causal factor in personal injury incidents.
	EPC No. 21	An incentive to use other more dangerous procedures.	0.1 (low)	Crew may use route short cuts to save time or reduce effort when moving between areas resulting from design decisions to collocate or segregate work areas.

The HEART calculation is done in two stages and allows inclusion of multiple EPCs. Firstly, actual effect of each EPC calculated based on the following formula:

$$\text{Actual effect} = [(\text{Max. effect} - 1) \times \text{POA}] + 1$$

The final error probability for the task is then determined by multiplying each actual EPC effect with each other and with the NUV of the selected generic task:

$$\text{HEP} = \text{NUV} \times (\text{Actual effect}_1) \times (\text{Actual effect}_2)$$

HEART was not used to represent the direct physical effect exposure some GDFs may have as physical aspects of task performance is out the scope the intended application of the method.

BBN sensitivity & uncertainty analysis

A sensitivity and uncertainty analysis of the personal injury risk model was performed as part of the model validation process.

The sensitivity analysis have shown that the FGPIM is responsive to changes in the GDF nodes which are reflected in changes in the probability of ‘no injury’, injury’ and ‘death’ of the ‘personal injury’ node outcome. The output of the FGPIM also broadly reflects personal injury outcome incident data in terms of the low relative frequency of deaths versus injuries observed within the marine industry. When all the GDFs are set to their lowest effect (i.e. best) state, the probability of ‘No Injury’ is at its highest. When all the GDFs are set to their worst state the probability of ‘Death’ (although very low) and the probability of ‘Injury’ both increase by 94% (when compared to the best case). This would suggest that the GDFs have an effect on the state of the outcome node.

In absolute terms, the FGPIM estimates the probability of ‘no injury’, ‘injury’ and death as shown in Table 2 for the base, worst and best cases respectively. This data demonstrates how vessel designs with different GDF characteristics may impact personal injury risk.

Table 2: Absolute probabilities of 'No Injury', 'Injury' and 'Death' outcomes generated by the FGPIM for the base, best and worst cases.

Probability	Base Case	Worst Case	Best Case
No Injury	0.718	0.711	0.982
Injury	0.281	0.288	0.018
Death	0.001	0.001	0.0001

When changing the state of a GDF one a time, there is a small change in the probability of the outcome as expected because the general effect of GDFs acting through the stressor pathway is weak. The greatest effect has been found through the DLEAA pathway that impacts the task demands. This is followed in strength by the physical pathway, especially from lateral accelerations, reflecting a potentially stronger effect of task disruption from physical disturbance associated with lateral accelerations.

The evidential uncertainty analysis qualitatively assessed the evidence underpinning each node identified in the sensitivity analysis as being highly sensitive. Each of these nodes was rated as having either minor, moderate or significant uncertainty based on pre-defined criteria.

The results of the sensitivity and uncertainty analyses were combined in a parameter importance analysis to provide a summary of the most sensitive and uncertain nodes within the model. A high importance rating identifies the nodes that have both a high uncertainty rating and sensitivity rating. These nodes are important in the interpretation of the model as they reflect influential nodes about which relatively little may be known. The results of these analyses are shown in Table 3. This analysis shows that the only GDF that is rated as having high importance is the Motion - Lateral Acceleration node, while the other DLEAA GDFs are rated ‘Moderate to high’. The other nodes rated ‘high’ reflect the overall topology of the model whereby the final personal injury outcome is generated exclusively by the antecedent nodes of ‘Safety Behaviour’ and ‘Injurious Hazard Exposure’.

Table 3: Sensitivity, Uncertainty and Parameter importance assessment results

Node (Parameter)	Sensitivity rating	Evidential uncertainty rating	Importance rating
Safety Behaviour	High	Moderate	High
Injurious Hazard Exposure	High	Significant	High
Incident Type	High	Moderate	High
Attention Management	Moderate	Significant	High
Room Geometry	Low	Significant	Moderate to high
Space Allocation	Low	Significant	Moderate to high
Location of Areas	Low	Significant	Moderate to high
Accessibility / Circulation	Low	Significant	Moderate to high
Motion - Lateral Acceleration	Moderate	Moderate	High

The states of the nodes with a ‘high’ and ‘moderate to high’ importance rating should be set especially carefully when comparing different ship designs as small changes in these parameters will have a large impact on the model output. However, as the model is only intended to compare vessel designs and not to provide a nominal estimate of the risk, this is only a caveat for applications outside of FAROS.

Conclusion

The FGPIM was created to model the risk of personal injuries of crew when exposed to the GDFs of ship motion, noise, whole body vibration (WBV) and DLEAA for both large passenger (RoPax) and cargo (tanker) vessels. The FGPIM provides a representation of personal injury risk in this context, utilising available research to its maximum extent. The FGPIM achieves its objective to provide a predictive measure of risk of personal injury due to exposure of operators to GDFs during vessel operations.

The FGPIM BBN is a stand-alone model that behaves in response to GDF inputs as intended and broadly reflects personal injury incident data from the marine industry. As with all models, the FGPIM comes with a number of assumptions, exclusions and caveats for use; however the facility to probabilistically assess and compare vessel designs based on personal injury risk was achieved. Subsequent work within FAROS sought to integrate the FGPIM with other risk models for collision, grounding and fire.

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Collision and grounding risk models for RoPax and tankers.

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Introduction

One of the aims of FAROS project is to develop risk models that would suit the purpose of risk-based ship design process (RBD). The risk models have to address specific question about the effect of specific performance-shaping factors known as global design factors (GDF) on human performance thus the probability of an accident and resulting consequences. These GDFs comprise ship motion, noise and whole-body vibrations (WBV). A workable approach for human performance risk modelling has emerged from the literature on the effects of exposure to ship motion, noise and vibration GDFs focussing on attention management, (Kivimaa et al. 2014). It is based on three theories: the Dynamic Adaptability Model, - (Hancock 1989) - Cognitive Control Model - (Robert and Hockey 1997) - and Malleable Attentional Resources Theory - (Young and Stanton 2002). The concept of Attention Management along with the experts' knowledge allowed us to develop two models that quantify the effect of GDF on the annual probability of collision and grounding for a RoPax and a tanker navigating along predefined routes. The models were developed with the use of Bayesian Belief Networks, which are powerful modelling techniques in the risk assessment (Fenton and Neil 2012).

Furthermore, the probability of an accident itself or combined with the consequences of the accident in terms of fatalities and the size of an oil spill allows us to determine the risk metric, which can be later used in the RBD as one of the objectives.

Methods

The risk models presented here are developed using Bayesian Belief Networks (BBNs), which are probabilistic tools being capable of representing background knowledge about the collision and grounding phenomena, the quantification of associated uncertainties, efficient reasoning and updating in light of new evidence. The models presented here are stand-alone that behave in response to GDF inputs as intended. The results are comparable with other existing models, and the data from the marine industry, (Porthin, Innes-Jones, and Puisa 2014). The models can enable comparative assessment of ship designs, which is their primary intention.

Adopted risk perspective

In this paper we adopted an uncertainty perspective of risk, where risk is seen as follows, (Aven and Renn 2009):

$$R \sim C\&U \tag{1}$$

This means that risk assessment is an expression of an assessor's uncertainty (U) about the occurrence of events and the associated consequences (C). Following this perspective, risk assessment can always be performed, as the risk model is seen as a tool to describe and convey uncertainties rather than a tool to uncover the truth. For this purpose, the risk model encompasses the events and their potential consequences.

General structure of the risk model

To describe the process through which exposure to GDFs causally affects the probability of the specified unwanted outcomes, a causal pathway was developed through the mediating agent of the crewmember. Importantly, the causal chain represents the effects of GDFs exposure on human performance in a way that could be developed and elaborated in the risk model. Two main paths linking GDF exposure to human behaviour, and subsequently to collision and grounding, have been identified:

- Path 1: Stressor effects. Exposure to a GDF acts as a stressor and can affect the perceptual, cognitive and physical capabilities of an individual (e.g. attention management), which can subsequently impair the performance of the individual (i.e. the actual behaviour produced).

- Path 2: Physical effects. Exposure to a GDF can have specific and direct effects on the behaviour produced. For example, Ship motion can result in Motion-Induced Interruptions (MII). MII does not affect the underlying human capabilities of balance or fine motor control, but it exceeds the ability of the human to compensate and produce the intended behaviour. Similarly, WBV can directly impact the actual behaviour produced.

These two paths show how GDF exposure affects human behaviour, which in turn influences the performance of safety critical tasks, as depicted in Figure 1. It is the outcomes of an individual's actions and behaviour that determine the success or failure of a safety critical task. Insufficient performance of the safety critical tasks associated with maintaining safe vessel navigation and avoiding collision or grounding create an antecedent for the unwanted outcome. However, insufficient task performance alone does not determine whether or not a collision or grounding occurs; the vessel must also be exposed to the collision or grounding hazard, as follows: a) for a collision to occur, another vessel must be on a collision course; b) for a grounding to occur, the ship must be in shallow water.

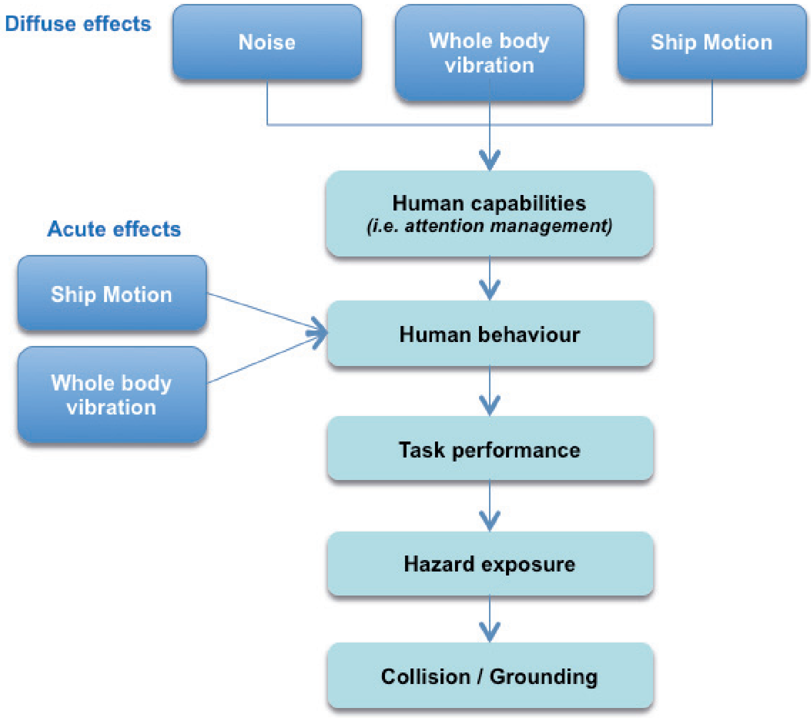

Figure 1: Causal chain describing the relationship between crew GDF exposure and unwanted outcomes, (Montewka, Goerlandt, Innes-Jones, et al. 2014)

Human performance model

The approach taken here to describe a mechanism that accounts for the impact of stressors on human performance, has been based on the principles of attention management, (Owen, Pozzi, and Montewka 2014). It combines the principles from three theoretical models:

1. Dynamic Adaptability Model (DAM), (Hancock 1989).
2. Cognitive Control Model (CCM), (Robert and Hockey 1997).
3. Malleable Attentional Resources Theory (MART), (Young and Stanton 2002).

Generally, task performance is only expected to degrade and become insufficient when compensatory mechanisms have failed. However, the literature does not allow prediction of how and when (chronologically) an operator would fail, under what conditions of GDF exposure, and what the specific effect on behaviour (i.e. type of error) would be.

In the risk models presented here, the main task around which the models revolve is to perform the accident evasive action. This task is complex and distributed in time, but it can be decomposed into three major phases: a) detection, b) assessment, c) action. These three phases reflect the basic cognitive functions of observation, interpretation and planning, and execution, see for example (Hollnagel 1998; He et al. 2008).

In terms of risk modelling, an approach based on attention management theory allows representation of the effect of GDF exposure as a stressor that sits either above or below the threshold of attentional capacity for any given task. If the stressor exceeds the attentional capacity then a negative effect is expected, whereas no negative effect on human performance would result if the stressor can be managed within the available attentional capacity.

Integration of Human Reliability Assessment in the risk model

Due to limitations in data on the effect of GDF exposure on human performance, one can't precise values in the scientific literature. Therefore, the HRA method Nuclear Action Reliability Assessment (NARA) was selected to provide the human error probabilities (HEPs) associated within collision and grounding model, (Spitzer, Schmocker, and Dang 2004). NARA was adopted to select validated (albeit non-marine specific) HEPs associated with task characteristics that are compatible with tasks performed by the Officer of the Watch (OOW) and helmsman. NARA also provided baseline error rates for a given Generic Task Type (GTT) unaffected by GDFs. This allowed probabilistic estimation of the effect of GDF exposure on HEPs.

However, NARA was not used to represent the direct physical effect exposure some GDFs may have as physical aspects of task performance. This is out the scope the intended application of the NARA method. The probability of insufficient human performance resulting from physical effects of GDF exposure was estimated based on judgement alone.

NARA categorises the factors that negatively influence human performance as one of eighteen Error Producing Conditions (EPCs). The EPC that best represented the causal mechanism from GDF exposure to human performance was EPC No. 15: *Poor Environment*. This EPC represents the stressor effect of GDF exposure on attention management capability. The potential strength of effect of this EPC was set using the Assessed Proportion of Affect (APOA) variable. The APOA level was set based on the application of the NARA methodology to subjectively determine an appropriate value, nominally between 0 (no effect) and 1 (maximum effect). However, based on the guidance available for NARA, it was decided to cap the maximum APOA associated with the EPC to 0.1.

To limit the complexity of the model, a single GTT was sought to represent all relevant navigational tasks performed by the OOW that are important in managing collision or grounding risk. The GTT that is most analogous is: *Task C1 – Simple response to alarms/indications providing clear indication of situation (Simple diagnosis required) Response might be direct execution of simple actions or initiating other actions separately assessed. (Nominal HEP = 0.0005)*

A second GTT was identified to account for possibility that a helmsman may also be present. In this case the helmsman is steering the ship based on verbal instructions communicated by the OOW. The GTT that is most analogous is: *Task D1 - Verbal communication of safety critical data.*

Having a helmsman present may introduce the possibility of a miscommunication error with the OOW. NARA also recognises a mitigating effect of a team. The NARA Human Performance Limiting Value for ‘Actions taken by a team of operators’ was used to cap the potential error rate at *1E-4* for the condition where a helmsman is present. The same value is taken for the probability of potential error of not performing evasive action by another ship involved in the encounter. The NARA calculation allows inclusion of multiple EPCs and an Extended Time Factor (ETF). In this risk model for collision and grounding, GDFs are represented using only one EPC and there is little justification to include the ETF. Thus, the HEP was calculated based on the following formula:

$$\text{HEP} = \text{GTT} \times [(\text{EPC}-1) \times (\text{APOA} + 1)] \qquad (2)$$

Following this logic one can estimate the probability of a failure in performing safety critical tasks (accident avoidance action) by a bridge team consisting of maximum two people (officer and the helmsman). The situation where an officer needs to take action in order to avoid an accident will be referred to as an encounter. The structures of the models estimating the probability of an accident per encounter are depicted in Figure 4 and 5. In order to assess the annual probability of an accident, the number of encounters that ship is exposed to over one year needs to be estimated.

Elicitation of collision and grounding encounters along predefined routes

To estimate the annual number of encounters for a ship the experts' knowledge was elicited in the course of two sessions. During the sessions we gathered bridge officers having vast experience in navigating RoPax and tankers along two routes as anticipated in the project. The routes are depicted in figures 2 and 3. Also the relevant information were collected about the bridge manning, traffic regulations and traffic monitoring services, as these affect the probability of human error. Collision encounter is defined here as a situation, where two ships meet on a collision course, and an evasive action is needed in order to avoid a collision. Grounding encounter is understood as a situation, where a ship can ground if her course is not altered, within 4 hours before the landfall, where the 4 hours corresponds to duration of a bridge watch. The numbers of encounters were assessed per one trip of a ship and then multiplied by the number of trips that a ship makes per year. Thus, the annual number of encounters for a given route was obtained. The detailed description of the elicitation method and the obtained results are given in (Montewka and Puisa 2014).

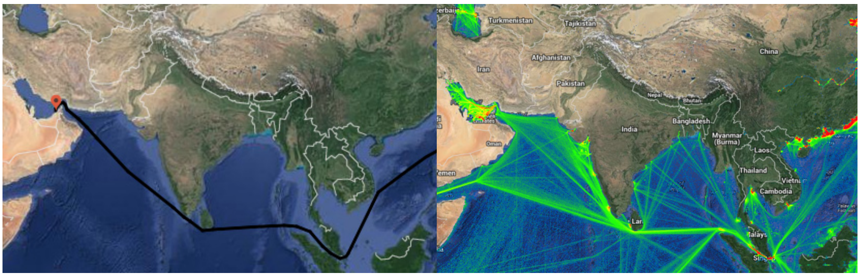

Figure 2: Tanker route from Port of Rachid (UAE) to Chiba (Japan) - to the left. Traffic density plot for the analysed area obtained from the Automatic Identification System – to the right. Total length of the route is 6452 NM.

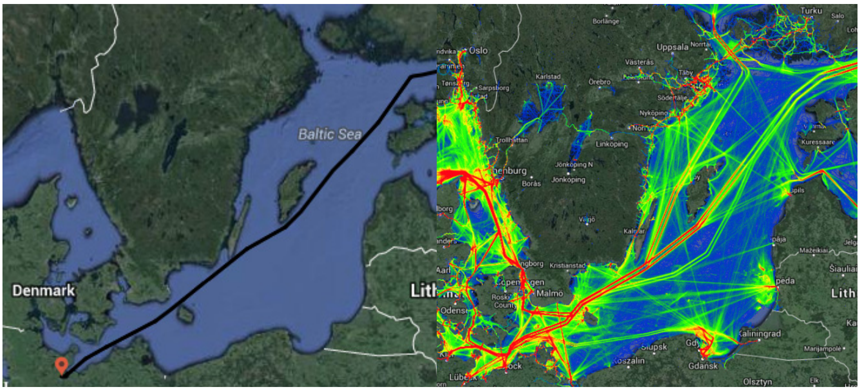

Figure 3: RoPax route from Helsinki (Finland) to Travemunde (Germany) - to the left. Traffic density plot for the analysed areas obtained from the Automatic Identification System – to the right. Total length of the route is 617 NM.

Quantification of accident probability

To make the task of encounter estimation more manageable for the experts, the routes were split into legs according to the traffic characteristics, and the numbers of encounters were estimated for each leg separately. Any specific seasonal activities were mentioned, that may occur along a leg, and affects the number of encounters. When the annual number of encounters has been obtained, the annual probability of collision and grounding for each leg of the routes has been calculated. To calculate the annual probability of an accident along the route, we applied rules, following the methodology presented in (He et al. 2008). Therein the human error probability is quantified for a task, which is composed of sub-tasks. In our case, a trip between two harbours is seen as a task, and each leg along the route is a sub-task, and the probability of an accident is associated with the lack of or improper human action. To calculate the probabilities we use the equation listed in ***Table 1***, and the following logic:

For sequential subtasks with high or complete dependence, we use the maximum probability of all subtasks, meaning that the task would fail when any of the subtasks fails, thus the highest failure probability of the subtasks is assigned as the failure probability of the whole task.

The task presented here (ship transit along the route), consists of sequential subtasks, where the failure in one of them (collision or grounding in any leg) leads to the failure in the task. Navigating a ship through a leg can be seen as a sub-task, carried out by a single bridge team, if the length of the leg is no longer than the distance covered by a ship during a watch, which are 4 hours for tankers and 6 hours for RoPax. If the leg length is greater than that, more than one bridge team carries out the sub-task. Thus, the number of encounters is split among the corresponding numbers of shifts that occur along that leg.

Table 1 *Rules for calculating the probability of an accident along the route*

Logic relation between sub-tasks	**Dependence between sub-tasks**	**The probability of not completing a task**
Only failure of all sub-tasks would fail the task (parallel subtasks)	High dependence Independent / low dependence	$P_{coll} \approx Min(P_{coll-leg})$ $P_{coll} = \prod P_{coll-leg}$
Failure of one sub-task leading to failure of the task (sequential sub-tasks)	High dependence Independent / low dependence	$P_{coll} \approx Max(P_{coll-leg})$ $P_{coll} = 1-\prod(1- P_{coll-leg}) \approx \sum P_{coll-leg}$

The probability of an accident per leg - where a leg is tantamount to a subtask - is obtained as follows:

$$P_{coll-leg}=1-e^{-pn} \qquad (3)$$

where n is a number of encounters over a given leg during one year and p stands for the probability of an accident per encounter. Following the logic presented in Table 1 the annual probability of an accident along the route (P_{coll}), composed of several legs yields:

$$P_{coll}=Max(P_{coll-leg}) \tag{4}$$

Models and results

The logic of the developed risk models accounting for the effect of GDFs on the probability of collision and grounding is presented in figures 4 and 5. With the use of the models and adopting the experts elicitation techniques to arrive at the number of encounters, we obtained the annual probability of collision and grounding for a RoPax and tanker navigating along predefined routes, as presented in tables 2 and 3. The results, which were obtained in the course of the modelling, showed good agreement with the statistical data for collisions for both types of ship analysed here. However, in the case of grounding accidents the model systematically overestimates the probability for this type of an accident, compared to the available statistical frequencies. The following reasons have been defined as possible causes for this bias, attributed mostly to the adopted method to estimate the HEP:

- In the model, grounding happens when a ship course is not altered as planned and ship navigates off the track and she grounds. In the modern bridge systems, there is a sequence of alarms, beginning with one that informs an officer that the ship is approaching a waypoint, another when a ship is in waypoint and subsequent, when the ship goes beyond the waypoint. To run aground an officer should not respond to any of these alarms (the sequences of failures), whereas the model presented does not account for such sequential failures.

- The grounding model does not account for the fact, that an officer navigating a ship is aware of the potential spots for grounding along the route.

These imply an increased awareness, which is not reflected in the model, and can be seen as a major reason for the model bias. Despite the evident bias, the proposed risk models can be directly used for the quantification of the effect of GDFs on risk in a comparative manner. However, if the model is to be used for the cost-benefit analysis, a correcting factor needs to be applied, which will remove the bias to a large extent.

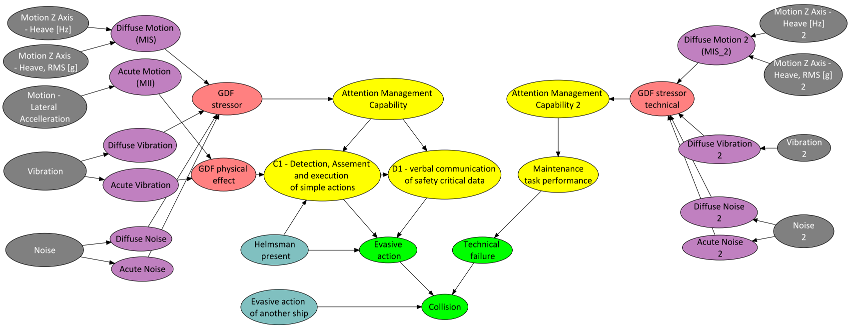

Figure 4: Risk model for ship-ship collision

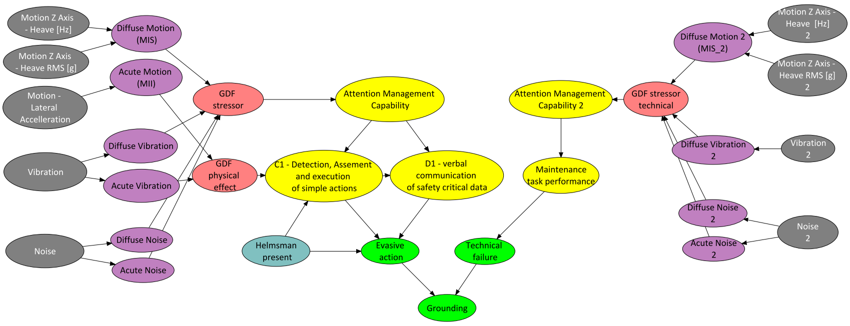

Figure 5: Risk model for ship grounding

Table 2 The annual probability of an accident (collision and grounding) for a RoPax along Helsinki-Travemunde route benchmarked against Incident frequencies for RoPax ships (GT > 4,000) for the period 1990-2013, (Montewka, Goerlandt, Owen, et al. 2014)

Type of an accident	The average probability from the model	Frequency from the statistics
Collision	5.1E-3	1.3E-3
Grounding	3.0E-1	7.0E-3

Table 3: The annual probability of an accident (collision and grounding) for a tanker along a route from Port of Rachid to Chiba benchmarked against Incident frequencies for tankers for the period 1990-2013, (Montewka, Goerlandt, Owen, et al. 2014)

Type of an accident	The average probability from the model	Frequency from the statistics
Collision	8.0E-4	1.12 - 1.56 E-3
Grounding	2.6E-2	0.56 - 1.59E-3

Discussion

The models presented in this paper offer a novel, evidence-based approach to modelling risk of ship-ship collision and grounding. They provide a flexible framework that could readily be extended to encompass the actions of third parties and mechanical failures in the future. The flexibility to extend the model's application is provided by the causal mechanism represented within the model that describes occurrence of an accident as the result of insufficient performance of an individual when exposed to hazardous situation.

The integration of NARA to support the calculation of HEPs within the risk models has clear positives and negatives. On the one hand, it provided a facility to generate 'reasonable' HEPs using a well-known method, which would not have been possible otherwise. On the other hand, the application of NARA to physical tasks associated with physical effect of the GDFs on *Detection, Assessment and Execution of Simple Actions*, is stretching its application to, and perhaps beyond, its limit.

Despite the limitations and the paucity in data supporting certain hypotheses, the application of BBNs as a modelling tools, allows for clear representation of the modelled problem and comprehensive distribution of all the recognised uncertainties. By adopting BBNs and performing the importance analysis, we learned that the crucial elements of the models are the nodes, where the human error probabilities are quantified. Whereas the detailed quantification of the levels of GDFs associated with a given ship design or their effect on the attention management capability is less important, (Montewka, Goerlandt, Innes-Jones, et al. 2014).

Finally, comparative assessment of vessel designs based on manipulation of the GDF input nodes is possible in principle. The models are responsive to changes in the GDF nodes as expected. Naval architects, vessel designers, and vessel system designers may use the models as intended, provided access to human factors expertise is available to assist with application and interpretation. It is important to recognise the relevance of human factors input during its eventual application. Human factor provides the understanding of the complexities of human behaviour in operational settings, its interdependencies and interactions.

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Jakub Montewka obtained his Ph.D. in technical sciences at Maritime University of Szczecin in Poland in 2008, where he has been working from 2001 until 2008. At the same time he gained an operational knowledge and skills working on board sea going vessels as a navigator (2001-2008). Since 2009 he has been employed at Aalto University, Marine Technology with the main task to develop models for maritime traffic safety assessment. At the moment the models for a holistic safety assessment are being developed with the use of Bayesian methods.

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Fire ignition modelling

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Background

Project FAROS has the ultimate goal of understanding, integrating and demonstrating the role of human factors in risk-based ship design. To that end, the risk models for each principal hazard are enhanced with human error and other human factors related aspects. Such models are then used in the ship design process, specifically focusing on assessment of initial design alternatives. The initial design stage is indeed most critical, for significant design modifications at this early stage are most cost effective. The project focuses on three principal hazards to crew and passengers onboard:

- Personal injuries (crew only), addressed in report D4.5 (Owen et al., 2014)
- Flooding, following collision and grounding events as described in report D4.6 (Montewka, 2013a)
- Fire, addressed in report D4.8 (Puisa et al., 2014) of which part is summarised in this paper.

Report D4.8 contributes to understanding of fire root causes, precursors and outbreak conditions. It specifically presents probabilistic ignition models, ignition scenarios and ignition statistics for various onboard spaces with human factors playing a decisive role in causing or insufficiently preventing the fire outbreak. Additionally, the report addressed the integration of human factors (e.g. human error) into the ignition models, where appropriate. In turn, the human factors were linked to the following global design factors (GDFs) addressed in project FAROS:

- Noise
- Vibration
- Ship motions
- Deck layout, equipment arrangement and accessibility (DLEAA)

In this work, human errors are assumed to cause either ignition preconditions (fuel or heat source) or technical faults which, with time, may lead to such preconditions. Figure 1 outlines the assumed causal chain that links GDFs, human performance, human errors and their consequences. The link between GDFs and human performance is addressed in report in D3.5 and D3.6 (Montewka, 2013b, 2013c), whereas the remaining part of the causal chain is treated in this paper.

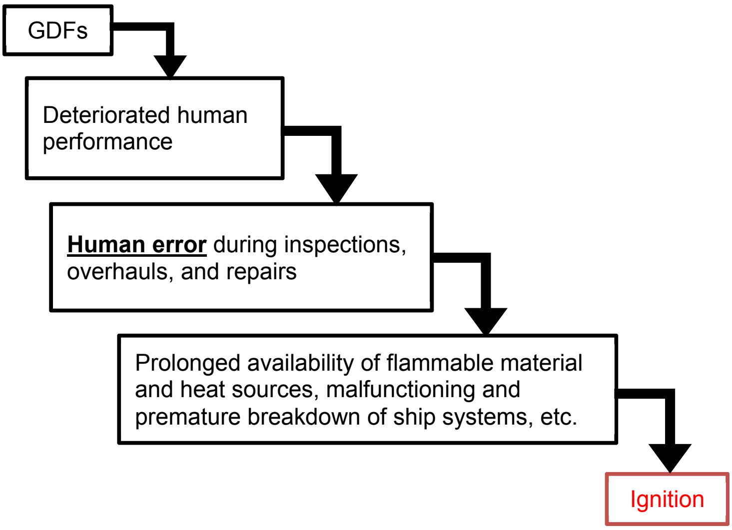

Figure 1: Used causal chain in the developed ignition models

Thus, modelling of fire ignition probabilities for various spaces on RoPax and tanker ships is the ultimate outcome of this work, as far as its application in FAROS is concerned. The modelled probabilities are then combined with the fire consequence model (Guarin and Logan, 2011) to calculate fire risk which is defined as the expected number of fatalities (or Potential Loss of Life (PLL), ref. MSC 83/INF.2) resulting from fire events. The integration of the ignition and consequence models is described in public report D5.1 (Montewka and Puisa, 2014).

There are a number of caveats which concern the validity of the modelled ignition probabilities. First, the estimated ignition probabilities should not be confused with fire accident probabilities (or relative frequencies) inferred from historical records. The latter normally correspond to medium and large scale fires with failed fire detection or/and suppression systems. The probability of such fire accidents would always be much smaller than corresponding probabilities of ignition. Second, estimated probability values cannot be guaranteed to be entirely accurate (probabilities are imprecise), although their order of magnitude is thought to be representative.

Introduction

Fires onboard are reoccurring events, causing losses of life and property. SOLAS[3] Chapter II-2 outlines basic ship design requirements for fire

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[3] International Convention for the Safety of Life at Sea (SOLAS)

protection, detection and extinction. The requirements are further expanded by class rules, international standards (e.g. FSS Code[4] , ISM[5] Code) and other safety measures. Fire has also been one of the main topics in the research community, involving the industry, academia and various research-driven SMEs[6] . In this topic, the European Commission (EC) has funded such research projects as PHOENIX, SAFETY FIRST, SAFEDOR, FIRE-EXIT, FIREPROOF, to name a few.

Past research projects have shed light on different aspects of fire risk, starting from a general probabilistic framework and consequence modelling (e.g., SAFEDOR) and ending with final stages such as evacuation and debarkation (FIRE-EXIT). As the fire phenomenon is highly complex and stochastic by nature, the subject is generally under-researched, remaining with many grey areas and knowledge gaps (Babrauskas, 2007, 2003). One of such grey areas is the fire inception. Regulation 4 of SOLAS Chapter II-2 explicitly refers to probability of ignition to be addressed in design and operation. A few existing probabilistic models, e.g. (Hakkarainen et al., 2009; Lindgren and Sosnowski, 2009), that allow estimating ignition probabilities in various onboard compartments are either over simplified or too complex and hence have limited engineering utility.

This paper provides a summary of the contribution—achieved in D4.8—to understanding of fire root causes, precursors and outbreak conditions in engine rooms. Fire inception is a primary part of fire risk and if suppressed, would irradiate the entire chain of events that follow, consequently reducing the cost of fire safety systems installed to tackle them.

Used data sources

Development of risk models, which are inherently probabilistic constructs, is challenging. A risk model, or just its part, is a collection of assumptions that have to be backed by evidence. Perhaps the most problematic part of this process is the derivation of probabilities, especially when the data is scant, as the case in the maritime domain (Grabowski et al., 2009; Wang et al., 2011). In this work we utilised the following sources of evidence and data:

- Accident records
- Ignition discipline, e.g. (Babrauskas, 2003)
- First principle computer simulations
- Human error probability databases
- Expert option

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[4] The international code for fire safety systems (FSS Code)

[5] International Management Code for the Safe Operation of Ships and for Pollution Prevention (ISM Code)

[6] Small and medium enterprise (SME)

Accident records

Sea-web[7] contains a large number of records over many years and different shiptypes worldwide. However, they do not contain detailed information such as the fire origin and root causes, and hence can be used for trend identification and other high level statistics only.

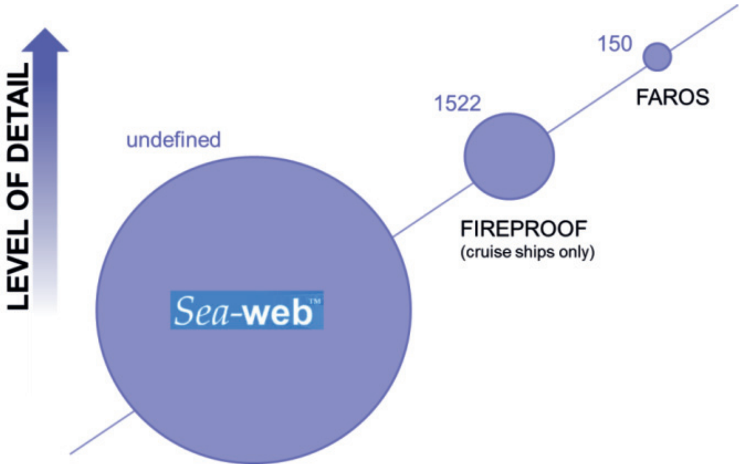

Figure 2: Used sources of fire incident records.

FIREPROOF[8] database contains quite substantial number of records, namely 1522, from 71 cruise ships from 3 cruise ship operators over the period of 9 years. The database contains fairly detailed descriptions of fire accidents. This database was mostly used to derive basis ignition frequencies for public and other spaces in this report. However, as narratives of accidents are missing, many details still remain unrevealed.

FAROS database contains 150 records collected based on detailed analysis of accident investigation reports. As accident narrative was accessed, detailed information about fire circumstances and root causes was extracted. The database was used to gain deeper understanding about plausible ignition scenarios, their precursors, and feasible assumptions to be then used in the process of mathematical modelling.

Mariners' Alerting and Reporting Scheme of the Nautical Institute was used to get access to accident investigation reports.

Ignition science

Another source of evidence and data came from the current understanding of the ignition phenomenon. On the one hand, the ignition modelling is quite limited in the maritime domain, although there are always examples that break the rule, e.g. (Li et al., 2010). On the other hand, the ignition discipline is pretty well developed (Babrauskas, 2003) and there is a multitude of various ignition models available, although, as noted in (Babrauskas, 2007), the

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[7] www.sea-web.com

[8] FIREPROOF is a recently completed EU project on fire safety of passenger ships.

majority of these models has little engineering utility, i.e. they are either inaccurate or too complex and hence impractical in everyday use.

CFD simulation
We also used first principle computer simulations, specifically CFD simulations, to work out physical behaviour of flammable oils transported in pressurised piping systems. Specifically, we were interested in determining the extent of spray (leak) when a pipe or other component develops a crack.

Human error probability database
Human error probability (HEP) databases and corresponding methods such as HEART (Williams, 1988, 1985) were used to work out HEPs under given circumstances such as the effect of the global design factors, time pressure and others.

Expert opinion
Expert opinions were gathered through structured questionnaires about the time to failure and failure modes of system components in engine rooms. Specifically, chief and 2nd engineers were asked to provide the sought estimates. The collected data was then processed using formal techniques (Cooke, 1991; Cooke and Goossens, 2008) to converge at failure probability distributions.

Data analysis through statistical inference
The evidence and data were combined and processed using methods of statistical inference.

Frequentist inference (FI) implies of drawing conclusions from sample data by the emphasis on the frequency or proportion of the data. FI is associated with the frequency interpretation of probability, specifically that any given experiment can be considered as one of an infinite sequence of possible repetitions of the same experiment, each capable of producing statistically independent results (Everitt and Skrondal, 2002). FI can be considered as a classical method in the maritime domain to arriving at probabilities of accidents solely based on accident records available and is widely exercised within the research community, e.g. (Kristiansen, 2005), and also at IMO. However, Bayesian inference, as an alternative to FI, has noticeably started earning its popularity as well, e.g. (Trucco et al., 2008).

Bayesian inference (BI) (incl. Bayesian networks) is a method of inference in which Bayes' rule is used to update the probability estimate for a hypothesis as additional evidence is acquired. The rationale behind using BI is to have a formal means of quantifying studied phenomena for which quantitative data is limited. Such quantification can then be improved once new data or evidence is available.

The interchangeable use of both inference methods allowed for greater flexibility, and the amount and quality of available historical data and evidence determined the choice of a specific method. Thus for example, Bayesian inference was used when historical accident records were either missing or very limited, otherwise frequentist inference was preferred. It is important to note that in light of generally limited historical data, the modelling was aimed to answer the question of what can happen rather than what has happened. In technical terms this means that the existing limited data and knowledge of modelled phenomena were used to support assumptions about probability distributions, rather than probabilities themselves.

Ignition Models

The space of fire origin can be anywhere onboard. However, some spaces have higher fire risk than others. The engine room is one of such spaces. It has been reported for both cargo and passenger ships that 2/3 of all fires onboard are likely to happen in engine rooms (DNV, 2000), as shown in Figure 3. Ship owner operating 20 cargo vessels can expect one major engine room fire every ten years. For cruise vessels, the frequency is twice as high (Tuva Kristine Flagstad-Andersen, 2013). Therefore, the overall fire risk would significantly decrease, if ignition probability and its consequences in merely machinery spaces were reduced.

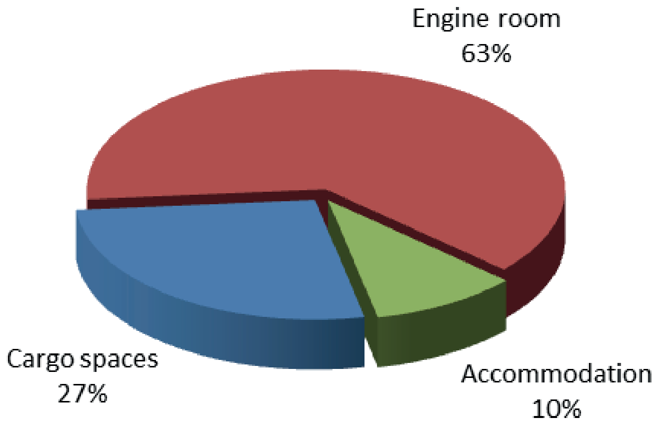


Figure 3: Distribution of fire origin on passenger ships.

Due to size constraints, this paper presents a summary of the engine room ignition model only. The complete set of the ignition models is found (Puisa et al., 2014).

Engine rooms

Evidence

Around 60% of all incidents in the engine room originate from oil leakages/spray on hot surfaces (Tuva Kristine Flagstad-Andersen, 2013), as shown in Figure 4. Other main contributors to risk of fire and explosion are:

- Excessive blow-by, causing scavenging-space fires or crankcase explosions,

- Hot-running of bearings,
- Leakages of hot gas due to bad pipe fixations or connections.
- Fires caused by oil leakage/hot spots are in general more serious than fires caused by other factors. Sources for oil leakage are many and difficult to reduce, whereas it is relatively easy to identify and remove hot surfaces.

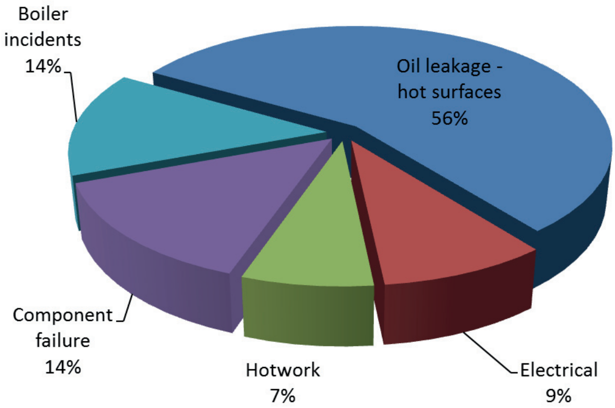
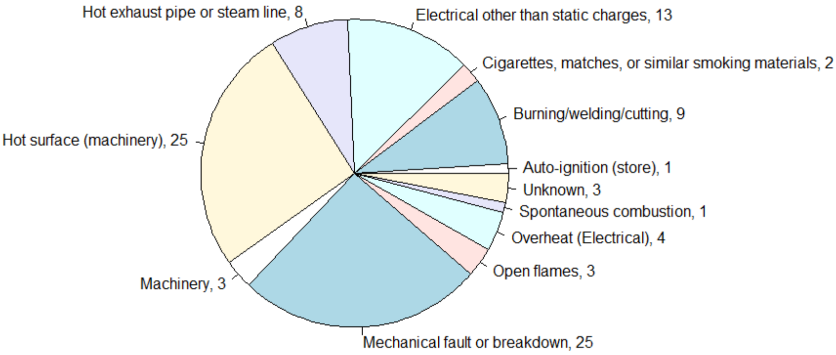
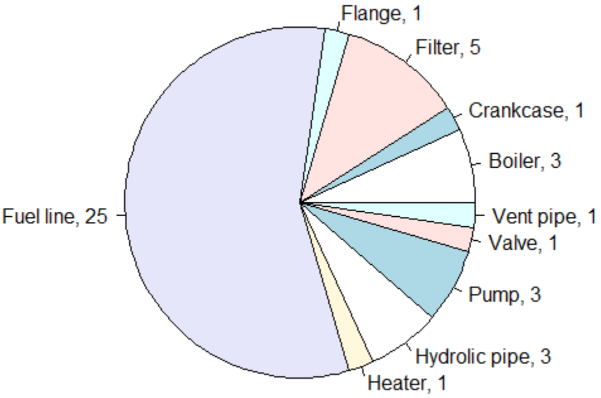


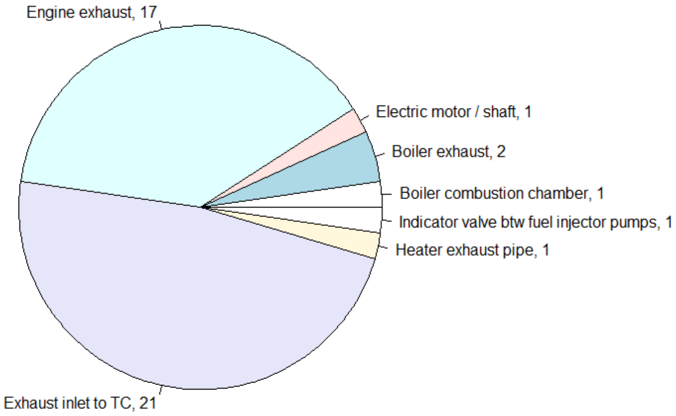
Figure 4: Fire causes in engine rooms (ref. DNV (DNV, 2000)).



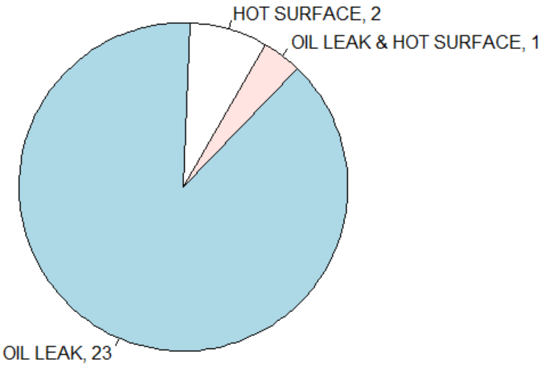
a) Heat sources in machinery spaces



b) Leak sources of flammable oils



c) Distribution of hot surfaces (TC – turbo charger) that ignited leaked flammable oils



d) Frequencies of contribution of human error to appearance of oil leaks, high temperature surfaces, or both

Figure 5: Some statistics on fire origins and scenarios in engine rooms (source: FAROS DB; absolute numbers of records are given).

Passenger vessels seem to have a higher fire frequency than other types of vessels. This could be because the focus on passenger vessels is high and such fires are usually reported in the media. In addition, passenger vessels normally have more compact engine rooms, with more machinery and equipment. Larger engine rooms may improve fire safety as the distance is greater between the source of ignition and the potentially combustible material.

The engine room is the main source of vibration and noise on the ship. It has been observed that vibration caused fatigue, pressure pulses in the fuel system are the primary culprits in the generation of leaks (Galpin and Davies, 1997; Goodwin, 2003; MSC.1/Circ.1321, 2009), with the human error as a likely precursor to a leakage incident. This often relates to installation, monitoring and maintenance errors. This could be, for example, insufficient care of high pressure pipe mating surfaces during engine overhauls, or a physical damage from contact with engine spare parts during storage. Thus, Figure 5 d) indicates that amongst all fire incidents attributed to the human error, the contribution to oil leaks is the most significant.

Figure 5 shows some interesting statistics on fire scenarios, which indicate that:

- The predominant majority of ER ignitions have happened within the exhaust area of a diesel engine, which can be either the main engine (primary mover) or a diesel generator used in the diesel-electric configuration. Thus, although there are other potential heat sources (e.g., overheated surfaces of electric motors and boilers), the number of heat sources is limited to a dozen or so (Tuva Kristine Flagstad-Andersen, 2013).
- Ignited flammable oils (e.g. HFO, MDO, and MGO) have mainly leaked from fuel supply lines. The lubrication line is another common source of leaks. Both sources are directly connected to the engine and are in close proximity to the exhaust piping.
- Human error during scheduled and unscheduled overhauls is a critical factor that affects reliability, or service time, of maintained systems.
- Based on the above, the ignition model in engine rooms can be solely based on the auto-ignition scenario when a hot surface, as the heat source, comes in direct contact with flammable oil vapour or mist (Holness and Smith, 2002), which is vaporised flammable oil due to a prior contact with the hot surface, for example.

Modelling

The IMO guidelines for measures to prevent fires in engine rooms and cargo pump rooms (ref. MSC.1/Circ.1321) outline specific requirements that help control availability of fuel, heat source and oxygen as essential elements of the fire triangle. The guidelines refer to control of flammable oils and ignition sources etc., alluding to the measures minimising their probabilities. This offers a basic modelling framework that deals with the logical conjunction of events displayed in the fire triangle. Thus, auto-ignition probability for a specific heat source (a high temperature surface with T > 220 °C as per MSC.1/Circ.1321) is written as

$$P(I_a) = P(I|\text{contact} \cap \text{FO} \cap H)\ P(\text{contact}|\text{FO} \cap H) P(\text{FO}) P(H) \tag{1}$$

$P(I\|\text{contact} \cap \text{FO} \cap H)$	Conditional probability of ignition once the flammable oil and a hot surface have come in contact. This probability is affected by ambient properties in the room (i.e., temperature, pressure, humidity etc.) and physical properties of the flammable vapour (i.e., concentration of flammable oil in the air, temperature etc.) and the surface (i.e., temperature, area etc.).
$P(\text{contact}\|\text{FO} \cap H)$	Conditional probability of flammable oil and the high temperature surface to come in contact. This probability is mainly driven by design of the engine room. Specifically, the relative distances between pressurised oil systems and the surface affect it.

$P(\text{FO})$	Marginal probability of flammable oil availability in the engine room. This probability relates to failures of leak/spry shields in pressurised piping systems (flexible pipes, hoses and hose assemblies, expansion joints, filters and strainers, oil level gauges etc.). More specifically, it is leak probability from any component of pressurised system.
$P(H)$	Marginal probability of any high temperature surface (above 220°C), in the engine room. This relates to insulation failure of exhaust gas piping and manifolds, cylinder head indicator cocks, superheated steam pipes etc.

Conditional probability of ignition, P(I☐contact∩FO∩H), is expressed as

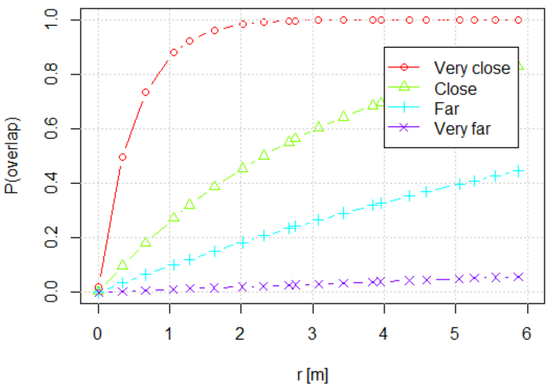
$$P(I|\text{contact}\cap \text{FO}\cap H) = P\big(T_h > E[T_{ign}]\big) = \begin{cases} 1, & T_h > E[T_{ign}] \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

T_h	Temperature of a high temperature surface, which is assumed to be equal to exhaust gas temperature of 314-340 °C (MAN, 2010; Wärtsilä, 2004).
$E[T_{ign}]$	Expected ignition temperature of released flammable oil, i.e. expected auto-ignition point in the leak zone. This temperature is an integral over pressurised components transmitting various flammable oils with individual ignition temperatures (MSC.1/Circ.1321).

Contact probability P(contact┤|FO∩H) is expressed as

$$P(\text{contact}|\text{FO}\cap H) = P(\text{dir}|\ \text{FO}\cap H)\cdot P(\text{overlap}|\ \text{dir}) \cdot P(\text{contact}|\ \text{overlap}) \tag{3}$$

$P(\text{dir}|\ \text{FO}\cap H)$	Probability of leak spray in direction of hot surface. This probability was linked to systems' arrangement in the engine room.
$P(\text{overlap}|\ \text{dir})$	Probability of physical overlap between the spray and a high temperature surface. The physical overlap between the spray and the engine is affected by the distance between the engine and the leaking component, and the extent of the leak (i.e. spray radius) as shown in **Figure 6**. This probability is linked to the size of the engine room.

	 **Figure 6:** Effect of the component proximity, to potential hot surfaces, and leak extent on the overlap probability (r stands for the expected spray radius which was estimated based on CFD simulations).
P(contact| overla	Probability of the actual contact between the flammable spray and a high temperature surface, provided the overlap exists. It is proportional to the projected area of the exhaust manifold, and other related components liable to overheating due to failure.

Marginal probability of flammable oil availability in the engine room is modelled based on the event tree-like interpretation of the event (Figure 7).

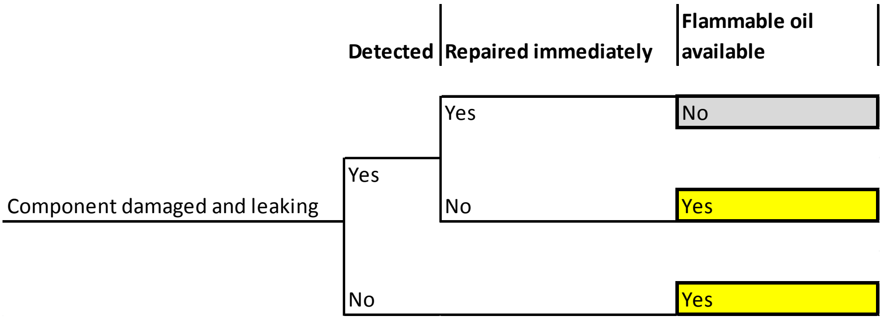
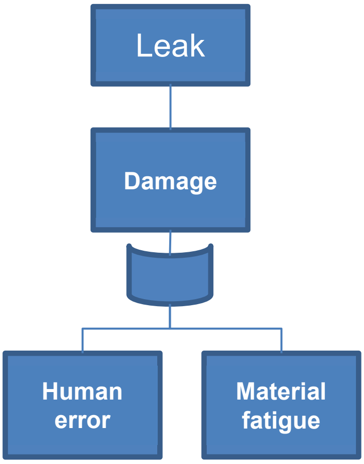


Figure 7: Event tree-like representation of availability probability of flammable oil.

Thus, probability of flammable oil to be available as a result of a leak / spray from component i is expressed as

$$P(\mathrm{FO_i}) = P(L_i)(1 - P(\mathrm{Det.} \cap \mathrm{Rep.})) \qquad (4)$$

$P(L)$	Probability of a leak / spray, which is expressed as a combination of event probabilities shown in **Figure 7**. The explicit expressed in shown in Eq. (5).

	 **Figure 7:** Fault tree representation of leak probability.
$P(\text{Det.} \cap \text{Rep.})$	Joint probability of successfully detecting and immediately repairing the leak. The probability of the joint event is a combination of marginal detection probability and conditional probability of immediate repair once the problem has been detected. The engine room components are inspected regularly (ref. MSC.1/Circ.1321), at least once a day. Detection probability is hence driven by the frequency and quality of the inspection.

Probability of a leak / spray is formally written as

$$P(L) = P(D|\text{AA})P(\text{HE.MPF}) + P(D|A) \tag{5}$$

$P(L)$	Probability of a leak of flammable oil (e.g., MDO, HFO, LO).
$P(\text{HE.MPF})$	Marginal probability of human error during maintenance in the engine room.
$P(D\|\text{AA})$	Conditional probability of damage due to quicker aging which accelerated because of earlier made maintenance / installation errors by the crew.
$P(D\|A)$	Conditional probability of a damage due to aging / fatigue as a result of vibration, pressure pulses etc.

The following assumptions were made to arrive at the above expression:

- Any damage to the oil supply / storage system with internal pressure above the ambient pressure leads to a leak
- The presence, in the engine room, of fatigue causing and related factors such as long term vibration, pressure pulses, and also factors such as manufacture and design faults is always positive.
- The immediate leak due to the human error during maintenance is possible, but its possibility was ignored because of immediate

rectification made by the crew, unless the leak has not been noticed, which is highly improbable.

Damage probability of a piping system due to aging, P(D□A), is modelled as probability of damage between two inspections, provided the component had been operational before the first inspection. Thus, we are modelling a time to failure (TTF) as a random variable. Regardless what probability distribution is used to represent TTF, the probability of interest is expressed as

$$P(D|A) \equiv P(t_F \leq t + \Delta t | t_F > t) = \frac{F(t + \Delta t) - F(t)}{1 - F(t)} \qquad (6)$$

t_F	Time to failure (TTF)
t	Period of time since the beginning of exploitation (i.e., t=0) until an inspection of interest. This corresponds to ship age.
Δt	Period of time since the inspection until the next one
$F(t)$	Cumulative distribution function (CDF) of TTF

It is important to note that probability P(t_F≤t+Δt□t_F>t) depends on the absolute time of inspection or ship age, t, only if the failure rate is variable, e.g. the failure rate increases with time due to the aging process as the component wears out. If the failure rate was constant, i.e. no aging is assumed, then P(t_F≤t+Δt□t_F>t)=P(t_F≤Δt), which would leads to the expression with one less factor.

Damage of ship systems that transport/store flammable oil may happen due to cyclic loads, which gradually lead to the growth of cracks of which development rate is proportional to their size (ref. Paris' law). In other words, such ship systems/components are subjected to the aging process with the increasing failure rate over time. For this reason, the Weibull probability distribution function (PDF) was selected to represent TTF. PDFs were derived according to the method by Cooke and Mendel–Sheridan (Cooke, 1991; Cooke and Goossens, 2008; Goulet et al., 2009; Mendel and Sheridan, 1989) based on empirical data elicited from 16 chief and 2nd rank engineers providing experiential estimates of TTF. A sample results of such data elicitation and processing is shown in Figure 9, Figure 10, and Figure 11.

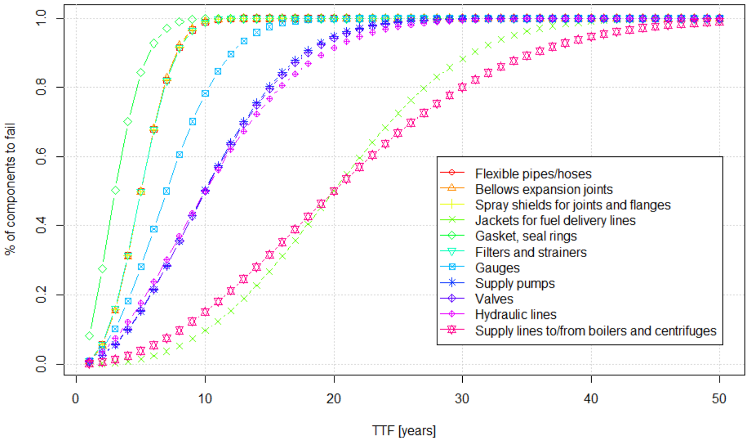


Figure 9: CDFs for TTF for components liable to leaking flammable oil (4 strokes machinery).

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

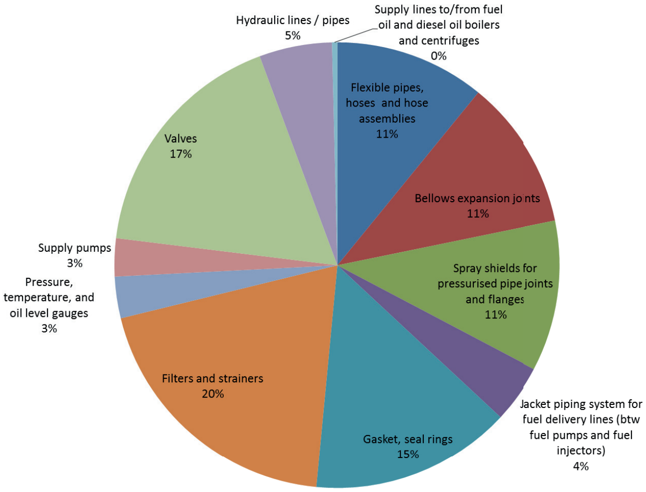


Figure 11: Normalised probability of leak before next day inspection (4 strokes machinery). The figures estimated for 15.5 years old vessel.

As for conditional probability of damage due to quicker aging which accelerated because of earlier made maintenance / installation errors by the crew, P(D□AA), it was modelled in a similar fashion as the probability of damage due to ageing. Thus, we assumed that maintenance errors affect the time to failure (TTF) of maintained system components. Specifically, TTF is shortened and the amount by which it is reduced corresponds to the scale of detrimental effect (SDE). Thus for example, when SDE=0.5, then the TTF of a given component has been shortened by half and when SDE=0, the TTF is not affected at all. It is important to note that SDE can be interpreted as conditional probability of reducing the service time of a repaired component, provided an error has happened during repair works. One can notice that the scale parameter of the Weibull distribution is the main determinant of the expected TTF value, or TTF value in general. This property of the Weibull distribution allowed us to make an assertion that SDE affects the scale parameter only. In this case, the affected scale parameter, □^', would simply be worked out as

$$\lambda' = (1 - E(\mathrm{SDE})) \cdot \lambda \tag{7}$$

Using SDE=0.5, Figure 12 demonstrates the difference between the derived damage probability due to maintenance mistakes and damage probability due to aging for the 4-stoke machinery configuration.

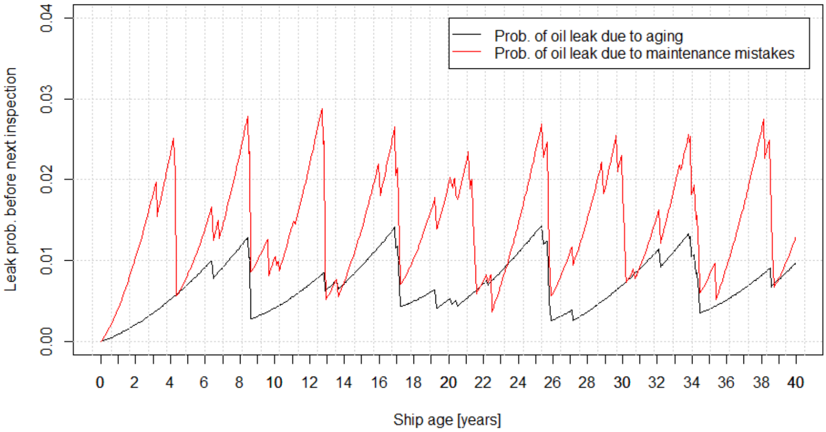


Figure 12: Fluctuation of probability of oil leak (before next day inspection) due to aging and maintenance mistakes which are assumed to accelerate the aging process.

Marginal probability of any high temperature surface, P(H), was estimated following the same process as for the marginal probability of flammable oil availability in the engine room. That is, a similar mathematical framework was employed, and experiential data was elicited from marine engineers serving on RoPax and tanker ships. This also applied to the probability of insulation damage due to human error.

As there are two insulation types of high temperature surfaces: removable (blankets, flexible jackets) and permanent, the engineers were asked to give estimates for both of insulation types. Figure 13 shows cumulative probability distribution functions for various isolated components, whereas Figure 14 shows fluctuation of the failure probity over ship's lifetime. Bearing the number of components analysed, there are 16 unique configurations of insulating these components, e.g. exhaust gas piping (removable), exhaust gas manifolds (permanent), cylinder head indicator cocks (removable), superheated steam pipes (permanent). Based on this, one can compare insulation configurations in terms of the number of failure over the ship's lifetime (Figure 15). Configuration 9 has highest reliability: exhaust gas piping (permanent), exhaust gas manifolds (removable), cylinder head indicator cocks (removable), superheated steam pipes (removable).

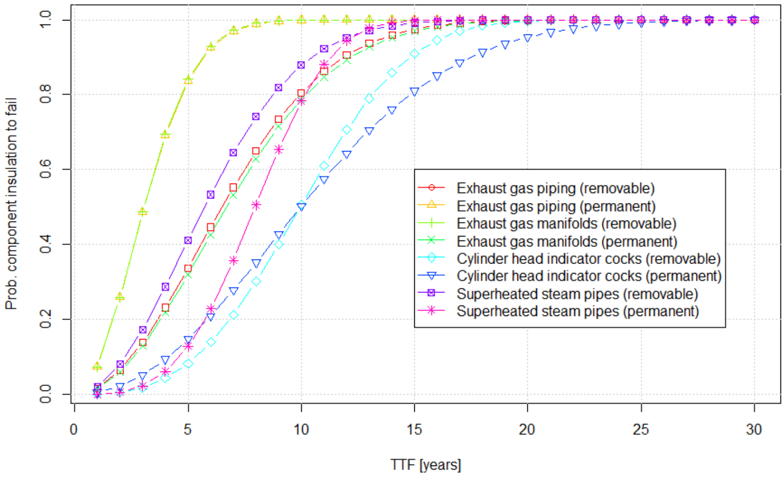


Figure 13: CDFs for TTF of thermal insulation of different components

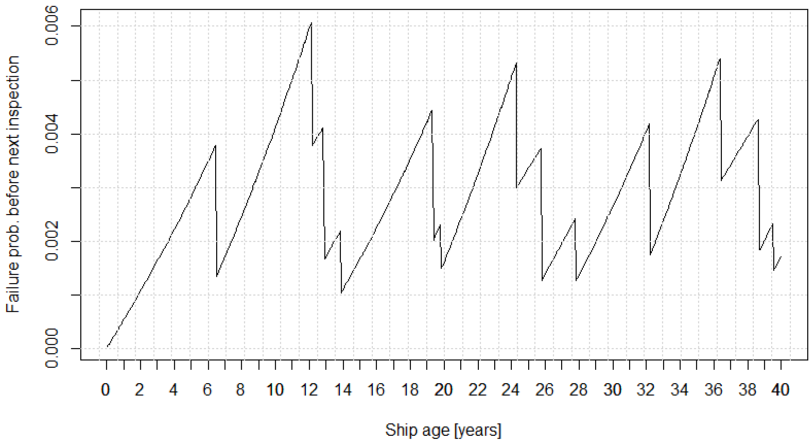


Figure 14: Fluctuation of the insulation failure probability before next day inspection from across all four components for insulation configuration #9. The peak period is approx. 6.4 years

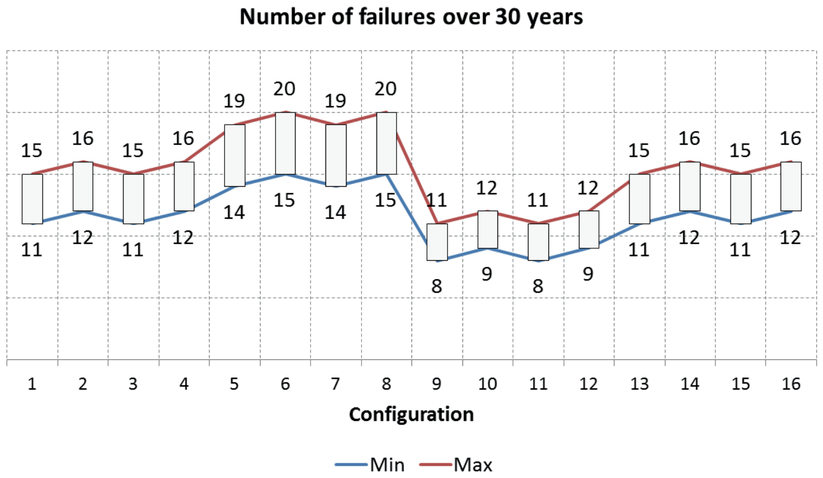


Figure 15: Total number of failures over all component insulations within a typical ship's lifetime of 30 years. The min values correspond to 95% percentiles of lifetime periods of individual component insulations, whereas the max values correspond to the expected lifetime periods (i.e. mean values of Weibull distributions).

In the engine room ignition mode, there are two human error types considered:

- The first one is related to failure to properly detect and asses a problem. This probability is generic, i.e. space and ship independent.
- The second type is related to any human error made during maintenance of ship systems

These probabilities are linked to the global design factors (GDFs) considered in the project, and the links are implemented by means of a Bayesian network shown in Figure 16. Note that the marked part of the network is described in deliverable D4.6 (Montewka, 2013a).

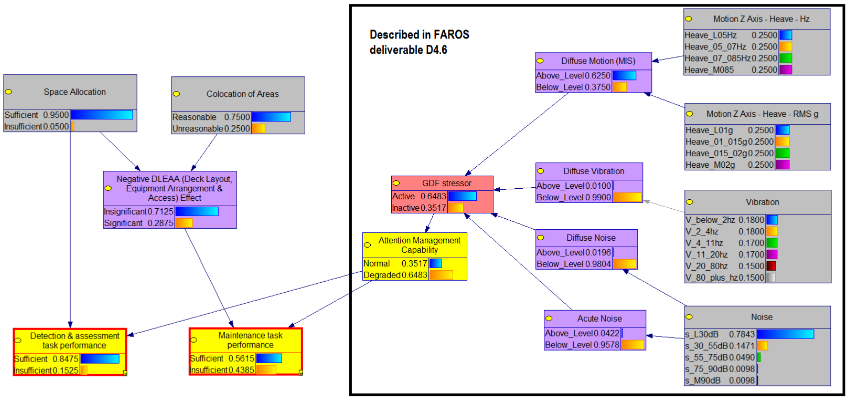


Figure 16: Bayesian network for estimating probability of sufficient detection, assessment and maintenance task performance. Note the marked part of the network in described in D4.6 (Montewka, 2013a).

The main input to this model is probabilities of insufficient space allocation and unreasonable collocation of functional areas. As described in deliverable D3.4 (Hifi and Garner, 2013), the deck layout, equipment access and arrangements (DLEAA) affects human performance directly and indirectly. It is clear that DLEAA presents certain physical and cognitive demands upon the seafarer which they must be able to meet in order to perform a task. These may be physical, due to factors such as confined space or impaired accessibility, or cognitive and working memory demands, due to factors such as the distance and separation between functional areas. As for the physical demands, DLEAA affects task performance, making specific tasks easier or harder to complete. Therefore the effect is relatively easy to grasp and quantify, assuming it manifests itself in physical obstacles that impede freedom of movement necessary for easy and therefore successful (supposedly) task execution. Examples of such physical obstructions are:

- Lack of space around the equipment under inspection / repair;
- Narrow pathways that require a mariner to slow down to avoid accidental and injurious contacts, especially when carrying heavy equipment;
- Obstructions on the way from one space to another (e.g., watertight doors, stairs and ladders), reducing the average walking speed and hence delaying execution of the task, which in turn may lead to time pressure.

Probability of insufficient space allocation was modelled as being proportional to the ratio of necessary space to space available around inspected / repaired equipment (e.g. according to the HSE guidelines[9] , the required space for safe and productive work is 11m3 per person). Probability unreasonable collocation of functional areas was modelled being proportional to the ratio of normal walking speed to expected walking speed along the vessel during repair and other tasks. That is, the more watertight doors an engineer has to cross to get from one functional space to another while completing a specific task (e.g. a repair in engine room), the more unreasonable allocation of spaces is.

Benchmarking and sensitivity analysis
By randomly varying input to the ignition model, a histogram of outputs was created and compared with the historical average obtained from the sea-web database (see Figure 17).

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[9] http://www.fbu.org.uk/wp-content/uploads/2011/08/HSE-Workplace-HSW-ACOP.pdf

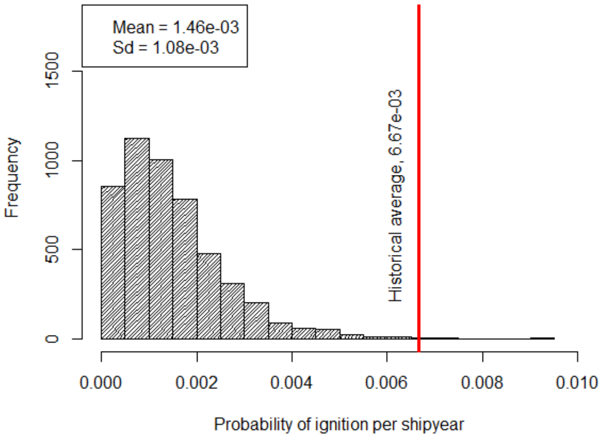

Figure 17: Histogram of ignition probability in the engine room per shipyear, when comparing with the historical average.

The simulation results have indicated that the ignition model delivers results of same order of magnitude but approx. 6 times lower values than the historical average given in (Puisa et al., 2014). However, as the historical average corresponds to frequencies of fully developed fires, whereas the ignition model is limited to fire inception event only, the ignition model did under predict the ignition probability. This meant that certain quantitative assumptions in the model had to be revised, which was done by introducing a corrective multiplier as described in (Montewka and Puisa, 2014).

Figure 18 shows the results of sensitivity analysis, specifically showing correlation between the ignition probability and its covering parameters used as input to the model.

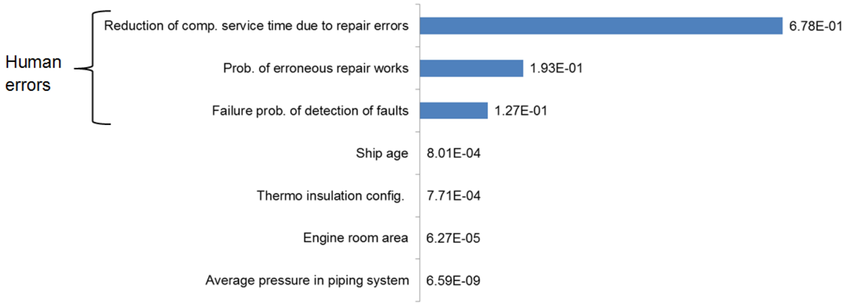

Figure 18: Results of sensitivity analysis. Main effects of a linear regression model are shown.

From Figure 18 one can observe that:

- Occurrence of human error, i.e. human factors and organisational failures, represents the principal cause for ignition in engine rooms.
- Ship age is another important factor, although its effect is orders of magnitude lower than the human error related factors.
- Both the thermo insulation configuration and pressure in the piping system (the latter affects the spray radius of flammable oil) have negligible effect on the ignition probability. In other words, the contact

between leaked flammable oils and high temperature surfaces will eventually occur as long as both flammable oil and high temperature surface are present. Improving reliability of thermo insulation should be a choice measure to further reducing the likelihood of contact between them.

- The direct effect of the ER floor area—being as a measure of proximity between potential leaks and hot surfaces—is negligible, as shown in the figure. However, its indirect effect through human error is much more significant, as explained found in the study.

Conclusions

The presented empirical model for the engine room ignition probability was developed following the bottom-up approach (starting from basic events and moving up to their assemblies). This allowed to control the level of granularity and hence occupancy of the model, although this increased its complexity. Sensitivity analysis of the model confirmed that human error during scheduled and unscheduled overhauls / repairs is the prevailing factor that affects reliability (service life) of maintained systems. This echoes observations in accident investigation reports and indicates the structural validity of the model.

The model can be used for design purposes by optimising the size of the engine room and interlocution of ship systems in the engine room. This is a prime application of the model in project FAROS. The model can also be used for scheduling of overhauls by looking at fluctuations of leak and insulation damage probabilities. Also, the fluctuation of the inter ignition probability can also be analysed for specific vessel configuration. For example, Figure 19 shows the fluctuation of annual ignition probability in the engine room of 140 m long RoPax. The distribution of peaks is affected by lifetimes of piping system and thermo insulation components, as well as other factors considered in the ignition model.

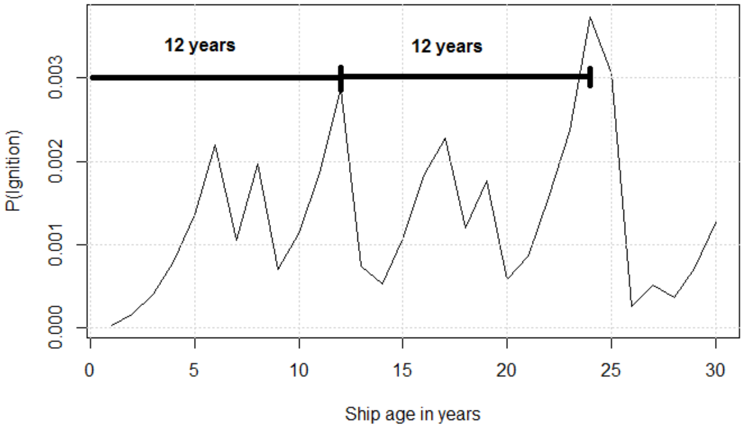

Figure 19: Variation of ignition probability in the engine rooms of a RoPax ship.

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Description of the overall risk model

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Introduction

In practice, risk wise comparison of ships has to be categorical. That is, the real question is which ship remains safe, should any hazardous incident happen, as opposed to the question which ship is safe with respect to hazard A, B, C, etc. The former question is particularly significant for the society who primarily concerns about the sheer fact that the life is lost, rather than what caused the loss. In contrast, the latter is more important for ship operators and regulators, for they are looking for preventive measures. To compare safety of ships categorically, the *total risk level*, which ought to reflect all potential hazards, has to be estimated.

The total risk will be treated as an extra performance indicator, alongside with economic and environmental performance metrics, while assessing multi-disciplinary ship performance in the following WP6.

It is important to note that by combining different risk aspects into a basically one number to be used for comparison of alternative designs, the information on individual risk aspects will not be lost. This information will still be available and used for detailed comparison of designs.

In this paper we present an approach taken to synthetize the individual risk models developed in the course of FAROS project into an overall risk model. Furthermore the results obtained form the experiments conducted with the use of bridge simulator and Virtual Reality are presented and integrated into the risk model.

Taxonomy of risk

Risk should at least be judged from two viewpoints. The first point of view is that of the individual, which is dealt with the Individual Risk (aka Personal Risk). The second point of view is that of society, considering whether a risk is acceptable for (large) group of people. This is dealt with the Societal Risk.

This risk expression is used, when the risk from an accident is to be estimated for a particular individual at a given location. Individual Risk considers not only the frequency of the accident and the consequence (here: fatality or injury), but also the individual's fractional exposure to that risk, i.e. the probability of the individual of being in the given location at the time of the accident. The purpose of estimating the Individual Risk is to ensure that individuals, who may be affected by a ship accident, are not exposed to excessive risks.

Societal Risk is used to estimate risks of accidents affecting many persons, e.g. catastrophes, and acknowledging risk averse or neutral attitudes[10]. Societal Risk includes the risk to every person, even if a person is only exposed on one brief occasion to that risk. For assessing the risk to a large number of affected people, Societal Risk is desirable because Individual Risk is insufficient in evaluating risks imposed on large numbers of people. Societal Risk expressions can be generated calculated for each type of accident (e.g. collision), or a single overall Societal Risk expression can be obtained, e.g. for a ship type, by combining all accidents together (e.g. collision, grounding, fire). Societal Risk may be expressed as, (IMO 2002):

- FN-diagrams showing explicitly the relationship between the cumulative frequency of an accident and the number of fatalities in a multi-dimensional diagram11.
- Annual fatality rate: frequency and fatality are combined into a convenient one-dimensional measure of societal risk. This is also known as Potential Loss of Life (PLL).

Societal Risk expressed in an FN-diagram allows a more comprehensive picture of risk than Individual Risk measures. The FN-diagram allows the assessment not only of the average number of fatalities but also of the risk of catastrophic accidents killing many people at once.

However, unlike Individual Risk, both FN-diagrams and PLL values give no indication of the geographical distribution of a particular risk. Societal Risk represents the risk to a (large) group of people. In this group, the risk to individuals may be quite different, depending e.g. on the different locations of the individuals when the accident occurs. The Societal Risk value therefore represents an average risk. There is a general agreement in society that it is not

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[10] Only criteria reflect societal risk attitudes, not the statistics used for risk quantification.

[11] This corresponds to the distribution of frequency F for occurrence of N or more number of fatalities per ship per year.

sufficient to just achieve a minimal average risk. It is also necessary to reduce the risk to the most exposed individual. It is therefore adequate to look at both Societal Risk and Individual Risk to achieve a full risk picture.

Methodology to synthesize the risk models

In this project we adopted an uncertainty perspective of risk, where risk is seen as follows (Aven and Renn 2009):

$$R \sim C\&U \tag{8}$$

The thorough analysis of various risk concepts has been reported in (Montewka 2013a), therefore this section contains only abridged explanation of the risk perspective adopted for the purpose of FAROS.

Adopting the uncertainty perspective of risk we express an assessor's uncertainty (U) about the occurrence of events and the associated consequences (C). Following this perspective, risk assessment can always be performed, as the risk model is seen as a tool to describe and convey uncertainties.

The adopted risk perspective allows defining the plethora of consequences and associated uncertainties. This makes it possible to expand the model with desired consequences, which can be very specific, depending on the ship type under analysis. For instance, in case of a RoPax ship, the focus is on the human losses, therefore the risk will be expressed through the probability of a number of fatalities, see for example (Montewka, Ehlers, et al. 2014). Whereas, in case of a tanker, environmental impact of an accident may be a key issue, therefore the risk is expressed as the probability of oil spill of certain size (Goerlandt and Montewka 2014).

In WP4, the focus of risk modelling was on the assessment of the probabilities of events such as unsafe behaviour, ship-ship collision, ship grounding and fire ignition onboard. Hence, the consequence part of the risk models was not worked on in the project and it was instead adopted from the literature (mainly EU funded projects over the last decade). The FAROS reports with risk models, except the personal risk model, include descriptions of consequence models as well. Thus, both parts of risk models are available and will be linked in Task 5.3.

The way all risk elements are assembled is illustrated in the flowchart of **Figure 9**. Note that the colour coding explains which WP risk parts come from.

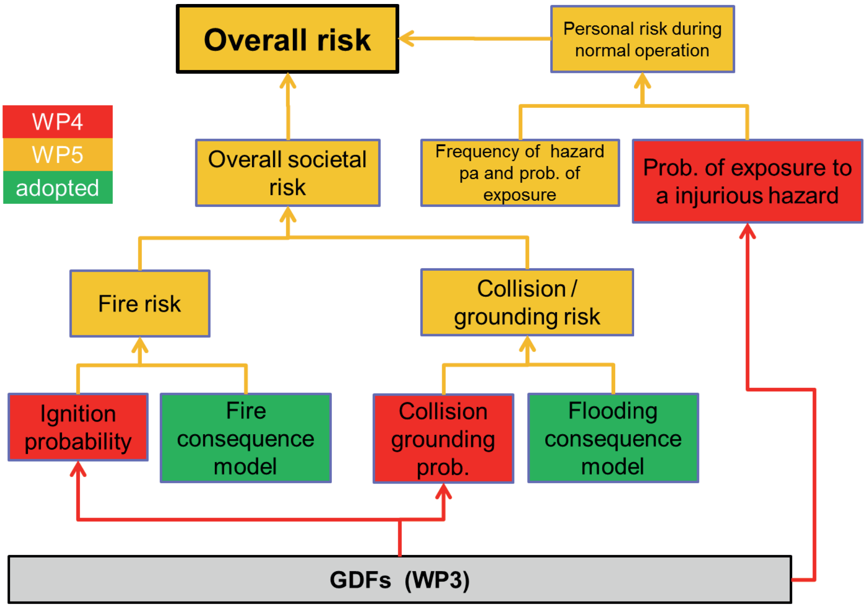

Figure 9: Synthesis of the overall risk model

The risk model presented in this report incorporates both societal risk (fatality due to collision, grounding and/or fire) and the personal risk (injury or fatality during normal working conditions), as shown in Figure 9. Some of the features of the overall risk model are:

- The Personal risk component:
    - Provides estimates of both fatalities and injuries
    - Considers crew members only (i.e. it does not consider passengers)
    - Covers all tasks performed as per normal operations only (i.e. it does not consider emergency situations such as flooding, fire, explosion etc.)
- The Societal risk component:
    - Provides an estimate of expected fatalities only (i.e. it does not consider injuries)
    - Considers both crew members and passengers on board
    - Covers emergency situations only (i.e. collision, grounding and fire events).
- As such, the overall model does not consider:
    - Fatalities or injuries to passengers during normal operations
    - Non-fatal injuries to crew and passengers during emergency situations
- As normal operations and emergency situations cannot co-occur, the Societal risk component and the Personal risk component are mutually exclusive as each one covers a different operational mode.

The above features allow us to deal with the two types of risk (societal and personal) as mutually exclusive events and express them as a sum:

$$\text{Risk} = \underbrace{\text{Risk}_{flooding\ |col.\text{or}\ gr.} + \text{Risk}_{fire}}_{\text{Overall societal risk}} + \text{Risk}_{personal} \tag{9}$$

To sum addressed risk contributions as shown above, they have been expressed as *the expected number of fatalities per shipyear*, aka Potential Loss of Life (PLL) per shipyear (MSC 83/INF.2). Therefore formally, the overall risk can be written as a total expectation, i.e.

$$\begin{aligned} \text{PLL} = E(N) &= E(N|col)P(col) + E(N|gr)P(gr) + E(N|fire)P(fire) \\ &\quad + E(N|usafe)P(usafe) \end{aligned} \tag{10}$$

PLL	Potential loss of life from societal risks per shipyear
$E(N)$	Expected number of fatalities per shipyear (either of hazardous events)
$E(N\|col)$	Expected number of fatalities during an accident involving collision between more than one ship.
$E(N\|gr)$	Expected number of fatalities during an accident involving grounding.
$P(col)$	Probability of collision accidents per shipyear
$P(gr)$	Probability of grounding accidents per shipyear
$E(N\|fire)$	Expected number of fatalities during an accident involving a fire
$P(fire)$	Probability (or expected frequency) of fire per shipyear
$E(N\|unsafe)$	Expected number of fatalities from insufficient safety behaviour. Expected number of injuries is not considered as it can be integrated as shown above; the figure should be kept separately.
$P(unsafe)$	Probability of insufficient safety behaviour (see FAROS report D4.5 for details) of crew members during normal operation. Such behaviour leads to various hazards such as slips, fall, trips etc. and hence compromises personal safety.

It is important to emphasise that all three risk components have to be expressed in PLL per ship-year. The following sections address the issue of compatibility and describe solutions to resolve it.

Societal risks

The models behind incident probabilities/frequencies and expected fatalities (consequence models) have been described in D4.6 (Montewka 2013a) and D4.8 (Puisa, Malazizi, and Gao 2014). As the FAROS project focuses on the effect of global design factors (GDFs) on human performance in an accident evasive action, the probabilities of collision and grounding are defined per *encounter*[12] rather than shipyear. However, it is straightforward to update to

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[12] The encounter is understood therein as a situation where an evasive action is needed to pass safely with the other ship or a shoal. The encounter can be understood as exposure to the hazards. In order to express risk on a yearly basis, as required by project, a number of exposures over a year has to be estimated.

annual probability of collision/grounding, provided the number of encounters per year within given geographical location is known. The process of assessing the number of encounters along the selected routes is presented in (Montewka, Goerlandt, et al. 2014). In FAROS two shipping routes have been selected (Zagkas and Pratikakis 2012):

- A ferry route from Helsinki (Finland) to Travemunde (Germany),
- A tanker route from Rashid (UEA) to Chiba (Japan).

Once the annual number of encounter has been determined, the risk magnitude is calculated as (Jasionowski 2011)

$$\mathrm{PLL}_{\mathrm{col/gr}} = \mathrm{P}_{\mathrm{col/gr}}\left(1 - cdf_{N_{max}}(N_{max})\right)(1 - A)N_{max} \tag{11}$$

$\mathrm{P}_{\mathrm{col/gr}}$	Probability of a collision or grounding accident per ship-year
$cdf_{N_{max}}(N_{max})$	Probability that a ship has the capacity of up to N_{max}persons (crew and passengers) in the fleet of given ship types.
A	Probabilistic subdivision index (SOLAS2009)
N_{max}	Number of persons considered (e.g. number of crew, or number of passengers, or both, onboard the ship)

The above risk formulation is applied to both ship types and both routes, whereas the environmental risk (Montewka 2013a) is assessed for tanker ships navigating along the second route.

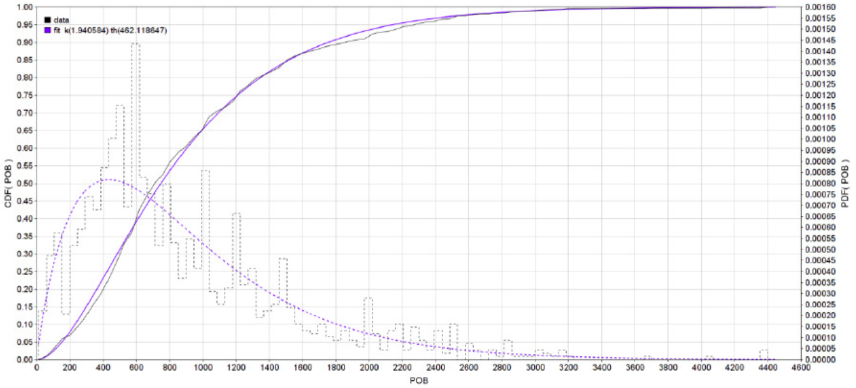

Figure 2: Probability distribution of the number of persons onboard RoPax ships, $cdf_{N_{max}}(N_{max})$ (Jasionowski 2011)

Personal risk

As indicated, the personal risk is also expressed in PLL per shipyear. To start, we can turn to MSC 83/INF.2 which offers the following expression for the personal risk:

$$\mathrm{IR}_{\mathrm{Y}} = F \cdot P_y \cdot E_y \tag{12}$$

IR_{Y}	Individual (personal) risk per shipyear
F	Frequency of an undesired event per shipyear (e.g., unsafe behaviour). This figure is individual independent.
P_y	Conditional probability of individual casualty (e.g., death) for individual Y given the fractional exposure to the risk and the undesired event has occurred.
E_y	Individual's fractional exposure to that risk, i.e. conditional probability of the individual of being in the given location at the time of the accident.

An illustration explaining the above personal risk formulation is taken from MSC 83/INF.2: The risk for a person to be killed or injured in a harbour area, due to a tanker explosion is the higher the closer the person is located to the explosion location, and the more likely the person will be in that location at the time of the explosion. Therefore, the Individual Risk for a worker in the vicinity of the explosion will be higher than for an occupant in the neighbourhood of the harbour terminal.

Eq. (12) can also be expressed (using the chain rule of probabilities) in a more generic and formal probabilistic form for better understanding of its formal rationale, i.e.

$$\mathrm{IR}_{\mathrm{Y}} = P(C \cap E \cap H) = \underbrace{P(C|E \cap H)}_{P_y}\,\underbrace{P(E|H)}_{E_y}\,\underbrace{P(H)}_{F} \tag{13}$$

$P(C \cap E \cap H)$	Probability of casualty, exposure and hazard to happen at the same time over one year for a given individual.
$P(C\|E \cap H)$	Conditional probability of casualty (e.g. death, injury) given that an individual has been exposed to an injurious hazard. The relevant question is: *Given unsafe behaviour and a hazard present (e.g., walking/running on a slippery surface while wearing inappropriate footwear), what is the probability of falling and fatally injuring oneself?* This probability is the output variable of the personal risk model developed in deliverable D4.5.
$P(E\|H)$	Conditional probability for a given individual to be at the location of the hazard in question. The relevant question is: *Given unsafe behaviour of a crew member, what is the probability of exposure to a hazard associated with this unsafe behaviour (e.g. probability of a slippery surface while wearing inappropriate footwear)? This also corresponds to probability of exposure to such hazards.* As the presence of a hazard is independent of unsafe behaviour, this probability can be interpreted as just

probability of exposure to a hazard itself. For example, this would be probability of

- walking on a slippery surface
- working on heights
- weight lifting and carrying
- significant engine repairs
- etc.

Additionally, as we are interested in annual probabilities of events, then the above is probability to get exposed to a hazard over one year. The probability equals to one when the number of exposures over a year is one or more.

It would be reasonable to assume the exposure to all such hazards to be certain over the enter year. So has been assumed in D4.5, which did not include the hazard variable into the BBN model therefore.

With the above in mind, $P(E|H) = 1$, i.e. probability of exposure to a hazard such as walking on a slippery surface etc., provided unsafe behaviour is present.

$P(H)$ Marginal probability (individual independent) for unsafe behaviour to happen within one year.
The relevant question is:
What is the probability of one or more unsafe behaviours per person-year (e.g., prob. that inappropriate footwear is worn)?
Probability of unsafe behaviour (or insufficient safe behaviour) has been addressed in D4.5:
If we assume that GDFs and other affecting factors have same average values (e.g. vibration level etc.) over a year, then this probability of unsafe behaviour would be valid for that year.

The above expressions can be interpreted in terms of an event tree shown in Figure 10. As can be seen, there is only one scenario resulting in personal risk and this very scenario is expressed using the formula above.

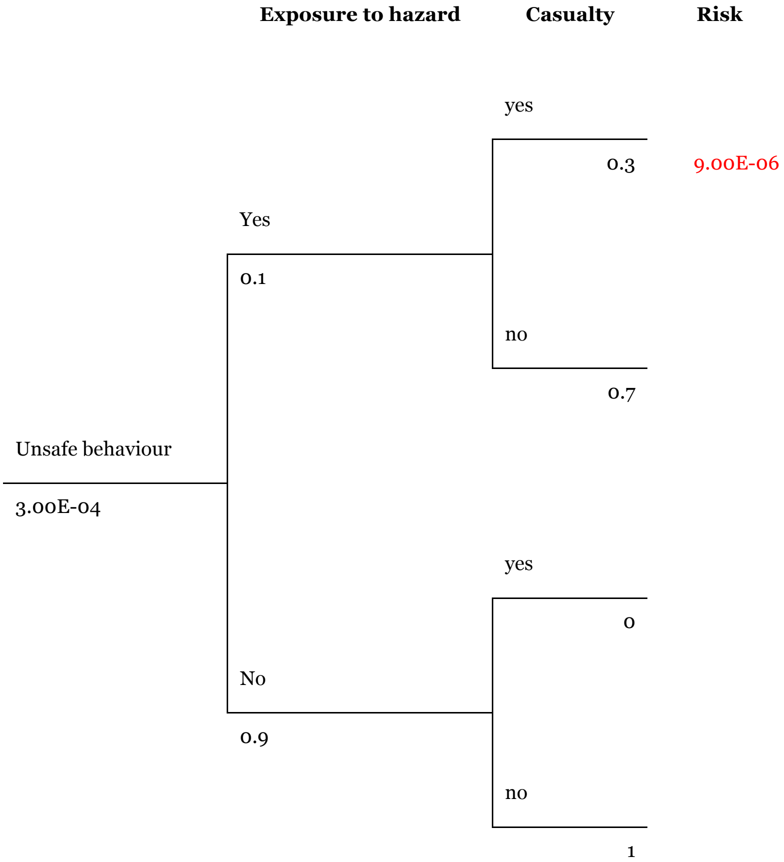

Figure 10: Event tree representation of the personal risk given in Eq. (13) (note: used values are hypothetical)

Thus, the above personal risk figure corresponds to annual probability for an individual to be fatally injured by a given hazard. If we assume that there are n crew members who are equally exposed to this hazard (i.e. unsafe behaviour), one can on average expect

$$\mathrm{PLL}_{\mathrm{idv|H}} = n_H P(C \cap E \cap H) = n_H \underbrace{P(C|E \cap H)}_{P_y} \underbrace{P(E|H)}_{E_y} \underbrace{P(H)}_{F} \tag{14}$$

fatalities per year, assuming that the event involving a personal injury/fatality, exposure to hazard (e.g. fall, slip) and unsafe behaviour per year is binomially distributed with probability $P(C \cap E \cap H)$. Eq. (14) corresponds to the expected value of a binomial variable or the annual potential loss of life, in the context of personal risk. In view of Eq. (10), the above expression for $\mathrm{PLL}_{\mathrm{idv|H}}$ can be rewritten as

$$\mathrm{PLL}_{\mathrm{idv|H}} = \underbrace{n_H \underbrace{P(C|E \cap H)}_{D4.5} \underbrace{P(E|H)}_{=1}}_{\boldsymbol{E(N|unsafe)}} \underbrace{\underbrace{F}_{D4.5}}_{\boldsymbol{P(unsafe)}} \tag{15}$$

NB: The above expression can analogically be applied to injuries. However, the expected number of injuries will not be integrated within the overall risk model and will be kept separately while comparing designs.

The number of crew members varies from shiptype to shiptype. Additionally, crew numbers may vary depending on the trading pattern, e.g. for short voyages in the North Sea, these numbers are increased by 2-3 persons. According to FAROS deliverable D3.1 (Zagkas and Pratikakis 2012), the selected VLCC and AFRAMAX tankers have 30 crew members each, whereas the selected large (200 m in length) and medium size (140 m in length) RoPax ships have 126 and 78 crew members, respectively. Below the additional indications of crew numbers on tankers are given.

The expected number of crew exposed to personal risk per year should be different to the number of crew onboard because there are hours when seafarers are resting and hence not affected by hazards considered in the personal risk model. Thus, the crew number exposed to risk can be expressed as follows.

$$n_H = N_Y \cdot p_d = N_Y \underbrace{\frac{(H_T - H_{SY})}{H_T}\frac{1}{R}}_{p_d = product\ of\ two\ ratios} = n\frac{(168 - H_{SW}) \cdot 52.1775}{8765.81} \qquad (16)$$

n_H	Annual number of crew members exposed to personal risk. This is the expected (average) number.
N_Y	Cumulative (total) number of crew members serving on the ship over the year. For example, if there are 3 rotations with 30 members each, then $N_Y = 3 \cdot 30 = 90$. This is the total number of crew members can be injured over the year.
p_d	Probability for a crew member (out of N_Y members) to be awake on any day of the year.
R	Number of annual crew rotations
H_T	Total number of hours per year, $H_T = 8765.81$.
H_{SY}	Sleep hours per year per crew member
H_{Sw}	Number of sleep hours per week per crew member. The number 168 corresponds to the total hours per week. Currently, ILO allows working up to 91 hours per week, STCW allows 98 hours per week (but not longer than for two weeks). Thus, assuming that 8 hours per 24 hours is a typical sleeping pattern, a crew member still has up to 3 hours of spare time per day. Hence, $H_{Sw} = 8 \cdot 7 = 56$ hours per week is used.
n	Number of crew members onboard at any time, i.e. per annual rotation (see above). The number 52.1775 corresponds to the number of weeks per year.

The above formulation results in the expected number of 20 crew members exposed to personal risk per year, if 30 members onboard who are awake for 2/3 of time are assumed. That is,

$$n_H = \frac{2}{3}n \qquad (17)$$

However, taking into account the uncertainty around sleeping hours as the life onboard goes all around the clock and there is nothing like sleeping hours for all the crew, a conservative approach is adopted. It is assumed that the annual expected number of crew exposed to personal risk is equal to the number of crew onboard, i.e.

$$n_H \approx n \qquad (18)$$

Integration of experiment results

The objectives of the virtual reality (VR) experiments were to study the effect of various arrangements of deck layout on very specific aspects of crew behaviour. In particular, the experiments studied the frequency of closing watertight doors (WTDs)—of which number and arrangement varied from deck layout to deck layout—and the likelihood of the engineer to avoid contact with hazardous objects in the engine room as the distance to them was manipulated.

These results indicate that deck layout may affect crew behaviour. In summary, a deck layout arrangement with fewer WTDs to cross and larger distances to hazardous objects in confined spaces (e.g. more spacious engine rooms) represents a preferable design alternative. Table 1 summarises the experiment results.

Table 1: Summary of VR findings (confirmed hypotheses)

#	**Findings**
VR1	The fewer WTDs to cross when crew have repetitive tasks, the higher the probability for crew to close them all. Open WTDs compromise watertight integrity of the ship; this finding contributes to the societal risk addressed in the risk model.
VR2	If more space around hazardous equipment in the engine room is available, crew will indeed use this space to reduce the risk of contact. This relates to a possibility to get injured by moving, high temperature or any other hazardous object.
VR3	Lower WTD crossing frequency may be associated with lower chance of doors being crossed at an unsafe degree of aperture. This relates to a possibility to get trapped by automatically closing WTD, which can be injurious and even fatal.

Physical experiments on bridge simulators (ref. (Butler 2014)**)**

The objectives of the physical experiments on a bridge simulator were to assess the effect of Global Design Factors (GDFs), namely noise and perceived ship motion, on human performance in wakeful and tired states. Twelve RoPax and twelve Tanker Officers of the Watch were involved in simulated bridge RoPax and Tanker scenarios. The specific experimental aims were to test the effects of noise and motion on collision or grounding avoidance measured in terms of the mean value of the closest point of approach (CPA). Table 2 lists key observations from the experiment results.

Table 2: Summary of experiment findings on the bridge simulators

#	**Findings**
BS1	The contribution of noise and ship motions did seem to compromise navigation performance of fully rested mariners a little but not significantly.
BS2	When noise and ship motions were present, navigation performance was still better of fatigued mariners, as opposed to fully rested mariners.
BS3	The best performed was observed with fatigued mariners and no noise and ship motions present
BS4	Thus, ship motions and noise may have slightly compromised the compensatory strategy, i.e. capability to compensate degradation in performance due to lack of rest

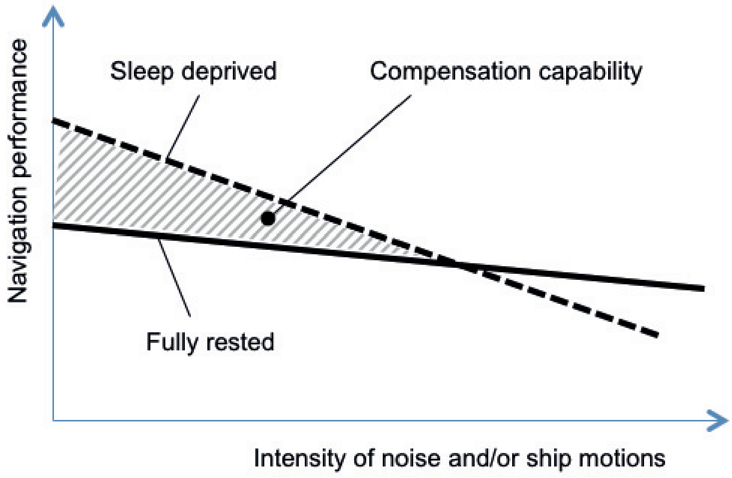

Figure 3: Graphical illustration of experiment findings on the bridge simulators.

In summary, it was noticed that mariners showed better navigation performance when they were tired (fatigued) following controlled sleep deprivation, which is perceived as a factor of compensation. However, this performance was less noticeable when bridge noise levels increased or when perceived motion was exacerbated due to higher waves. Figure 3 illustrates the causality observed during the experiments with the compensation capability (the shaded area) degrading as nose and/or ship motions intensify. However, the interpretation in Figure 3 remains hypothetical, for more research is necessary to confirm it with full confidence.

Discussion

The integration of the experiment results is considered in two ways. First, it is done in terms of design recommendations, then and then, in terms of their utilisation in the developed risk models.

Design recommendations

Based on findings VR1, VR2 and VR2 the following design recommendations are proposed and they will also be followed during the design exercise in WP6:

1. Areas frequently visited during normal operation (e.g. during scheduled overhauls) should have a minimum number of watertight doors. To achieve this, corresponding functional spaces have to be collocated and if possible jointed.
2. Damage stability calculations may involve checking the ship's flooding survivability with certain watertight doors open.
3. Maximum distances to hazardous objects in confined spaces (e.g. more spacious engine rooms) have to be maintained, as long as practicable i.e. cost effective.

Risk models

Collision / grounding risk model and finding VR1

This finding is related to the consequence part of the risk model. Consequence model takes into account the probabilistic index of damage stability (aka Index "A"), which corresponds to probability of surviving any damage case causing flooding of the vessel. Currently, the Index "A" is calculated assuming all watertight doors being closed. To take the finding into account and therefore produce a more robust and resilient ship design in the subsequent WP6, some watertight doors (chosen randomly or based on other considerations) will be keep open during damage stability calculations.

Collision / grounding risk model and findings BS1, BS2, BS3, and BS4

The experiments did not rejected the initially assumed effect of GDFs on crew performance, as described in (Montewka 2013a; Montewka 2013b). Therefore, the risk model were left to take into account the slight degradation of navigation performance with the intensity of GDFs, reflecting the causality represented by the continuous line in Figure 3.

The dashed line Figure 3 remains unconsidered in the model. The primarily reason stems from the fact that the experiments have only indicated the possible causal relationships, but have not been sufficient provide their quantification. Thus, it remains unknown by how much the navigation performance of a sleep deprived mariner is better than of a fully rested mariner, and what is its degradation rate as the GDFs intensify. Large scale experiments on bridge simulators and possibly at sea, which were not planned in FAROS, are required to provide the needed quantification. This is the subject of follow-up research.

Personal risk model and findings VR2 and VR2

The findings are related to the effect of deck layout on the personal risk. As with other results, the experiments have only indicated the possible causal relationships, but have not been sufficient provide their quantification. It hence remains unknown what would the minimum distance to hazardous objects be, for example. However, if the above indicated design recommendations are followed, the personal risk may be reduced.

Conclusions

The paper has presented the process behind integration of the personal and societal risk models, which were previously developed in WP4 of the project, into an overall risk model. The proposed mathematical approach is simple and easy to implement as a software tool.

The integration of the experiment results in the form of design recommendations and updated risk models has been described. Generally, the integration has been effective but limited due to lack of quantitative data. The experiments have only indicated the possible causal relationships, but have not been sufficient provide their quantification. Therefore, more research—outside project FAROS—is necessary to overcome this deficiency.

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Jakub Montewka obtained his Ph.D. in technical sciences at Maritime University of Szczecin in Poland in 2008, where he has been working from 2001 until 2008. At the same time he gained an operational knowledge and skills working on board sea going vessels as a navigator (2001-2008). Since 2009 he has been employed at Aalto University, Marine Technology with the main task to develop models for maritime traffic safety assessment. At the moment the models for a holistic safety assessment are being developed with the use of Bayesian methods.

Romanas Puisa is a Research Project Manager with degrees in Mechanical Engineering, specifically in Machine Design. His principal research activities involve: ship design, design optimisation strategies, safety and reliability engineering, and development of corresponding software products. He has been involved in numerous European (e.g. SAFEDOR, VIRTUE, BESST, TARGETS, FAROS) and small domestic research projects (e.g. UK MCA RP625), acting as a researcher and research manager. He has numerous publications in scientific journals, books, conference proceedings, and technical reports.

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Benchmarking of the overall risk model

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Introduction

The ultimate objective of the FAROS project is to understand, integrate, and demonstrate the role of human factors in risk-based ship design. The focus is on human error, which is an integral part of the causal chain leading to societal and personal risks on board a ship from collision, grounding, crew personal injury and fire.

To achieve the above objective, FAROS has developed a series of risk models that describe the impact of vessel Global Design Factors (GDFs) on human performance and the subsequent occurrence of unwanted outcomes (personal injury, collision, ground and fire). These were then synthesised into a single comprehensive risk model, see Figure 1.

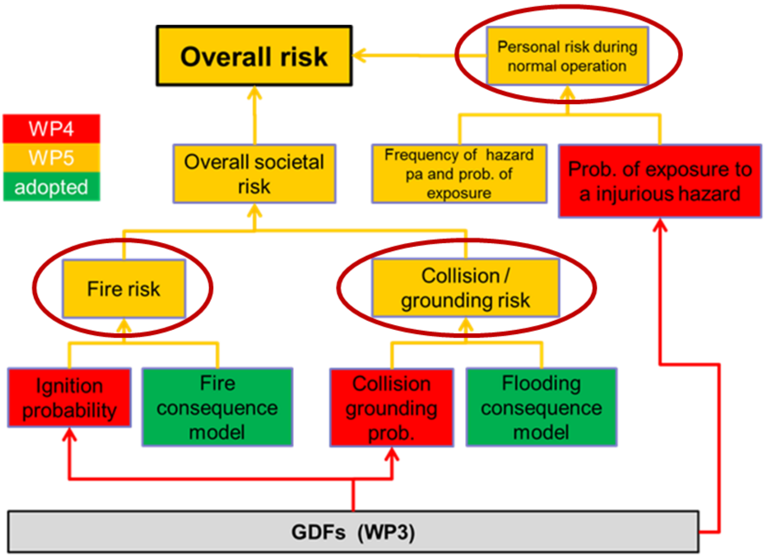

Figure 1: Structure of the overall risk model. The benchmarked quantities are marked with red ovals.

Following the development of the risk models, the next step was to verify the ability of these models to provide valid output. This paper describes in short the benchmarking exercise that has been performed to assure the credibility of the FAROS risk models. The objective was to study whether they produce results of similar magnitude as observed in historical data, while detailed validation of the models was beyond the scope of the study. For further details, see (Innes-Jones et al., 2014).

Methodology

The general approach to benchmarking the model was to determine how accurately the model predicts the unwanted outcomes using simulated model input. The adopted technical approach comprised three main steps: First, random model inputs are generated using Monte Carlo (MC) simulations. Second, these were then propagated through the risk model in order to generate model outputs. Third, the model outputs generated were compared against benchmarking data. Relevant historical and empirical data as well as As Low As Reasonably Practicable (ALARP) and target values set out by the International Maritime Organization (IMO, 2007) were utilised as the benchmarking data. A specific acceptance criterion was used: The model was judged acceptable if at least 5% of the simulated MC samples fall within the interval $[\mu_h - \delta, \mu_h + \delta]$, where μ_h is the historical average and δ is 5% of the observed data range of the MC samples (i.e. 0.05 · [max(x) – min(x)]).

Where the model output data was consistent with the benchmarking data, it provided assurance that the risk models deliver credible results. Where the model output data was inconsistent with the benchmarking data, correcting factors were developed for the risk model to ensure that acceptable outputs can be achieved. The simple solution of correcting factors scaling the outputs to the desired level was seen acceptable, since no new information with which to amend the model assumptions was produced during the benchmark study. Table 1 shows the model output measures considered in the benchmarking.

Table 1: Output measures of the risk models considered for benchmarking.

Risk Model	**Measure**	**Ship Type**
Individual (personal) risk	Probability of fatality of crew member per shipyear	Not ship type specific
Collision	Probability per shipyear	VLCC AFRAMAX Handy-Size RoPax Large RoPax
Collision	Potential loss of lives per shipyear	VLCC AFRAMAX Handy-Size RoPax Large RoPax
Grounding	Probability per shipyear	VLCC AFRAMAX Handy-Size RoPax Large RoPax
Grounding	Potential loss of lives per shipyear	VLCC AFRAMAX Handy-Size RoPax Large RoPax
Fire	Outbreak probability per shipyear	Tanker (VLCC / AFRAMAX) RoPax (Handy-Size / Large)
Fire	Potential loss of lives per shipyear	Tanker (VLCC / AFRAMAX) RoPax (Handy-Size / Large)
Fire	Engine room ignition probability per shipyear	Not ship type specific

Results

The benchmarking exercise demonstrated that the personal risk and collision risk models deliver results that are to the most part consistent with the benchmarking data and pass the acceptance criterion. The risk models accurately represented the expected level of risk to crew members and the expected collision probability. Figures 2 and 3 show the histograms from the MC sampling of individual risk per shipyear and collision probability per shipyear for large RoPax, respectively.

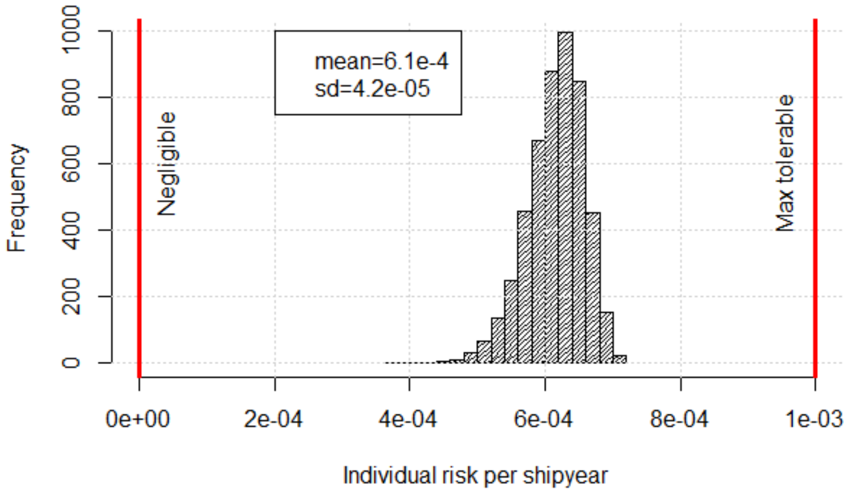

Figure 2: MC results for individual (personal) risk per shipyear with respect to the ALARP region. The red line to the left represents the lower bound of the ALARP region, while the one to the right represents its upper bound. The box shows the numerical mean and standard deviation obtained from the MC simulations.

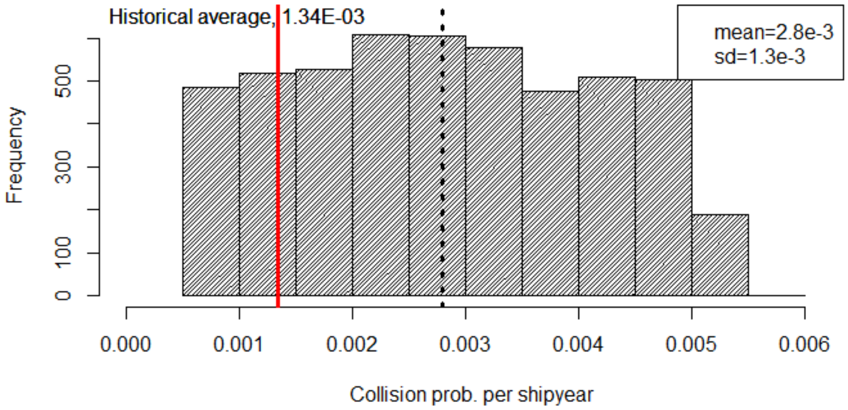

Figure 3: Histogram of collision probability per shipyear for large RoPax. The red line shows the historical average identified as the benchmarking criteria and the dotted line the mean value obtained from the MC sampling. The box shows the numerical mean and standard deviation obtained from the MC simulations.

However, the results regarding potential loss of lives (PLL) due to collision were less accurate. Although being within the same order of magnitude as the historical data, the model tends to slightly underestimate the PLL for tankers (failing the acceptance criterion) and overestimate for RoPax ships (passing the acceptance criterion). For this part of the collision model, corrections were proposed, so cost-benefit analyses based on the risk model would deliver acceptable results. The proposed corrections did not require redevelopment or any other algorithmic adjustments to the risk model, rather a correcting multiplier was applied to the final result, see Table 2.

The model outputs from the grounding and fire risk models were not consistent with the benchmarking data and did not pass the acceptance criterion. The grounding risk model tends to overestimate the risk by approximately two orders of magnitude, see Figure 4. The fire risk model underestimates the PLL by approximately one order of magnitude (Figure 5) and the fire outbreak probability by approximately two to four orders of magnitude. This means that while it is not appropriate to use the grounding and fire model outputs to determine absolute risk, they can be used in ranking different design alternatives. For these models, corrections were proposed using the same approach as for the collision caused PLL, see Table 2.

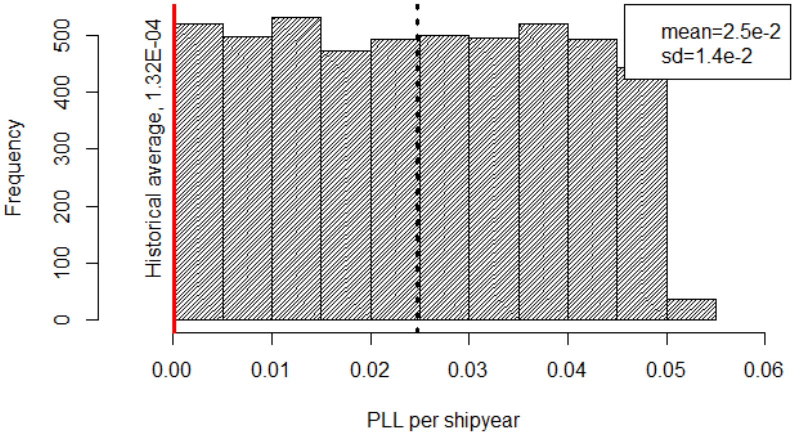

Figure 4: Histogram of grounding caused PLL per shipyear for AFRAMAX. The red line shows the historical average identified as the benchmarking criteria and the dotted line the mean value obtained from the MC sampling. The box shows the numerical mean and standard deviation obtained from the MC simulations.

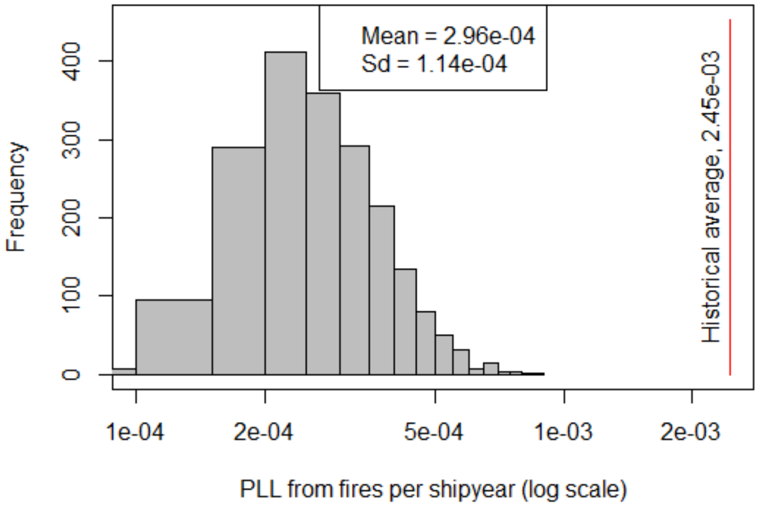

Figure 5: Histogram of fire caused PLL per shipyear when comparing with the historical average (log scale). The red line shows the historical average identified as the benchmarking

criteria. The box shows the numerical mean and standard deviation obtained from the MC simulations.

Table 2: Summary of corrections for the Collision, Grounding and Fire risk models.

Risk Model		**Correcting multiplier**			
		VLCC	**AFRAMAX**	**Handy-Size RoPax**	**Large RoPax**
Collision	**Risk (PLL) per shipyear**	3.4	2.7	1.01E-01	1.70E-01
Grounding	**Risk (PLL) per shipyear**	6.29E-03	5.28E-03	3.61E-03	6.50E-03
Fire	**Risk (PLL) per shipyear**	8.28		3.73E+01	

Conclusion

The benchmark study showed that some parts of the overall risk model produced results that are in line with historical data, while other parts did not. To those parts not in line with historical data correcting multipliers were suggested.

The benchmarking results are to be applied in subsequent work of the project. Specifically, the benchmarked overall risk model, along with the benchmarked individual risk models are planned to be used to make comparison of design alternatives of RoPax and tankers ships. The designs can then be optimised with respect to risk, commercial viability, and environmental impact.

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Navigation and Lighthouse Authorities) concerning these matters. His current main research topics include human reliability assessment.

Gemma Innes-Jones is a Senior Human Factors Consultant at Lloyd's Register Consulting Ltd. With post-graduate degrees in Psychology and Human Factors, her research and consultancy work has focused on understanding human performance in safety-critical work environments. Her current research interests include perception and cognition, resilience engineering and risk-based design.

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Adopted approach for achieving commercially robust design concepts

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Background

Amongst other objectives, project FAROS aims at developing optimised concepts for RoPax and tanker ships, based on existing baseline designs. For the optimisation process to end up with robust design solutions, future variations in exogenous factors that govern commercial performance of the ship will be integrated in the design process. To this end, literature reviews has been carried out to collect information about such exogenous factors as:

- Future market trends in terms of cargo and passenger volumes, freight rates, fuel prices etc.
- Future changes in statutory and class design requirements (e.g., new safety criteria, environmental constraints) that might be applied retrospectively.

The literature review has identified certain (e.g., adopted future caps on emissions by IMO) and less certain exogenous factors—usually expressed in a few plausible development scenarios—such as cargo and passenger volumes, fuel price, freight rates, and changes to stability and other requirements in the aftermath of recent European (e.g., FP7 GOALDS 09/2009 - 08/2012, EMSA/OP/08/2009) and other research projects. The accumulated information has been processed and fed into a newly developed methodology (presented in this paper) that ensures a target performance of optimised ship concepts against any plausible state of the future in terms of exogenous factors.

This paper is based on public FAROS report D6.3 (Puisa, 2014) available on the project website[13].

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[13] www.faros-project.eu

Introduction

Ships are designed to very specific design requirements imposed by ship owners and regulators. However, fuel prices, cargo volumes, freight rates etc. are likely to change over ship's lifetime. Additionally, there are could new regulatory requirements to be applied retrospectively to existing ships. If the knowledge about such future changes in design requirements is available at the early design stage, new vessels must be designed with them in mind—as long as economically justified—so they become robust to external influences. This would allow the operators to remain competitive and offset often significant cost of refurbishment or/and service interruption.

The difficulty to quantify the future arises when uncertainty is deep (O'Riordan and Jäger, 1996). The term deep uncertainty refers to the condition where decision makers do not know or cannot agree upon the system model relating actions to consequences or the prior probabilities on key parameters of the system model (Lempert et al., 2002). In such circumstances, all assumptions, future scenarios etc. are accepted with "a grain of salt". In the maritime domain, policy analysts and strategic planners are aware that they are facing deep uncertainty. But most of them still develop plans based on the assumption that the future can be predicted. They develop a static "robust" plan using a few future scenarios (e.g. low, reference, and high), often based on the extrapolation of trends. A more frequent situation is when a static "optimal" plan is developed simply based on a single "most likely" future.

This strategy, however, is deeply flawed. Such a plan will likely to fail if the future turns out to be different, and it is easy to demonstrate that the probability for the future to be different is much greater than to be as predicted. McInerney et al. (McInerney et al., 2012) compared this strategy to "dancing on the tip of a needle". Thus, the performance of a plan optimised for a most likely future can deteriorate very quickly due to small deviations from the most likely future, let alone in the face of surprise (Walker et al., 2013). Even analysing a well-crafted handful of scenarios will miss most of the future's richness and provides no systematic means to examine their implications (Annema and Jong, 2011; Goodwin and Wright, 2010). Too often, analysts ask "what will happen?" and trap themselves in a losing game of prediction, instead of the question they really would like to have answered: "Given that one cannot predict, which actions available today are likely to serve best in the future?" (Walker et al., 2013).

Broadly speaking, the literature offers four (overlapping, not mutually-exclusive) ways for dealing with deep uncertainty in making sustainable plans (van Drunen et al., 2009; Walker et al., 2013):

- Resistance: plan for the worst possible case of future situation.
- Resilience: whatever happens in the future, make sure that the system can recover quickly.

- Static robustness: aim at reducing vulnerability in the latest possible range of conditions.
- Dynamic robustness (or flexibility): plan to change over time, in case conditions change.

The first two approaches use mathematical models to produce forecasts, whereas the other two do not. The first approach is likely to lead to very costly plans and might not work well because of surprises (aka “Black Swans”) (Taleb, 2010). The second approach accepts temporal system malfunctioning, and focuses on recovery. The third and fourth approaches aim to determine a plan which is robust, i.e. the one which can achieve reasonable level of goodness across a wide spectrum of plausible futures. In the majority of cases, dynamic robust plans demonstrate higher efficacy than their static counterparts, e.g. (Kwakkel et al., 2010). However, static robust plans are of interest when the plan is in early stages of development and only a fraction of all factors governing the plan itself are known. This is the case during the concept ship design stage which is considered in the FAROS project.

A static robust plan (i.e. a ship concept) can be developed in various ways (Walker et al., 2013). In this paper we focus on Robust Decision Making (RDM) as an approach for its development. We consider conjugating the RDM with such data mining techniques as Scenario Discovery performed by Patient Rule Induction Method (PRIM) (Bryant and Lempert, 2010). Robust optimisation methods, which have been applied to optimisation of ship concepts under uncertainty, e.g. (Diez and Peri, 2010; Sundaresan et al., 1995), are considered to be irrelevant. Firstly because these methods deal with uncertainty in plan governing parameters, which is of little interest in our case. And secondly, they are computationally expensive and are outside of computational strategy adopted in project FAROS.

Robust Decision Making in a Nutshell

RMD is composed of four steps as shown in Figure 1 (Lempert et al., 2002):

- Problem definition, decision choices under consideration, and utility functions to express decision criteria (step 1).
- Using computer simulations and mathematical modelling, RDM takes a design plan and puts it to the test against thousands of plausible futures (step 2).
- The resulting data (typical thousands of records) is statistically analysed by means of data mining techniques to find out what is most important for plan’s success and failure (step 3).
- This provides the evidence for decision makers to design more robust strategies (back to step 1), i.e. to make the plan more robust so it performs well no matter what the future holds. Or trade-off analysis is performed to check if decisions are worth adopting (step 4).

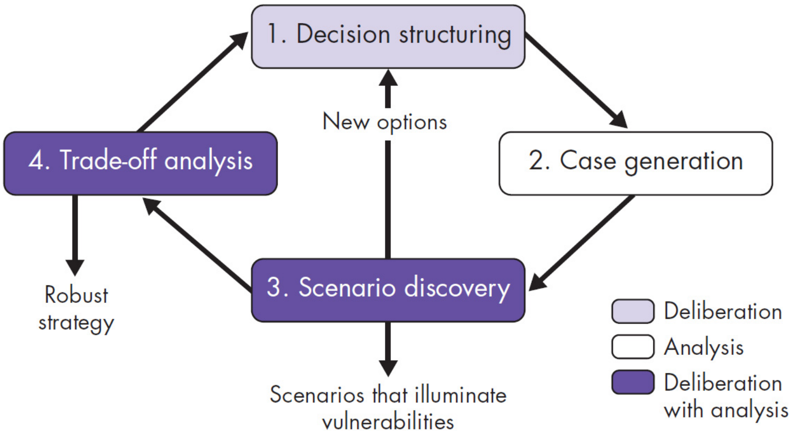
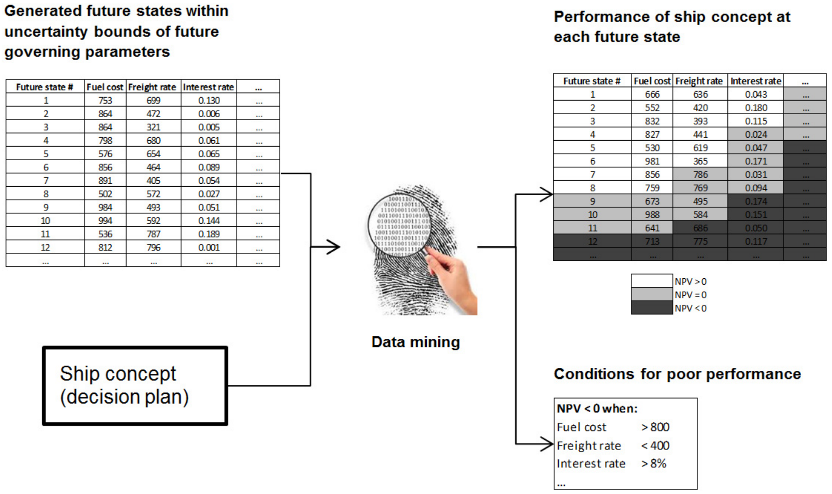


Figure 1: Iterative, participatory steps of an RDM analysis; adopted from (Lempert and et al., 2013)

By embracing many plausible futures within a quantitative analysis, RDM can help reduce overconfidence and the deleterious impacts of surprise, can systematically include imprecise information in the analysis, and help decision-makers and stakeholders with differing expectations about the future reach a well-grounded consensus on action, even when uncertainties are deep (Lempert and et al., 2013).

An illustrative example of RDM application is shown in Figure 2. The example shows the conventional input and one of possible outputs from the RDM process. One of the conventional outputs is conditions (aka discovered scenarios) of poor performance of the plan. This helps identify its vulnerabilities in order to go back to the drawing board and improve it.



Generated future states within uncertainty bounds of future governing parameters

Future state #	Fuel cost	Freight rate	Interest rate	...
1	753	699	0.130	...
2	864	472	0.006	...
3	864	321	0.005	...
4	798	680	0.061	...
5	576	654	0.065	...
6	856	464	0.089	...
7	891	405	0.054	...
8	502	572	0.027	...
9	984	493	0.051	...
10	994	592	0.144	...
11	536	787	0.189	...
12	812	796	0.001	...
...	...	...	...	...

Performance of ship concept at each future state

Future state #	Fuel cost	Freight rate	Interest rate	...
1	666	636	0.043	...
2	552	420	0.180	...
3	832	393	0.115	...
4	827	441	0.024	...
5	530	619	0.047	...
6	981	365	0.171	...
7	856	786	0.031	...
8	759	769	0.094	...
9	673	495	0.174	...
10	988	584	0.151	...
11	641	686	0.050	...
12	713	775	0.117	...
...	...	...	...	...

Conditions for poor performance

NPV < 0 when:	
Fuel cost	> 800
Freight rate	< 400
Interest rate	> 8%
...	

Figure 2: Illustration of RDM application

Implementation in FAROS

In FAROS the application of RMD with Scenario Discovery (SD) is conceptually different but algorithmically the same as the conventional approach. As described in FAROS report D5.4 (Puisa and Pawling, 2014), the design space, which is defined by numerous design parameters, will be sampled to produce hundreds of distinct design alternatives. Each design alternative (ship concept) represents a unique plan (using the RMD terminology) to be put to the test against plausible states of the future, using a holistic performance criterion defined by some utility function. The objective is not to find future conditions under which a given design will fail, as it is conventionally done. Instead, conditions for design parameters will be sought to demarcate regions in the design space with low (utility < target utility) and high (utility ³ target utility) utility values. The high utility regions will be used to define feasible ranges for design parameters, whereas the low utility regions will be analysed to learn about design vulnerabilities.

The utility function is defined as probability for a design concept to be successful (to have target commercial performance) in any state of the future:

$$P_{success} = P(eNPV \geq NPV_{target}) = \int_{NPV_{target}}^{\infty} f(eNPV)\, d(eNPV) \qquad \text{Eq. 1}$$

The success probability corresponds to part of the area under the probability distribution function (PDF) of expected NPV values, denoted as $eNPV$. Thus, once the database of future states has been populated (see Figure 2), k future states—corresponding to each financial year in ship's lifetime, for example—for exogenous parameters are randomly selected to calculate a corresponding eNPV. This operation is repeated many times to produce a set of expected NPV, its histogram and then PDF which is then used for calculation of the success probability.

The expected NPV is a modified form of the conventional NPV formula. The modification is done to account for potential financial liabilities arisen from maritime accidents leading to people fatalities, environmental pollution (for oil tankers only), and major ship repair work (total loss is not considered, assuming the insurance will fully cover it). In this respect, the modified NPV expression becomes akin to the classic risk-adjusted NPV, rNPV, where the annual cash flow is multiplied by probability that it will actually occur (Stewart et al., 2001).

To illustrate the above described approach, we take a simple two-variable example of deciding on commercially viable capacity (in range of 4k – 11k TEU) and operational speed (in 17 – 25 kn) for a new container ship[14], subject to volatility in banker cost (100 – 1000 $/ton) and capacity utilisation (50% – 100%). The ultimate outcome is the feasibility ranges for the cargo capacity

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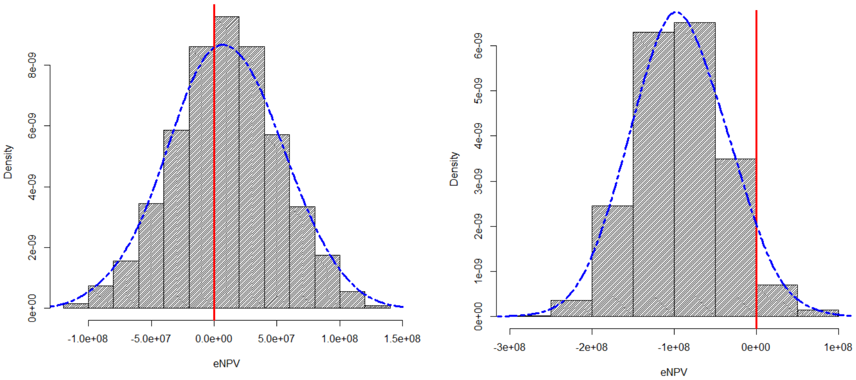
[14] Note, this example is used for the sake of illustration only, and it was not aimed to accurately solve the presented decision problem.

and speed. A full description of the example is found in the public report (Puisa, 2014). Note, a container ship was selected due to availability of cost data (Stopford, 2009) and relative simplicity, and yet absent results from FAROS RoPax and tanker ship concepts when this paper was written.

During the simulation, we checked 1,500 unique combinations for the container's capacity and operation speed. For each combination, 1,000 plausible futures in terms of banker cost and capacity utilisation were considered, forming histograms and corresponding PDFs as shown in Figure 12. The success probability was then calculated from the PDFs (Figure 13) and used to make both design parameters (capacity and speed) confine the feasible region (success > 60%) of the design space (Figure 14).



TEU = 9,185, speed = 18 kn,
success = 59%

TEU = 10,346, speed = 19 kn,
success = 4%

Figure 12: Two design sample cases with different success rates (the red vertical line denotes the NPV threshold, whereas blue dashed lines represent PDFs)

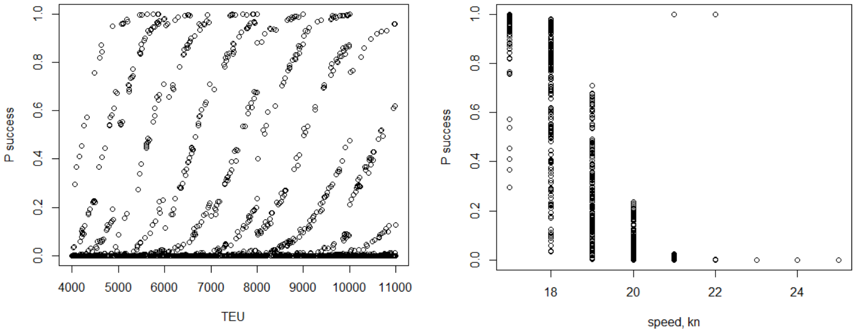


Figure 13: Success probability vs. ship's capacity and operation speed

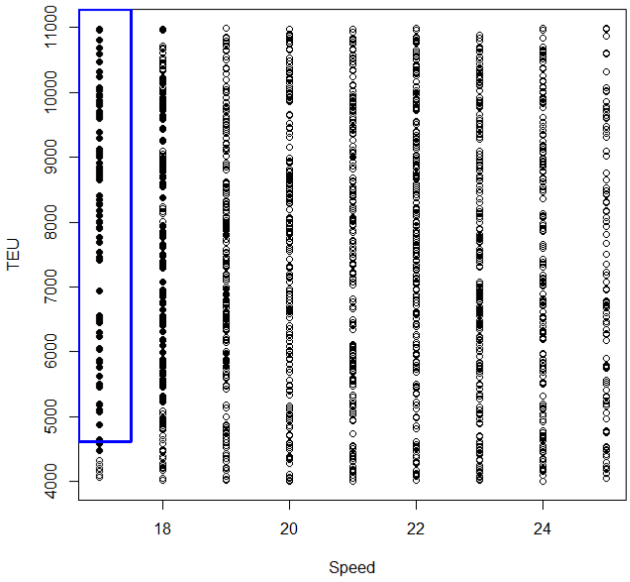


Figure 14: Resulting the region in the design space (speed < 17.5 kn, TEU > 4,614) with the commercial success probability above 60%

Conclusions

This paper has presented a rigorous scientific methodology that allows integrate uncertainties in future exogenous factors into the ship design process. The methodology is based on the Robust Decision-Making (RDM) which has been successfully applied in civil engineering, policymaking and other fields where decision makers face with deep uncertainty[15] about the future performance of their decisions. Thereby we asserted that ship-owners are facing the same challenge when it comes to predicting the future state of the market, either its separate trends or as a whole.

In the context of project FAROS, this methodology will be applied in conjunction with the following exogenous factors (they are the result of sociopolitical pressures and macroeconomic changes):

- Future market trends in terms of cargo and passenger volumes per ship (number of vessels at sea, i.e. overall supply of capacity), freight rates, fuel prices etc.
- Future changes in statutory and class design requirements (e.g., new safety criteria, environmental constraints) with retrospective effect (i.e. no Grandfather Clause applicable).

The work is limited to only the above exogenous factors, ignoring others influences such as climate change, macro and micro economic cycles, political

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[15] Deep uncertainty refers to conditions where the parties to a decision do not know or do not agree on the system model(s) relating actions to consequences or the prior probability distributions for the key input parameters to those model(s).

conflicts and others which might affect world or local economies and regulatory regimes. However, the presented methodology is generic and can be successfully extended to encompass such factors, provided corresponding mathematical models linking exogenous influences to ship's economy are available.

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Tanker Exploration and Optimisation Model Development

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Introduction

The Design Research Centre (DRC), a part of the Marine Research Group of the Department of Mechanical Engineering of UCL (http://www.ucl.ac.uk/mecheng/research/marine) is involved in Work Packages 5 and 6 of the FAROS project. These involve the development of parametric cargo ship models, the integration of the design and design evaluation tools, including those developed in FAROS to represent the human element, and the optimisation of the cargo ship designs using the suite of analysis tools.

Parametric Cargo Ship Models

The DRCs' main area of research is concept ship design, in particular the application of the Design Building Block approach (DBBa) (Andrews and Pawling, 2003), an architecturally-centred approach to concept ship design that has been applied to a wide range of concept ship design studies and research projects, including the EC FP7 funded FIREPROOF project, examining fire safety in passenger carrying ships (Andrews and Pawling, 2006; Andrews and Pawling, 2009; Pawling et al, 2012). The UCL developed approach has been implemented in the commercially available ship design software Paramarine and this tool is being used to develop parametric models of two tankers; an Aframax and a VLCC. This position paper focusses on the VLCC as it is currently at a more advanced stage of development. These models have three main levels of parameterisation; hullform; compartmentalisation; and arrangement.

Hullform

A baseline hullform was provided by the project partner NAP. This hullform was then recreated in Paramarine using its Hull Generator module. The resulting hullform is shown in Figure 1 below. The red curves in Figure 1 were provided by NAP while the black curves were generated by the user in Paramarine in order to achieve the required hullform.

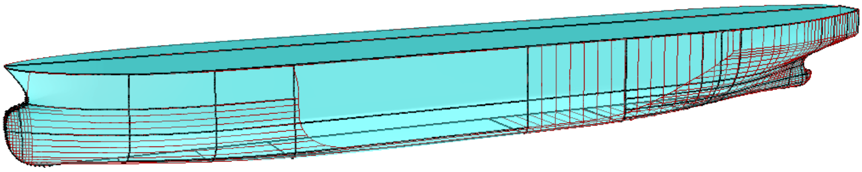


Figure 1: VLCC Parametric hullform model

The hullform is parameterised at two levels; main dimensions; and local hull features. The overall size of the hull is scaled to meet input overall main dimensions such as length, beam and depth. Local features such as the shape of the bow and stern are controlled using a scaling factor that allows the fineness of the forward and after sections to be changed. The overall topology of the hullform is not changed however – it still has a bulbous bow and single screw. The use of a small number of input parameters leads to a model that will generate hullforms over a wide range of values, but will not necessarily be able to precisely match combinations of target hullform parameters (such as C_B, C_W). This trade-off between flexibility and accuracy is necessary due to both the available programming resources and the number of parameters that can be assessed in an exploration or optimisation campaign of practical duration.

Compartmentalisation

The VLCC subdivision model is illustrated in Figure 2 with the transverse watertight bulkheads and decks visible. It should be noted that the two longitudinal bulkheads are not shown in the figure for clarity.

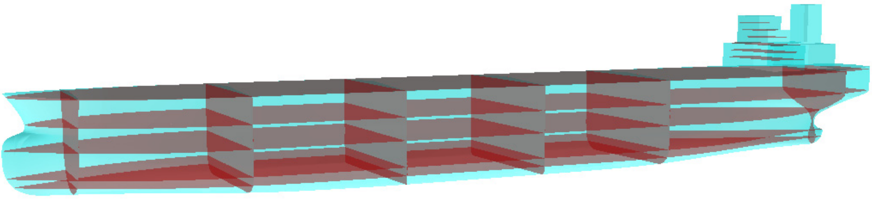
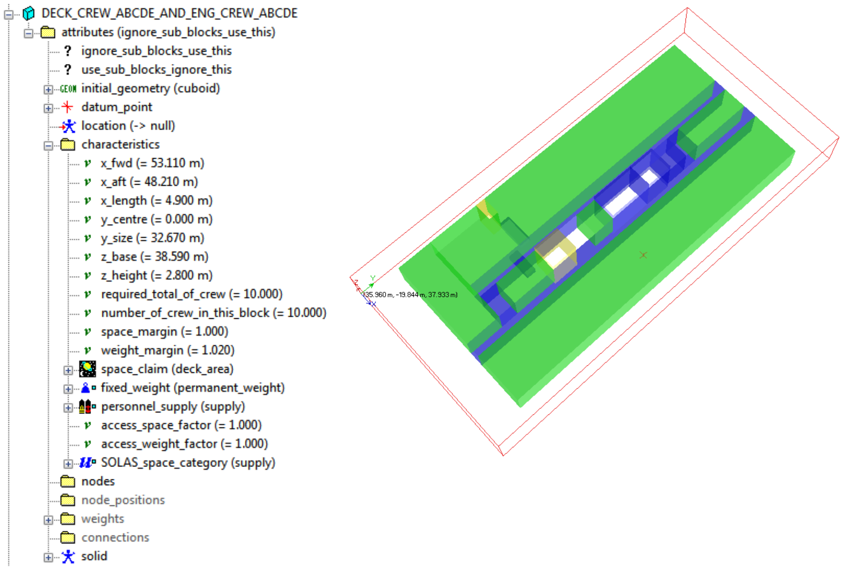


Figure 2: VLCC Parametric compartmentalisation model

The location of the subdivisions can be varied by the designer or by optimisation tools. These subdivisions are used for damaged stability analysis and define the location of internal spaces. They also define the structure and so may be used to input into noise and vibration analysis at a later date.

Arrangement

The internal arrangement of the cargo ships is modelled using the Design Building Block objects in Paramarine. DBBs are objects in the design space that may be assigned numerical and geometric properties, and parameterised by connection to each other or to other features of the design, such as the subdivisions shown in Figure 2. Figure 3 shows the characteristics of a typical DBB representing an accommodation area, along with a screenshot showing the local arrangement of accommodation spaces (green) and access passageways (purple). As with the hullform, there is a trade-off to be made between the flexibility and speed of editing the model and its absolute accuracy. In the case of the arrangement, adjacent spaces with similar roles have been grouped as “Super Design Building Blocks”, e.g. a group of cabins, rather than modelling the individual cabin spaces.



- DECK_CREW_ABCDE_AND_ENG_CREW_ABCDE
  - attributes (ignore_sub_blocks_use_this)
    - ? ignore_sub_blocks_use_this
    - ? use_sub_blocks_ignore_this
  - initial_geometry (cuboid)
  - datum_point
  - location (-> null)
  - characteristics
    - x_fwd (= 53.110 m)
    - x_aft (= 48.210 m)
    - x_length (= 4.900 m)
    - y_centre (= 0.000 m)
    - y_size (= 32.670 m)
    - z_base (= 38.590 m)
    - z_height (= 2.800 m)
    - required_total_of_crew (= 10.000)
    - number_of_crew_in_this_block (= 10.000)
    - space_margin (= 1.000)
    - weight_margin (= 1.020)
    - space_claim (deck_area)
    - fixed_weight (permanent_weight)
    - personnel_supply (supply)
    - access_space_factor (= 1.000)
    - access_weight_factor (= 1.000)
    - SOLAS_space_category (supply)
  - nodes
  - node_positions
  - weights
  - connections
  - solid

Figure 3: Example of a DBB representing a group of cabins in the superstructure

VLCC Ship Product Model and Analysis Tools

Figure 4 illustrates the complete VLCC Ship Product Model (SPM). In total, the SPM contains over 150 DBBs. A range of numerical performance analysis tools, such as stability (intact and damaged), resistance and powering and seakeeping, are built into the Paramarine software and are being used in the FAROS studies. Additional analysis tools to examine the various elements of risk have been developed in the FAROS project and are not being integrated with the Paramarine model. Instead, they remain independent and data is transferred between the models and tools using the .spiral software integration framework developed by the Ship Stability Research Centre of the University of Strathclyde.

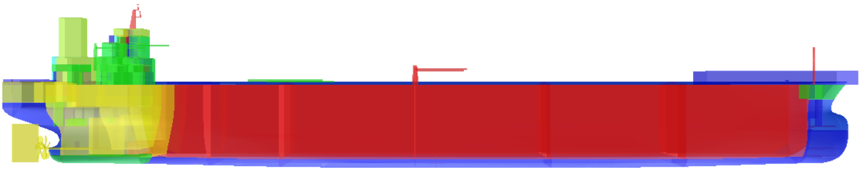


Figure 4: Complete SPM of the VLCC in Paramarine

Software Integration for Optimisation Studies

The .SPIRAL tool allows the automation of the entry of the various input parameters for the ship model, the extraction of output data from the model and Paramarine analysis tools and the transfer of that data to FAROS specific risk analysis tools. The .spiral Network Editor illustrates the connections and workflow in an interactive flowchart and that for the current optimisation toolset is shown in Figure 5.

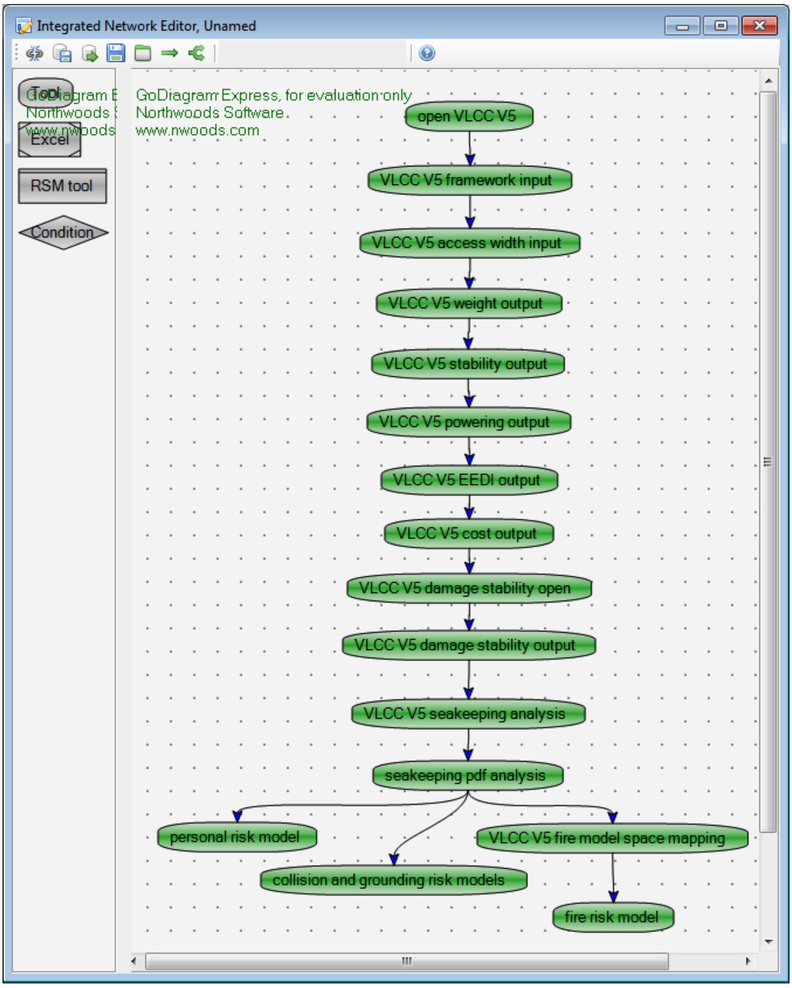


Figure 5: Integrated Network Editor of .spiral showing tools used

In Figure 5, each tool integrated in the .spiral model is represented by a labelled green box. The tools on the top part of the network, shown in series, communicate with Paramarine in order to input various parameters and extract outputs. Paramarine is linked to .spiral through ParaMessenger, a small utility which allows external programs to communicate with Paramarine by means of a Kernel Command Language script. The tools at the bottom of the network, in parallel, are the risk design software provided by the FAROS project partners. The general process may be summarised as:

- Open the design file;
- Make changes to certain parameters;
- Extract numerical data on the resulting design;
- Post process this for transfer to risk models;
- Transfer data to risk models;
- Run risk models;
- Update input files with values of parameters to be changed.

The overall functionality of this interface method has been successfully demonstrated. However, there are a large number of detail tasks to complete before the risk models can be regarded as fully integrated. Even with the current state of model development is it is possible to map out the design exploration and optimisation campaign to be undertaken as part of Work Package 6.

Selection of Parameters for Exploration and Optimisation

As noted in the description of the parametric model, there is a trade-off to be made between the number of parameters that can be assessed in any systematic exploration and the time available to carry it out. Further, it should be noted that, being primarily designer-driven and not automated, the models developed in Paramarine are of a fixed topology (number of decks, bulkheads, relative positions of spaces in internal arrangements, etc.). The input design variable space available for design exploration and optimisation is thus constrained to some extent, and can be evaluated at the same three levels of parameterisation described above: hullform; compartmentalisation; and arrangement.

The key points of the exploration optimisation plan are to: identify the parameters that will be used as inputs to drive the design variation; define the limits on continuous variables & numerical parameters; define the options that will be assessed for discrete variables or topological alternatives; and determine the order in which assessments will be made, particularly if combinations of variables are to be used. It should be noted that this paper is a discussion of the possibilities for exploration and optimisation, not a complete description of the plans within FAROS, as these are currently under development.

Hullform Optimisation

The hullform is described by purely numerical parameters and so the hullform dimensions can be varied around a baseline. The shape of the forward and after sections can also be varied. The current structure of the model would hold the installed engine power constant and allow the design speed to vary with ship size and hull shape. Iterating the design to make power meet a fixed design speed would add complexity to the model, so an alternative approach of assessing each hullform design with different installed power and recording if the power is sufficient will be used. This is easier to program as the tool does not need to make design decisions, and can discard options with insufficient power.

Compartmentalisation

The size of the different compartments shown in Figure 2 can be varied. Currently the number of compartments is fixed, but if the overall length is to be changed enough to warrant a change in the number of cargo tanks then those alternative topologies would be implemented. It is also possible to investigate alternative overall arrangements, such as moving the superstructure forward (with some tanks aft of the superstructure) to improve motions in the working areas.

Arrangement

The opportunities for arrangement exploration and optimisation for the tanker designs are different from those for a RoPax. Most operations involving personnel take place in a relatively small area of the tanker, which is highly constrained in arrangements by the need to maximise the tankage capacity and broader functional requirements on arrangement topology. Although the hullform may be continuously varied over a range of numerical values, the highly constrained arrangement makes the exploration of a limited set of discrete options (topologies) more appropriate.

Currently only a limited number of numerical geometric parameters have been identified for variation, such as the passageway width. Changing the arrangement topology (moving spaces around) is difficult as the DBB model does not contain any automation or logic and cannot automatically compensate for the changing size of operational spaces. However, it is possible to carry out exploration of certain changes to the topology. The overall arrangement of the superstructure can easily be changed by moving complete decks, allowing the investigation of a different “stacking” of the superstructure. It is also possible to implement multiple arrangement topologies representing different internal arrangements for the superstructure, based on the arrangement “styles” found in practice.

Assessing Performance

Although the input parameters will be a mix of numerical and topological options, the output parameters used to assess the performance of the design variants will be purely numerical. These include both the technical and economic performance of the vessels evaluated in Paramarine and the quantification of the personal and societal risk generated by the risk models developed for FAROS.

Summary and the Way Ahead

UCL is developing parametric models of a baseline VLCC and Aframax tanker for use in design exploration and optimisation studies in WP 5 and 6 of the FAROS project. The .spiral software integration tool has been used to integrate these models with third-party analysis tools developed by members of the FAROS consortium to allow the holistic analysis of risk, including the human factors element.

Although this integration task is still ongoing, it is possible to draw up the overall plan for the exploration and optimisation tasks. The fundamental nature of the parametric vessel models permits a limited range of numerical continuous variables to be explored. It also permits a range of discrete variables, in the form of alternative arrangement topologies, to be assessed.

Current work is focussed on completing the software integration to allow the exploration phase of the WP6 investigations to begin. This phase is significant in that it will assist in the development of the full optimisation plan, by allowing the selection of the variables and topologies that will be allowed to vary as part of the optimisation process.

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Prof David J. Andrews (BSc(Eng), MSc, PhD, FREng, FRINA) was appointed Professor of Engineering Design at UCL in September 2000 following a career in ship design and acquisition management in the UK Defence Procurement Agency. He leads UCL's design research in computer aided ship design, design methodology and design practice. He is a Fellow of RINA, Fellow of IMechE and was elected to the Royal Academy of Engineering in 2000 and as a Vice President of RINA in 2006.

Parameterisation and integration of RoPax concepts

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Background

One of the key objectives of project FAROS is to demonstrate how personal and societal risks onboard can cost-effectively be mitigated by design. To this end, risk models were developed in WP4 and integrated in WP5 into a multi-disciplinary performance assessment process. The process is essentially a design process which allows to assess the effect of any design modification to risk, cost, profitability, environmental impact and other performance metrics (Puisa and Pawling, 2014). As such, this design process is referred to as risk-based ship design, because all major design decisions are risk-informed.

It is important to note that this multi-disciplinary performance assessment process is automated. This was achieved by integrating individual software tools that can run automatically. These are design and performance assessment tools. As for the former, specialised CAD software tools with parameterisation capabilities have conventionally been used to automate design modification. The term parameterisation refers to definition of ship's geometry and attributes (e.g. materials and their properties) in such a way that they are automatically (usually but not always) modified in response to changes in design parameter values (usually real and integer numbers). Design parameterisation is hence a prerequisite for optimisation of RoPax ships selected and described in FAROS public report D3.1 (Zagkas and Pratikakis, 2012).

This paper is based on FAROS report D6.2 (Puisa, 2014) which describes an adopted methodology for design parameterisation of RoPax ships, specifically focusing on the hull shape and general arrangement.

Introduction

Design of a ship, as of any other engineering artefact, is defined in terms of geometric and other parameters. The ultimate objective of a naval architect is to decide on the optimal values for design parameters so that the ship fulfils functional and non-functional (aka performance) requirements in the desired way or degree. The innate parametric description of ship's design definition theoretically enables the designer to achieve this goal.

In practice however, the pursuit for truly optimal values ought to be computerised to achieve it. This stems from the fact that the tuning process of design parameters towards their optimal values is time consuming. It is not only the right design decision itself which takes time to find, but it is also the assessment of its effect on the multi-disciplinary ship performance which has to be done. This cause-and-effect cycle, or the modify-and-check loop, is tedious and laborious process, unless it is automated, as described in public FAROS report D5.4 (Puisa and Pawling, 2014). The report specifically describes how the automation is actually implemented and then used to arrive at optimal design solutions in FAROS.

Automatic design modification (i.e. design modifications without manual input) is essential for automated design optimisation, and therefore only design software (aka computer aided design or simply CAD) with automation capabilities should be used. This paper, addresses this very issue. The paper describes the work carried out to parameterise designs of two RoPax ships so they become part of the automated process of design optimisation.

Adopted methodology

Design parameterisation, which may also be seen as design discretisation, can be done to different levels of granularity. The finer the parameterisation, the more flexibility the designer gains in optimising the design. However, very fine parameterisation results in many parameters, i.e. many dimensions, and hence in more resources required to solve the design problem. Therefore, a trade-off between flexibility and practicability has to be sought.

Figure 1 shows the four levels of parameterisation that can be achieved. In project FAROS only three first levels are considered, whereas the fourth level, System, will be addressed only partly. It will cover main system equipment such as main engines and/or diesel generators and various tanks of which locations and sizes are parameterised.

With this in mind, the project focuses on the macro and meso levels of the design definition. The macro level covers main dimensions, location and number of bulkheads etc., i.e. the design features that affect the performance across and along the vessel. The meso-level (aka middle-level) encompasses such design features as equipment dimensions, equipment location, number and locations of openings / doors etc.

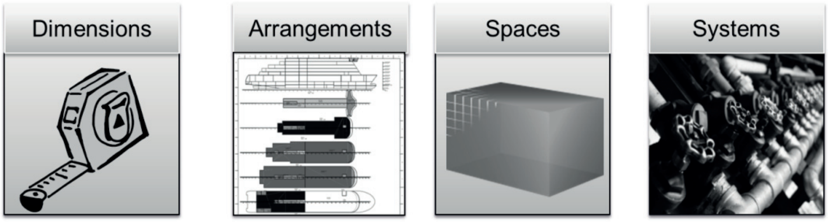

Figure 1: Parameterisation of ship design on four (4) levels.

There are many software tools that allow describing the ship parametrically. One of those is NAPA[16] . NAPA has gained its popularity due to its flexibility in defining the design and manipulating design information by means of NAPA macros, i.e. programming codes written in the native language NAPA BASIC. Another great advantage of NAPA compared to its counterparts—according to our experience—lies in its high speed of calculations, especially stability calculations. Because of these reasons, NAPA has been a popular tool for defining parametric arrangements to be then optimised or used in research studies (e.g. (Puisa et al., 2013, 2012)).

However, the cost of NAPA's flexibility is a relatively long time—might take months—required for development of a parametric design. Although a part of NAPA macros can always be reused, the best part of the code still has to be tailored—often by substantial modifications—to new functional requirements. Because of this bottle neck in the process, development of some parameterisation aiding method was deemed necessary to overcome it. A generic parametric modeller (GPM) was therefore developed to facilitate the process of parameterisation in NAPA. The GPM acts as a pre-processor to NAPA and allows defining any parametric internal arrangement in a short period of time; typically within a few days, depending on a design complexity.

Generic Parametric Modeller (GPM)

As seen in Figure 2, the GPM takes into account the functional requirements and produces a set of NAPA macros, passed in the form of text files, which are read by NAPA, resulting in a complete NAPA project. Internally, the PM requires the input from the user in a particular order, which may resemble an onion-like hierarchical process, as shown in Figure 3. First, main particulars and the hull geometry has to be described, then a 3D grid of bulkheads (transverse and longitudinal) is defined within the main particulars, and only then tanks, casings and rooms are defined within the 3D grid. All entities in this hierarchy are parametrically controlled.

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[16] www.napa.fi

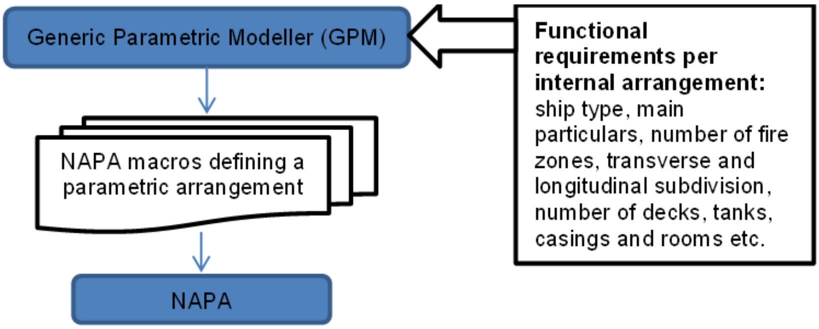


Figure 2: The role of the parametric modeller and its place in the overall design development process.

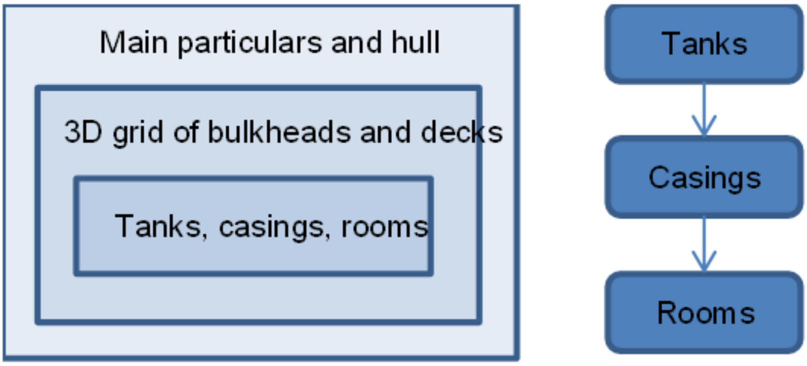


Figure 3: The onion-like architecture of the parametric modeller.

A few GPM screenshots are shown in Figure 4 - Figure 9, whereas a detailed, but not exhaustive. One can notice horizontal line segments just above the bulkheads (see Figure 5, for example). The segments correspond to variation intervals, defined by the designer, for the bulkheads. The longer horizontal lines that connect bulkheads (see Figure 6, for example) define the dependency between bulkheads: when one bulkhead moves, the dependent bulkheads follow. A similar approach is applied to other elements as shown in other screenshots below.

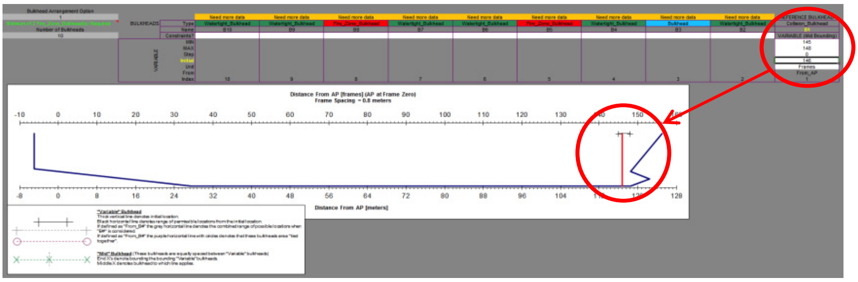


Figure 4: Location definition of the collision bulkhead.

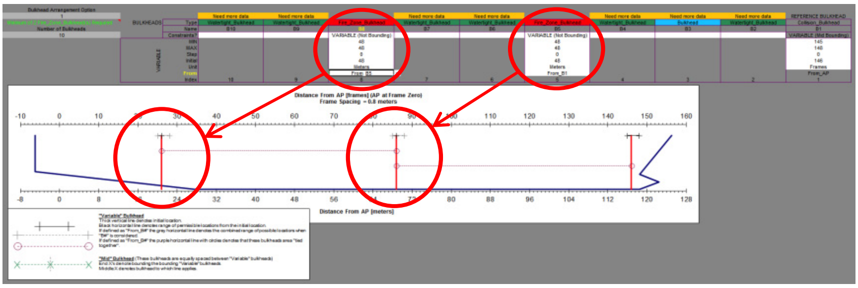


Figure 5: Location definition of Fire Zone bulkheads.

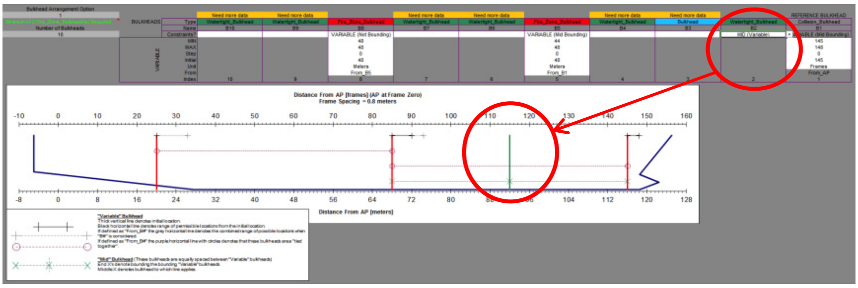
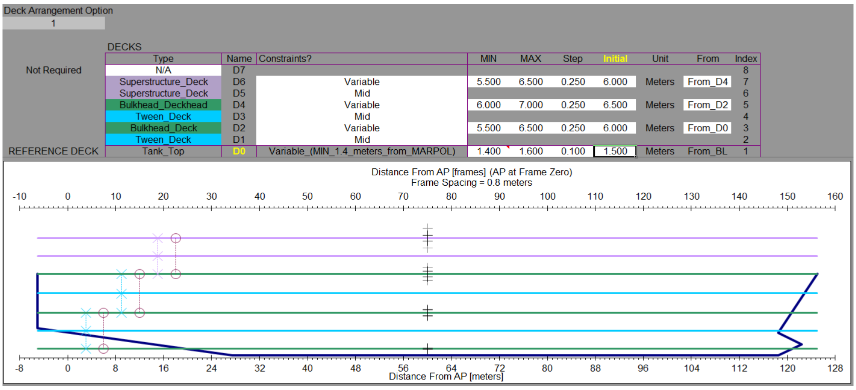


Figure 6: Definition of intermediate bulkheads. The green bulkhead is set to be in the middle between the fire zone bulkheads, and it will move as they move.


Deck Arrangement Option
1

DECKS

	Type	Name	Constraints?	MIN	MAX	Step	Initial	Unit	From	Index
Not Required	N/A	D7								8
	Superstructure_Deck	D6	Variable	5.500	6.500	0.250	6.000	Meters	From_D4	7
	Superstructure_Deck	D5	Mid							6
	Bulkhead_Deckhead	D4	Variable	6.000	7.000	0.250	6.500	Meters	From_D2	5
	Tween_Deck	D3	Mid							4
	Bulkhead_Deck	D2	Variable	5.500	6.500	0.250	6.000	Meters	From_D0	3
	Tween_Deck	D1	Mid							2
REFERENCE DECK	Tank_Top	D0	Variable_(MIN_1.4_meters_from_MARPOL)	1.400	1.600	0.100	1.500	Meters	From_BL	1

Figure 7: Definition of decks.

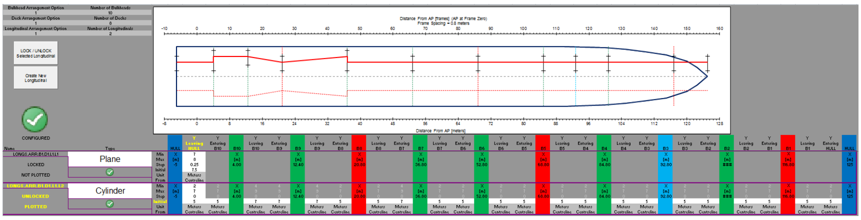
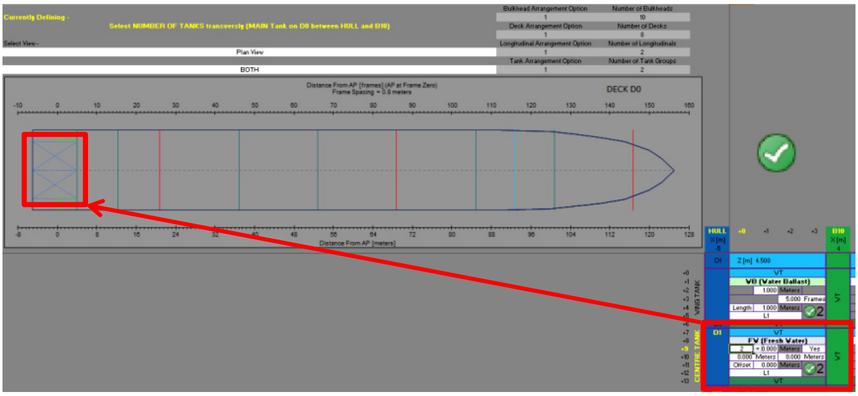


Figure 8: Definition of longitudinal bulkhead (cylinder option is shown).



Currently Defining - Select NUMBER OF TANKS transversly (MAIN Tank on D0 between HULL and B10)

Select View - Plan View

BOTH

Bulkhead Arrangement Option	Number of Bulkheads
1	10
Deck Arrangement Option	Number of Decks
1	8
Longitudinal Arrangement Option	Number of Longitudinals
1	2
Tank Arrangement Option	Number of Tank Groups
1	2

Figure 9: Centre tank configuration – two tanks. Tanks, casings and rooms are linked to adjacent bulkheads and decks directly or by offsets.

Parametric Napa model

This section explains what exactly is parameterised in both baseline RoPax designs detailed in (Zagkas and Pratikakis, 2012). Additionally, the section clarifies how the parametric models are handled during the actual optimisation process.

Hull shape

Two principal hull shapes will be explored during the optimisation process:

- Conventional hull shape
- Unconventional hull shape, which is also referred to as the UFO hull, is displayed in Figure 10. Benefits of the UFO shape are presented in (Puisa et al., 2013) and they essentially are the significantly increased damage stability and relocated (or extra) cargo space from lower decks. More precisely, the UFO hull allows distributing the watertight volume high and wide on the ship, thereby significantly increasing the damage stability. Furthermore, the design as a whole becomes simpler: as there is enough cargo space on car decks, the notorious long lower hold becomes redundant, and the transverse subdivision of lower decks can be less densely subdivided, potentially joining functional spaces and reducing the number of watertight doors thereby. Certainly, the UFO hull introduces new engineering challenges, e.g. structural difficulties and slamming risk, but they are deemed to be solvable.

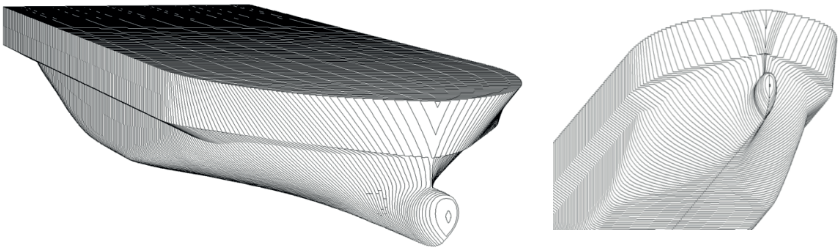


Figure 10: Unconventional hull shape (aka the UFO hull).

The list of design parameters to be varied during the optimisation process is shown in Table 1. Note, the variation ranges / options might be reconsidered during the optimisation and their actual values will be reported in the deliverable D6.4.

Table 1: Hull shape alternating parameters.

Parameter	Envisaged ranges / options[17]		Comments
	Handy-size RoPax	Large RoPax	
Hull type	Conventional, UFO hull (+3 or +6 metres on each side)		Indicates what hull type is used in calculations.
Waterline breadth (baseline 21 and 25.8 m)	19, 20, 21, 22, 23	24, 25, 25.8, 27, 28	
Depth up to main deck, (baseline 7.5 and 9.8 m)	[6, 9]	[8, 12]	
Hull length overall (baseline 142 and 200.65 m)	[138, 145]	[197, 203]	

General arrangement

There are three fundamental parameters which control the functional and geometric representations of the GA (see also Figure 11):

- Number of spaces overall and of particular type (compartments / rooms including cargo spaces)
- Size of spaces (dimensions of compartments)
- Location of spaces (global locations on the ship, or locations with respect to other spaces, i.e. colocation or separation by other spaces or decks). Location can also be altered by changing the space type.

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[17] Ranges (i.e. min and max value) are specified for real parameters, whereas options (i.e. values the parameter can take) are prescribed for integer (discrete) parameters.

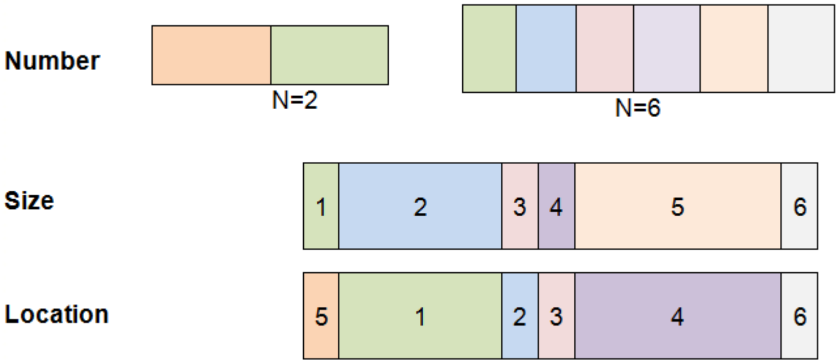


Figure 11: Visualisation of concepts of Number, Size, and Location. The outer frame boundaries can be seen as the deck boundaries.

It is important to note that generally these parameters are dependent. Thus for example, for given ship's breadth and length, the increased number of spaces inevitably reduces their sizes, and vice versa. In turn, the location can be affected by the space size, as there could be area requirements (i.e. max area) for certain functional spaces or their groups. The problem becomes more acute when breadth and length are also varied.

This dependency is also hierarchical, as shown in Figure 12. Essentially, the size of spaces is overwritten by the number and location, which define the GA topology (aka configuration). That is, if during the optimisation all three parameters were varied at once, any change in space sizes would in principle be cancelled by changes in the topology. Due to this hierarchical dependency, these parameters cannot be optimised simultaneously, and a specific order of optimisation, which reflects the hierarchy, should be considered.

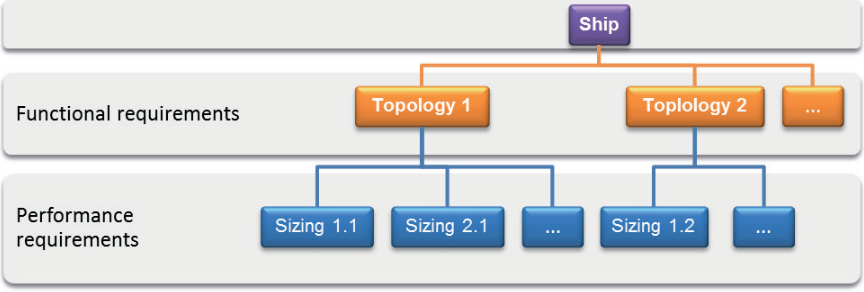


Figure 12: Hierarchical dependency of GA parameters.

Thus, Figure 12 also shows that the topology is designed to primarily reflect functional requirements of the GA, e.g. number of fresh water tanks, number of engine rooms, presence of absence of long lower hold etc. To optimise the performance of a given topology, its sizing (or sizes of spaces and equipment) should be carried out to achieve target values of performance requirements (aka non-functional requirements). This sequence results in a two-stage optimisation processes which also takes into account the discussed hierarchical dependency between the parameters by decoupling them.

The difficulty with this two-stage optimisation lies in its big demands of computational resources. Specifically, if we had N number all topology alternatives (this number can be in the order of thousands (Puisa et al., 2012)), we would need to perform N sizing optimisations with each of them usually taking days or even weeks to complete. Even with only one day per sizing optimisation, the whole process would exceed one year.

An alternative, more time-efficient approach is to use certain criteria for selecting just one topology, as opposed to many of them, and undertake its sizing optimisation. It is important to note that the selection criteria have to be based on performance metrics and be invariant with respect to design modifications during the sizing optimisation. It appears that part of capital cost of the vessel, i.e. total capital cost minus the cost of the hull, can be used as such a criterion. This part of the capital cost is fully determined by the GA topology and hence it does not change during the subsequent sizing optimisation.

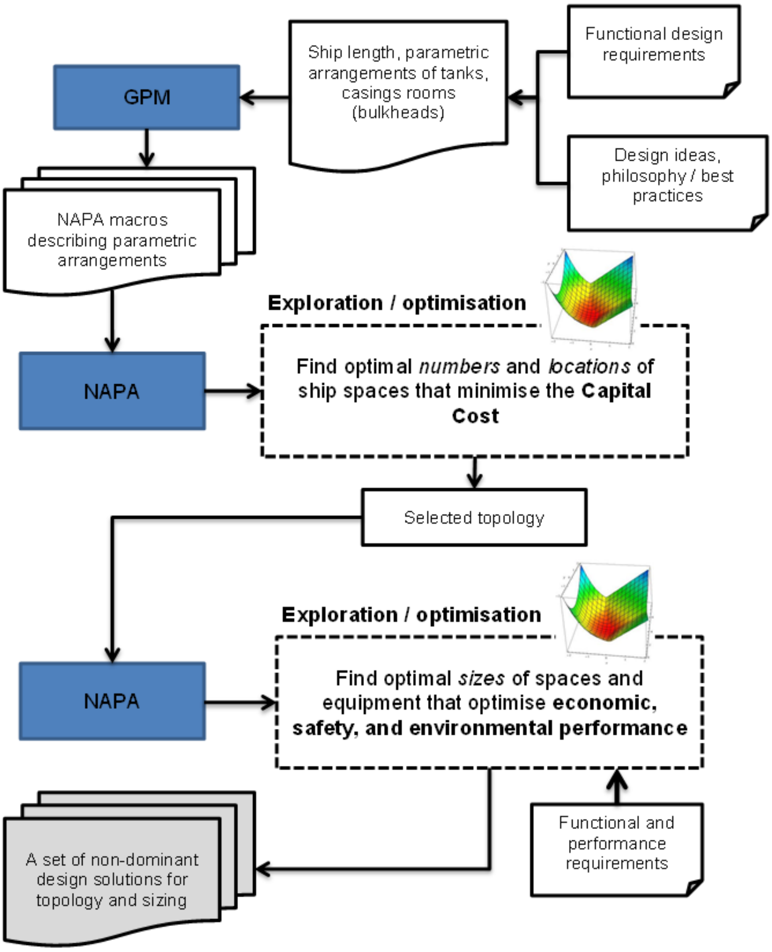


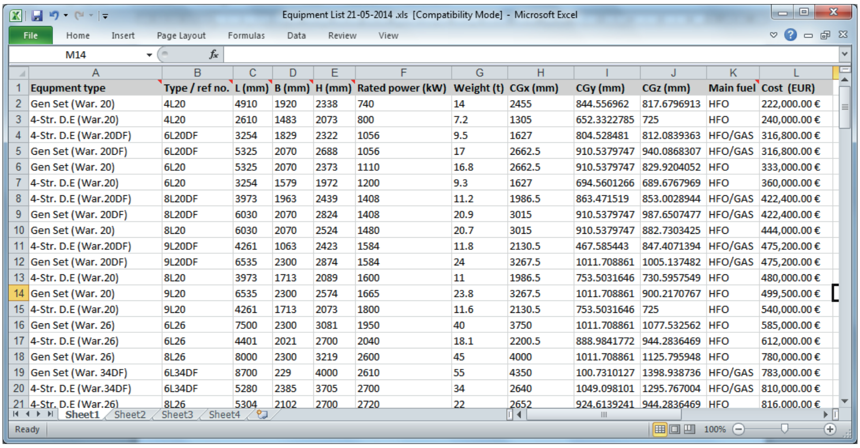
Figure 13: Two-stage optimisation process adopted to optimise the parametric models.

Figure 13 summaries the above considerations into a two-stage, time-efficient optimisation process which will be applied to the parametric models described in this report. Note, optimised objectives and satisfied constraints and not indicated in this diagram as they are detailed in (Puisa and Pawling, 2014). The exact variations ranges are not provided in this report because they might change in the course of the optimisation exercise, and, therefore, will be reported in later public deliverable D6.6.

Ship systems

As indicated earlier, parameters of main and auxiliary engines will be subject to optimisation. The engines, or their configuration sets, will be selected from the lookup tables (Figure 14) that contain their design parameters, interpolating or approximating values between records if necessary. The selection will aim to deliver the cheapest and hence most compact engine configuration that satisfies the following requirements:

- Main fuel type: HFO, MDO or other;
- Propulsion configuration: diesel, diesel-electric or other;
- Required propulsive power;
- Required auxiliary power;
- Given dimensions of the engine room.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Equpment type	Type / ref no.	L (mm)	B (mm)	H (mm)	Rated power (kW)	Weight (t)	CGx (mm)	CGy (mm)	CGz (mm)	Main fuel	Cost (EUR)
2	Gen Set (War. 20)	4L20	4910	1920	2338	740	14	2455	844.556962	817.6796913	HFO	222,000.00 €
3	4-Str. D.E (War.20)	4L20	2610	1483	2073	800	7.2	1305	652.3322785	725	HFO	240,000.00 €
4	4-Str. D.E (War.20DF)	6L20DF	3254	1829	2322	1056	9.5	1627	804.528481	812.0839363	HFO/GAS	316,800.00 €
5	Gen Set (War. 20DF)	6L20DF	5325	2070	2688	1056	17	2662.5	910.5379747	940.0868307	HFO/GAS	316,800.00 €
6	Gen Set (War. 20)	6L20	5325	2070	2373	1110	16.8	2662.5	910.5379747	829.9204052	HFO	333,000.00 €
7	4-Str. D.E (War.20)	6L20	3254	1579	1972	1200	9.3	1627	694.5601266	689.6767969	HFO	360,000.00 €
8	4-Str. D.E (War.20DF)	8L20DF	3973	1963	2439	1408	11.2	1986.5	863.471519	853.0028944	HFO/GAS	422,400.00 €
9	Gen Set (War. 20DF)	8L20DF	6030	2070	2824	1408	20.9	3015	910.5379747	987.6507477	HFO/GAS	422,400.00 €
10	Gen Set (War. 20)	8L20	6030	2070	2524	1480	20.7	3015	910.5379747	882.7303425	HFO	444,000.00 €
11	4-Str. D.E (War.20DF)	9L20DF	4261	1063	2423	1584	11.8	2130.5	467.585443	847.4071394	HFO/GAS	475,200.00 €
12	Gen Set (War. 20DF)	9L20DF	6535	2300	2874	1584	24	3267.5	1011.708861	1005.137482	HFO/GAS	475,200.00 €
13	4-Str. D.E (War.20)	8L20	3973	1713	2089	1600	11	1986.5	753.5031646	730.5957549	HFO	480,000.00 €
14	Gen Set (War. 20)	9L20	6535	2300	2574	1665	23.8	3267.5	1011.708861	900.2170767	HFO	499,500.00 €
15	4-Str. D.E (War.20)	9L20	4261	1713	2073	1800	11.6	2130.5	753.5031646	725	HFO	540,000.00 €
16	Gen Set (War. 26)	6L26	7500	2300	3081	1950	40	3750	1011.708861	1077.532562	HFO	585,000.00 €
17	4-Str. D.E (War.26)	6L26	4401	2021	2700	2040	18.1	2200.5	888.9841772	944.2836469	HFO	612,000.00 €
18	Gen Set (War. 26)	8L26	8000	2300	3219	2600	45	4000	1011.708861	1125.795948	HFO	780,000.00 €
19	Gen Set (War. 34DF)	6L34DF	8700	229	4000	2610	55	4350	100.7310127	1398.938736	HFO/GAS	783,000.00 €
20	4-Str. D.E (War.34DF)	6L34DF	5280	2385	3705	2700	34	2640	1049.098101	1295.767004	HFO/GAS	810,000.00 €
21	4-Str. D.E (War.26)	8L26	5304	2102	2700	2720	22	2652	924.6139241	944.2836469	HFO	816,000.00 €

Figure 14: Lookup table for diesel engines / generator sets used for main and auxiliary power generation.

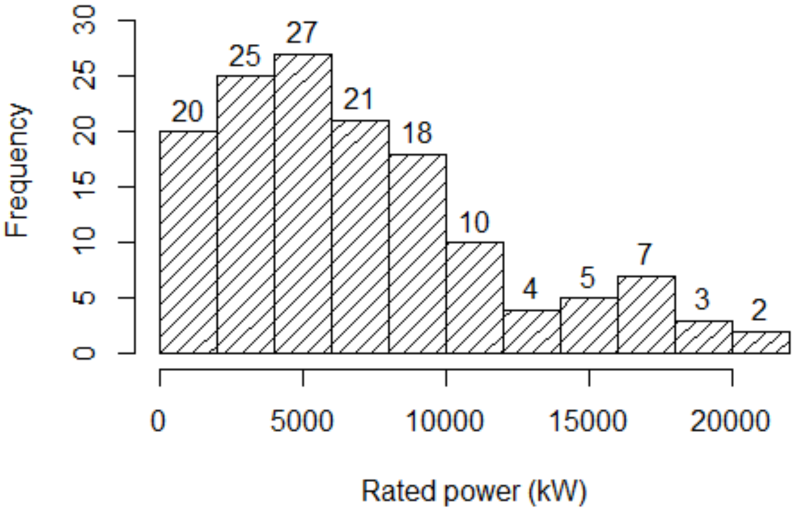


Figure 15: Histogram of rated power values for diesel engines included in the lookup table in Figure 14. The distribution shows the ranges of rated power available in the table.

- Due to changes in fuel oil sulphur limits (expressed in terms of % m/m – that is by weight) from 2015 in sulphur emission control areas (SECAs), shipowners have to consider several design alternatives for operating in SECAs:
- Switching to marine gas oil (MGO). This option will probably be most popular due to the fact that using marine distillate in the main engines does not pose a major technical challenge;
- Using alternative fuels such as LNG;
- Installing scrubbers.

The use of MGO has some safety implications. MGO has lower viscosity than conventional heavy fuel oil (HFO) and hence requires higher pressure piping systems with associated risks of leaks. It has been established that a contact between leaked flammable oil and high temperature surfaces (>220° C) is the prevailing fire scenario in engine rooms (Puisa et al., 2014). These options will also be investigated in project FAROS in the design optimisation exercise. I particular, the choice of the alternatives will be included into the ship stability and cost models.

Application context

As aforementioned, parametric RoPax models are created by the General Parametric Modelled and then passed to NAPA to be integrated into a multi-disciplinary optimisation process (see Figure 13). The process will be serviced by software integration platform .spiral™ (Puisa and Mohamed, 2011) which, amongst others, automates the processes of data exchange between software tools. The software platform automates the laborious processes of

- tool integration and data exchange between them (e.g., files are automatically transferred),
- data storage and retrieval (a mysql database is used for this purpose),
- sequential/parallel tool execution for each design variation, and
- data analysis.

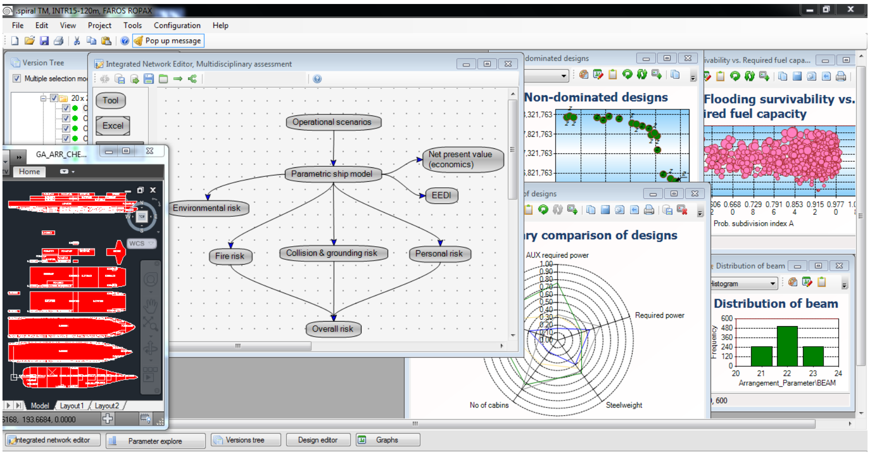


Figure 16: Promotional screenshot of software .spiral™.

Figure 16 shows a screenshot of the software, displaying the integrated process (note, behind each box there is a software tool automatically run in the order implied by the arrows), data access, and visualisation capabilities. It is important to note that the visualised data pertains to numerous design alternatives stored in a database. As Figure 17 shows, each design alternative (i.e. version) has input and output information of which generation, storage, and retrieval is automated.

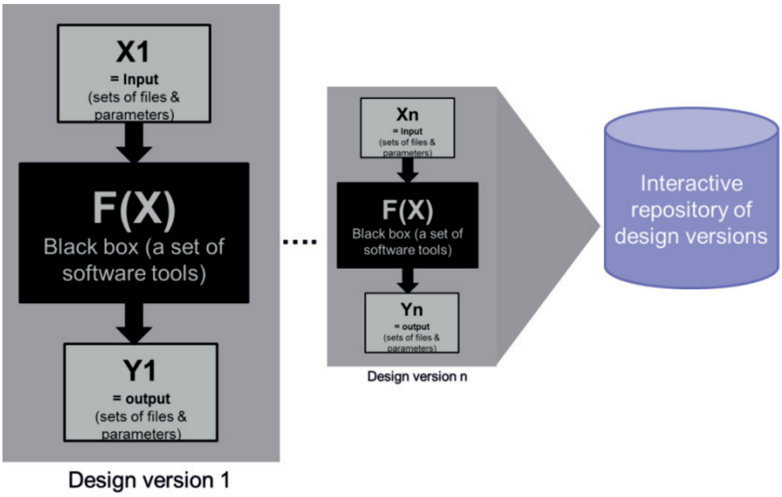
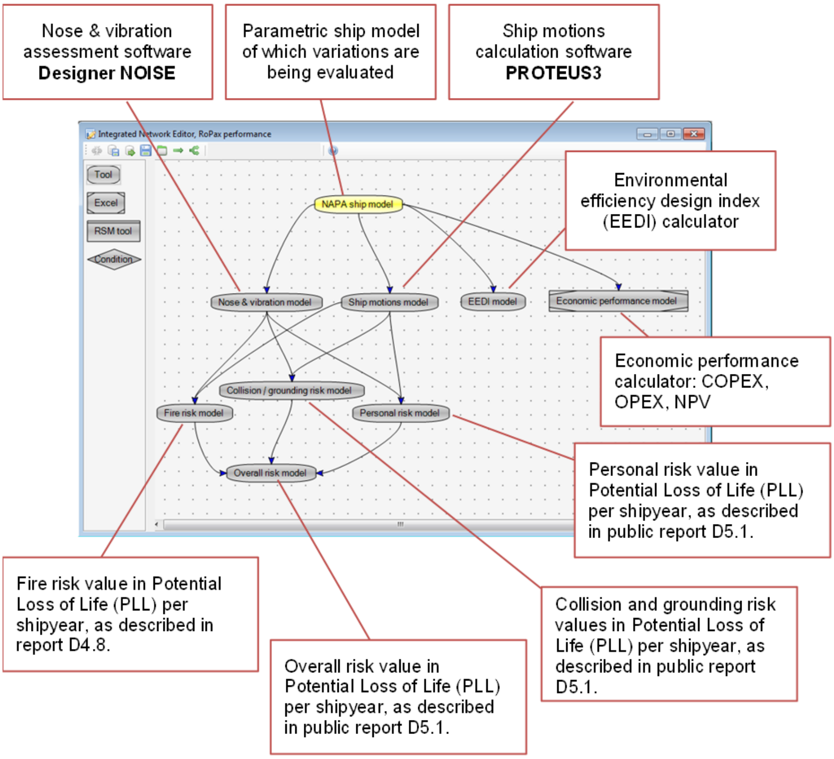


Figure 17: Storage of design information.

Figure 18 demonstrates the explicit multi-disciplinary assessment process in .spiral™ to be used for optimisation of RoPax ships in FAROS. NAPA with parametric models is shown as a yellow box passing down calculation results to other software tools waiting on these results. The data between tools is exchange by means of text files. This is a conventional implementation of data exchange and was successfully used in numerous research projects in the past, e.g. (Puisa and Zagorski, 2012). The callouts refer to FAROS reports where corresponding models have been described.



Nose & vibration assessment software **Designer NOISE**

Parametric ship model of which variations are being evaluated

Ship motions calculation software **PROTEUS3**

Environmental efficiency design index (EEDI) calculator

Economic performance calculator: COPEX, OPEX, NPV

Personal risk value in Potential Loss of Life (PLL) per shipyear, as described in public report D5.1.

Fire risk value in Potential Loss of Life (PLL) per shipyear, as described in report D4.8.

Overall risk value in Potential Loss of Life (PLL) per shipyear, as described in public report D5.1.

Collision and grounding risk values in Potential Loss of Life (PLL) per shipyear, as described in public report D5.1.

Figure 18: Specific implementation of the automated multidisciplinary asssesment in FAROS (screenshot of .spiral™ is shown).

It is useful to mention one of the integrated tools adopted for FAROS needs. Designer-NOISE™[18] is a software program designed to allow for quick and accurate predictions of noise levels on surface ships and other stiffened plate structures. The core solver uses a hybrid Statistical Energy Analysis approach to predict spreading of vibration throughout the vessel. Architectural acoustic methods are used to predict the spreading of airborne noise. Solution time for most models is on the order of seconds. The prediction accuracy is very high, usually within 3 dB for A-weighted noise levels. Noise and vibration calculations are necessary for risk models used in FAROS.

Conclusions

The paper has presented only main aspects behind design parameterisation of the selected RoPax ships. Thus, certain technical details have been excluded to

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[18] www.noise-control.com/designernoise.php

maintain clarity and conciseness. Additionally, these technical details might change in the course of application, and hence their mention in this report could prove misleading. Nevertheless, partners of related tasks will have access to all technical information necessary to achieve the objectives of the project.

The development of the Generic Parametric Modeller (GPM) took the best part of time. These GPM features helped overcome the technical bottlenecks of NAPA and save considerable amount of time. NAPA, however, remains the main tool for design representation, modification and evaluation. It is important to note that GPM is not only generic, i.e. can be used to quickly parameterise any shiptype, but—by virtue of its flexibility—also allows quickly correcting any mistake or adding extra functionality to parametric models developed. This will be very helpful during the application stage of GPM.

The parameterisation was done on macro (e.g., hull dimensions, number of bulkheads and their positions) and meso- (e.g., sizes and location of equipment in spaces, distribution of openings) levels. The micro level (e.g. design of watertight doors, piping and other components of ship systems) was considered irrelevant due to the focus on the early ship design stages, such as concept design.

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Aalto-ST 14/2014

FAROS is an EC FP7 funded, three year project to develop an approach to incorporate human factors into Risk-Based Design of ships. The project consortium consists of 12 members including industry, academia and research institutes.
The second FAROS Public Workshop was held in the Dipoli Congress Centre in Otanemi, Espoo, Finland, on the 30th of September 2014. The workshop included keynotes from industry, papers on risk models for aspects such a collision and grounding, fire and the human element, descriptions of parametric ship models and the overall approach being adopted in the FAROS project.

ISBN 978-952-60-5873-3
ISBN 978-952-60-5872-6 (pdf)
ISSN-L 1799-4896
ISSN 1799-4896
ISSN 1799-490X (pdf)

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