Final Report: Guidance on the Design of Ships for Enhanced Escape and Operation

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Background / Context

Traditionally, when designing a ship the driving issues are seen to be powering, stability, strength and seakeeping. When the broad form of the layout has been finalised, human factors issues related to crew numbers, ship operations and evolutions, such as evacuation, are either ignored, considered as an after thought or incorporated through a set of prescriptive rules. This can result in significant operational inefficiencies and potentially hazardous environments onboard. Today, demonstrating compliance with evacuation requirements is compulsory for merchant ships, as set by IMO regulations, and is usually achieved through the use of sophisticated evacuation simulation software, such as maritimeEXODUS. However, this analysis is undertaken within the overall constraints of a finalised ship design and so cannot substantially influence the design. Furthermore, there is no agreed method of identifying and measuring the performance of the vessel under important normal operations (NOP) scenarios, nor is there a methodology for determining the overall human factors (HF) performance of the vessel i.e. incorporating both evacuation and NOP HF performance.

The most significant of the stages of ship design is preliminary design, when the major decisions are made as to the characteristics of the product and so the analysis of crew or passenger movement must be integrated with the design process to have an influence on the ship design. Thus a methodology, composed of a set of software tools (PARAMARINE-SURFCON and maritimeEXODUS) and a procedure for using them effectively, is required to fully integrate the analysis of personnel movement, in a wide range of scenarios, into preliminary ship design. The Design Building Block approach, implemented in the SURFCON-PARAMARINE software, permits an integrated initial synthesis that brings together numerically based sizing, hullform selection and, most significantly, the stylistic and configurational aspects crucial to evaluating human factors issues early in design. These are integrated in a single software package that utilises an information rich graphical user interface, greatly enhancing the ability of the designers and stakeholders to evaluate the performance of the design. The maritimeEXODUS personnel movement simulation software is capable of simulating both the evacuation and non-emergency circulation of large numbers of people within a variety of complex enclosures. The simulation model incorporates a wide range of factors, such as passenger behaviour, smoke and fire and the heel of the vessel. Significantly in the context of NOP scenarios, the individuals modelled in the simulation can be assigned specific tasks, so allowing the evaluation of complex procedures such as those that might be expected on a naval vessel.

Key Advances and Supporting Methodology

The two academic partners provided complimentary expertise and access to the necessary software essential for the success of this project. Expertise in naval ship design and in the use of the PARAMARINE-SURFCON tool for the early stage design of ships was provided by UCL, while UoG provided its personnel movement expertise and its maritimeEXODUS personnel movement simulation software. The industrial partner provided the all important end-user requirements and expertise in the operation of warships.

The partnership achieved all objectives, as stated in the original proposal, demonstrating the viability of the methodology and the benefits that can be derived through its use. Further development in the methodology is anticipated through application to specific projects with the industrial partner. Key significantly novel advances made in the project include:

a) The use of simulations to evaluate personnel movement applied in the earliest stages of ship design.
b) The evaluation of personnel movement extended to include non-emergency scenarios.
c) A transparent and reproducible methodology developed to determine overall HF performance of a given ship design and shown to be both discriminating and diagnostic.
d) Guidance provided on the level of design definition necessary to carry out personnel movement simulations in preliminary ship design.
e) The project provided insights to ship designers on specific features that either enhance or restrict personnel movement onboard heavily populated vessels.
f) The project indicated those research areas that remain to be addressed for the comprehensive simulation and assessment of personnel movement in non-evacuation scenarios onboard ships.

Figure 1 illustrates the overall relationship between the expertise domains and software tools on which each research partner led. This shows, in flowchart form, the design and analysis activities that were carried out in each of the tools. The interface tools developed in this project were separate from the PARAMARINE-SURFCON and maritimeEXODUS software and permitted the required information to be transferred between them.

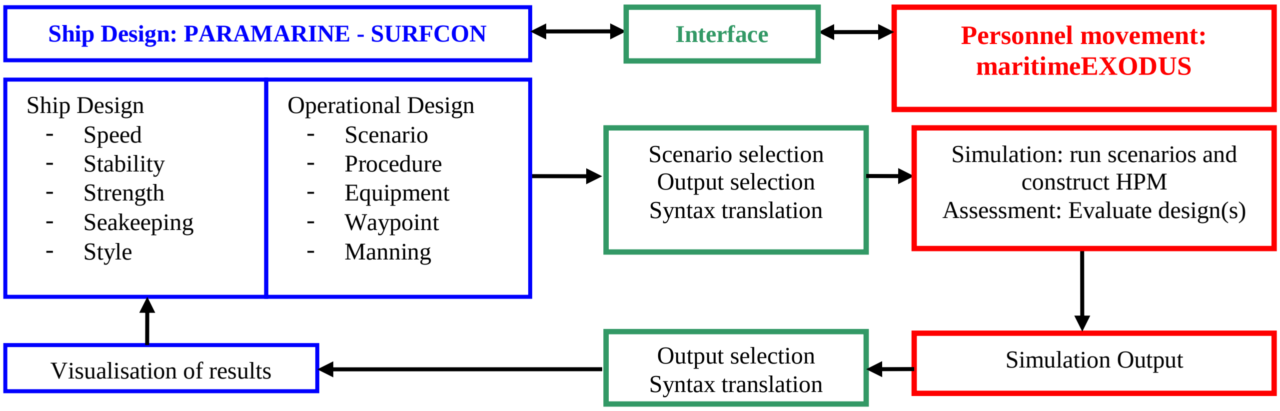

Figure 1: Flowchart showing the activities carried out in each of the main tools used in the project

Achievement of each of the objectives, stated in the original proposal, are outlined below.

1. To explore the impact on naval ship configurational design of issues associated with crew manning numbers, function and movement.

This overall aim covers two distinct aspects investigated – the impact on the naval ship design process of the availability of personnel movement simulations in the early stages [1, 5] and the changes to the configurations that should be adopted based on the results of those analyses. The first of these aspects was extensively investigated using a new methodology, which was demonstrated through meaningful analyses able to be made at an early stage and incorporated into the design process. The second aspect was investigated by the investigation of the primary access route configuration – a major layout feature (see objective 5 for further details).

2. To identify key performance measures for successful crew performance in normal and extreme conditions.

The only agreed guidelines for evaluating HF performance of ship design relate to evacuation (i.e. time to muster and levels of congestion) and so conclusions drawn concerning the overall suitability of a ship design by one naval architect can be quite different from those of another. The complexity of the task grows as the size and complexity of the vessel increases and as the number and type of evaluation scenarios considered increases. The challenge addressed here was the development of a procedure that allows accurate, rapid, transparent and reproducible assessment of HF issues associated with vessel layout and crew operating procedures.

The unique technique developed to address these issues is known as the Human Performance Metric (HPM) [3, 6-10]. The HPM works by systematically evaluating one layout design against another, whether two variants of the same design or two completely different ship designs. The methodology involves defining a range of relevant Evaluation Scenarios (ES) against which the vessel will be tested. In order to gauge vessel HF performance across a range of criteria, the ES are made up of both evacuation and NOPs scenarios. The nature of the scenarios are dependent on the type of vessel. For the surface combatant vessel used as the exemplar in this project, some seven scenarios were identified, three evacuations: Normal Day Cruising A, Normal Day Cruising B, Action Stations and four NOPs: Blanket Search, State 1 Preps, Family Day A, Family Day B [8, 9]. In addition to defining the ES, a range of Performance Measures (PM) are defined to measure various aspects of personnel performance in undertaking the tasks associated with the ES. Examples of PMs for evacuation and NOP scenarios include; the time required to complete the assembly process and the total number of water tight doors (WTD) operated during the scenario [3, 6-10]. The PMs are determined through evaluating the output produced by the maritimeEXODUS simulation software, or its equivalent. In total some 32 PM [8, 9] have been defined for the selected surface combatant. Both the ES and PM were defined in consultation with our collaborating partners, the Ministry of Defence (MoD).

The suitability of the vessel layout is then evaluated for fitness of purpose through a combination of the PMs resulting from the execution of the ES. The numerical values generated by the PMs for each ES are arranged to produce the HPM. The overall vessel HF performance is then determined through a weighted summation process of the various elements within the HPM [6-10]. Clearly, the HPM will be specific to the type of vessel being investigated, thus an aircraft carrier will have a different HPM to a submarine. However, the underlying concept of the HPM is common to all types of vessels and some components that make up the HPM may be similar across different vessel types. Using the HPM technique it is now possible to systematically evaluate the HF performance of a vessel in a manner which is reproducible and transparent and which provides both discriminating and diagnostic information [8-10].

3. To extend the ship evacuation software maritimeEXODUS to include additional non-emergency simulation capabilities.

The maritimeEXODUS software forms the core of the HF evaluation component of the system. This software was specifically designed to simulate evacuation scenarios and, as part of this project, its capabilities were extended to include the simulation of the NOP scenarios, as identified under Objective 2 above. This capability built on an existing feature known as the Itinerary List (IL). Using the IL it is possible to assign crew (and passengers) a list of tasks to perform. As part of this project a range of new tasks were developed including: **'Terminate'** command, used in the NOPs scenarios, allowing crew to stay at their last location once a task has been completed; **'Repeat'** command, used to allow crew to repeat predefined set of tasks a number of times as is required in the patrol task; **'Search Compartment'** command, which instructs crew to enter a list of assigned compartments to undertake a search as part of the blanket search scenario; '**Close Door'** command, which instructs a crew member to check that a door has the correct status for the current ship state and, if not, change the status of the door; **'Give'** and **'Receive'** command, allowing a senior member of the ship's staff to issue tasks to lower ranked members, who 'Receive' the task [6-9].

In addition to these capabilities, a range of other modifications and additional software have been developed including:

- A separate utility program was developed (the Human Performance Metric Analyser) which automatically constructs the HPM matrix of human performance scores from maritimeEXODUS output that are used in the evaluation of the vessel design.
- The process of building vessel geometries ready for analysis was automated. Previously, the process of preparing a geometry could take as much as two weeks to complete, with the automation the majority of this process can now be completed within half an hour (based on the Type 22 Batch III Frigate exampled).
- A new scripting language (SSF) was developed which enables third parties to easily set up a population and their itineraries within maritimeEXODUS without the need to navigate through a complex user interface, reducing a considerable amount of tedious time consuming effort.
- Additional output files were required from maritimeEXODUS in order for it to interact with the ship configuration software SURFCON. These include images of contour maps displayed within maritimeEXODUS showing the locations of severe congestion and footfall maps. Animated output files were also implemented in order to illustrate individuals moving around the design

4. To extend the ship design software so that it can provide a modelling environment that interactively accepts maritimeEXODUS simulation output for a range of crew evolutions.

The original proposal anticipated making changes to the PARAMARINE-SURFCON software to allow the interactive display of processed results from the maritimeEXODUS simulations. This focussed on the "visualisation of results" activity shown in Figure 1. The purpose of this functionality was to place the numerical data generated by the simulations into the context of the spatial configuration of the ship design, enhancing designer understanding of the results and aiding subsequent decision making. The early development work identified the changes that needed to be made to the PARAMARINE-SURFCON software to provide the desired functionality. The main enhancement proposed was the ability to display both static and animated two-dimensional texture maps, containing graphical representations of the maritimeEXODUS simulations, overlaid onto the three-dimensional CAD representation of the ship. The possibility of adding new output file formats (or enhancing those that already existed) was also considered. The early research also investigated alternative third-party visualisation tools and approaches that could be used to illustrate the desired functionality. Subsequent discussions with GRC (the vendor of PARAMARINE-SURFCON) indicated that the time required to make the necessary modifications was beyond the scope of the project and so this option was not pursued. Further discussion with GRC has suggested that the modifications proposed are possible and GRC is now keen to implement them as part of the ongoing development of the software (E-mail Dr Fowler, General Manager of GRC October 2007). Meanwhile, the UCL research team developed alternative visualisation techniques to be used in the current research project. These visualisations were divided into three main types, each of which was addressed in a different way:

- Tabular data: Certain data produced by the HPM (see figure 2), is best represented in tabular form and this was viewed in a spreadsheet tool and by adapting the spreadsheet functionality already existing within PARAMARINE.
- Graph data: Other data was best represented by line graphs, and this was illustrated by adapting the range of 2D graph functionalities available within PARAMARINE.
- Graphical data: In order to fully place the personnel movement numerical data into the context of the vessel configuration, some data needs to be represented in 3D, and this was implemented using the VRML 3D modelling language. Although this required a free third-party viewer to use and was not integrated with the PARAMARINE-SURFCON model of the ship, a level of interactivity was provided allowing the designer to investigate the extensive numerical data.

Another aspect of this functionality was the UoG developed 'HPM Analyser', which reads the results of maritimeEXODUS simulations and generates output files read by PARAMARINE and displayed and interrogated by the naval architect. In addition, the output files from maritimeEXODUS and the HPM Analyser can be read by newly developed translation software and converted to VRML.

5. To demonstrate a methodology for ship design that integrates ship configuration design with modelling of a range of crewing issues through PARAMARINE-SURFCON.

The method developed in the research project consisted of taking existing and developed software tools, which are then used for personnel movement analysis at the early stages of ship design. The methodology is broadly described in terms of these software tools by Figure 1. The key features of the developed methodology are:

- A procedure for modelling design features crucial to personnel movement analysis in PARAMARINE–SURFCON: Modelling techniques and standards were developed to allow the definition of design details, such as doors, hatches and ladders, and of the Watch and Station Bill (W&SB), which contains all the necessary information on the locations of the ship's crew for each operating condition.
- A procedure and software tools for transferring PARAMARINE-SURFCON ship definition models to maritimeEXODUS: A tool was developed to convert the existing PARAMARINE-SURFCON output files into a format accepted by maritimeEXODUS and the new 'scenario generator' program.
- Enhancements to maritimeEXODUS: These enhancements included new commands and a scripting language outlined under Objective 3 above.
- A procedure and software tools for viewing, investigating and transferring martimeEXODUS simulation results to PARAMARINE–SURFCON: The use of existing PARAMARINE-SURFCON functionality and third party tools to allow visualisation of the results is outlined under Objective 4 above.

The procedure developed can be summarised in the following steps:
1. Model the balanced ship design using the Design Building Block approach (see original Case for Support).
2. Populate the model with personnel movement oriented design features and define the W&SB.
3. Output definitions of the geometry, connectivity and operational design using existing outputs (DXF and KCL).
4. Translate KCL to maritimeEXODUS and scenario generator input format (NMTA) using spreadsheet tool.
5. Input NMTA and DXF files into maritimeEXODUS, mesh the model and generate scenarios.
6. Run 50 simulations and perform analysis to produce HPM.
7. Output files for the required scenarios: images, videos, and graphs plus the whole HPM in KCL and CSV format.
8. Import the KCL into PARAMARINE to visualise results using graphs and tables.
9. Translate HPM file and links to images and videos into VRML format for interactive 3D display of results.

The procedure and software tools were demonstrated by application to the Type 22 Batch III Frigate design [2, 4]. This class is currently in service with the Royal Navy and MoD provided numerical and geometric information. In addition to producing a higher than normal resolution PARAMARINE-SURFCON model of the design as built, several variant models were produced for assessment:
- Variant 1, High Resolution: Model of the design as built, with detailed configurational and numerical data.
- Variant 1, Intermediate Resolution: Model of the design as built, but with a simplified representation of the layout more appropriate to preliminary design.
- Variant 1, Very Low Resolution: Greatly simplified model of the design as built, with only the basic internal subdivision (decks, watertight compartments, doors and damage control zones) represented, to scope Variant 1 (IR).
- Variant 2, High Resolution: A variant using two side passageways in place of the single centreline passageways on No. 1 and No. 01 Decks of the baseline, with detailed configurational and numerical data.
- Variant 2, Intermediate Resolution and Variant 2, Very Low Resolution.

Each of these was a balanced ship design, assessed for feasibility in the traditional naval architectural performance areas, such as stability and powering. Importantly, they all used the same crew breakdown and W&SB for 262 ship's staff, given the generation of a representative W&SB was vital to perform personnel movement simulations. This range of models assessed a major design feature in ship layout and personnel movement – the arrangement of the main passageways – and importantly assessed the effect of the use of different levels of detail, particularly the reduction in detail to a level more representative of that likely in preliminary ship design.

After analysing the HPMs, it was found that the single passageway Variant 1 design just marginally outperformed the double passageway Variant 2 design. Thus the HPM technique was able to discriminate between two competing designs and identify which produced the superior HF performance, based on the selected evaluation scenarios and performance measures. Analysis of the HPMs for the very low resolution early design configurations also suggest that Variant 1 was marginally the superior layout overall, although the actual HF performance differed markedly for different scenarios. Thus for Variant 1, State 1 Preps was the best performing scenario and Action Stations evacuation scenario was the worst performing scenario. This suggests that when using early design configurations, the ES and PM contributing to the HPM need to be slightly modified, reflecting the lack of HF relevant detail likely to be available on the design.

Evaluative scenario	Scenario Weight	Variant 1	Variant 2
Normal Day Cruising A	1	46.15	44.94
Normal Day Cruising B	1	47.74	48.78
Action Stations Evacuation	1	46.69	49.78
State 1 Preps	1.5	66.63	76.60
Blanket Search	1.5	80.33	84.74
Family Day A	1.5	44.80	49.81
Family Day B	1.5	53.04	57.89
Overall Performance of design		507.8	547.1

Figure 2: HPM for Variant 1 (with additional ladder) compared with Variant 2. Design with the lower score is the superior one.

Detailed examination of the results demonstrated that the State 1 Preps scenario was the best performing scenario, for Variant 1, while the Action Stations evacuation scenario was its worst performing scenario. Once the better configuration had been identified, the HPM was then used, in diagnostic mode, to determine if that design could be further improved. Thus further interrogation of the HPMs, revealed considerable congestion developed during the Variant 1 evacuation scenarios. These results suggested that the congestion levels could be reduced through the introduction of a strategically placed single ladder between No. 2 and No. 1 Decks. The ladder was added to the design and the Variant 1 simulations re-run producing an updated HPM. Analysis of the updated HPM revealed that the modified Variant 1 design now out performed Variant 2 by some 8%, as shown in Figure 2, demonstrating the diagnostic capabilities of the methodology [6-8, 10].

There are several key points regarding the development of the methodology:
1. A practical procedure and toolset was developed for analysing personnel movement in the early stages of ship design.
2. The production of a representative W&SB should be part of preliminary ship design, so that any changes due to simulation results can be reflected in future designs.
3. The HPM technique was able to discriminate between two competing layouts and to identify which produced the superior HF performance, based on the selected evaluation scenarios and performance measures.
4. The HPM technique is applicable to both detailed design definitions, based on as built features, and the less detailed models, more typical of preliminary ship design.

Project Plan Review

The programme outlined in the original proposal described three main phases of the project – development, integration and demonstration. As the project evolved it became apparent that more effort was required on the development phase than had been anticipated, primarily in the acquisition of data for and development of the detailed ship design models, maritimeEXODUS simulation software enhancements and the development of the HPM (defined under Objectives 2-4). In addition, the initial concepts for the integration of the two tools via modifications to PARAMARINE were not possible, and so alternative methods of integration were used (see Figure 1). The adaptations needed to overcome these challenges lead to a reduction in the extent of the demonstration activities in the later stages of the project. However, it was still possible to demonstrate the application of the approach and the functionality of the enhanced software tools developed during the project.

Sixteen formally minuted meetings were held over the course of the project, covering management and technical issues. Seven of these included a representative of the industrial partner (MoD). The industrial partner also received extensive progress reports at the end of each of the three years. There were also technical meetings between the individual researchers at the two institutions on a frequent basis and with the industrial partner as required.

Research Impact and Benefits to Society

This project is the first example of research into the extension of personnel movement simulation from evacuation into the much wider problem of personnel movement in operational scenarios. Secondly this extension has been applied to preliminary ship design, when the ship configuration is being initially determined. The open ended extensible approach pioneered in this project will offer a number of advantages through being incorporated in preliminary ship design. This project has resulted in the following significant developments:

- A novel methodology, known as the Human Performance Metric (HPM), has been developed that allows, for the first time, accurate, rapid, transparent and reproducible assessment of Human Factors (HF) issues associated with vessel layout and crew operating procedures. The technique provides an overall measure of HF performance encompassing both emergency and normal operations conditions. Use of the HPM will lead to safer and more efficient vessel design.
- The HPM concept has been incorporated into the ship design cycle through linking the maritimeEXODUS software with the PARAMARINE-SURFCON software. In this way vessel designs can be assessed for HF performance in the earliest stages of ship design cycle. This enables the identification of areas of poor design leading to poor HF performance early in the design cycle where changes can be made quickly, easily and hence cheaply. Through the life time of a naval vessel, personnel costs, in part dependent on early layout decisions, far exceed the capital cost of the vessel, thus using this approach to improve procedures and, potentially, reduce crew size can lead to considerable savings in through life costs.
- The HPM methodology also provides fleet operators with a consistent and verifiable method for setting HF design objectives for new vessel concepts and evaluating proposed designs.
- The HPM methodology and the linkage to ship design software can be applied to other types of vessel, such as passenger ships. This will lead to the design of safer and more efficient passenger vessels.
- The HPM methodology can be applied to other industries, in particular the building industry allowing the assessment of HF issues associated with the design of buildings, terminals and the layout of large public events.
- This research has had strong academic content, with two of the project team currently writing up their PhD dissertations based on the work produced for this project (Mr S.J. Deere – HPM concept and Mr L. Casarosa – HF Integrated into the ship design cycle).

Explanation of Expenditure

The overall expenditure on the project was in line with the allocated budget. There was a slight increase in salary costs at UoG as more than the allocated 75% of Dr Lawrence's time was required on the project. The difference was made up by funding from UoG.

Further Research and Dissemination Activities

The work undertaken in this project has contributed to 10 publications in journals and conferences. Further details on these can be found at the web sites ##UoG URL## and http://www.homepages.ucl.ac.uk/~ucemrgp/gdseeo.html. These included presentations at seven international conferences in Italy, Germany, Korea and the UK, including an invited key note address at a conference in Canada. Two further journal publications are under preparation and will be submitted to the SFPE Journal of Fire Protection Engineering and the SNAME Journal of Ship Research. Papers will also be submitted to several conferences including IAFSS Germany 2008 and the 5th RINA HF Conference. Results from the project have also been disseminated to students on the Master Training Programme in Computational Science and Engineering at Greenwich (see http://cse.gre.ac.uk/) and will be presented to the Masters in Naval Architecture at UCL (http://www.mecheng.ucl.ac.uk/learning/graduate/msc/naval-architecture/). Results from the project will also be discussed at an international short course on evacuation simulation at the University of Greenwich in April 2008 (see http://fseg.gre.ac.uk/fire/course1.html#short_course_intro).

Future proposals are currently being written between the partners. A follow on EPSRC project is under investigation that will focus on applications of the HPM to passenger vessels. Also under investigation is a proposal focusing on current new MoD ship design projects. This will again involve close collaboration between the partners in this project and funding is being sought directly from the MoD.

The University of Greenwich markets the maritimeEXODUS software internationally. The new features and capabilities developed for the maritimeEXODUS software will be incorporated into the next release of the software, further improving the software's unique position in the market place. The enhancement of PARAMARINE-SURFCON in regard to HF simulation interfacing now intended by GRC Limited is a direct result of the prototyping undertaken by UCL in this project. This will then be made available to PARAMARINE's many users in the UK ship design community.

Papers Published or Awaiting Publishing:

1. Andrews, D J, "The Use of Simulation in Preliminary Ship Design, Proceedings of 12th International Conference on Computer Applications in Shipbuilding", Busan, Korea, August 2005, pp 419-432.
2. Andrews, D J, Pawling, R and Casarosa, L, "Integrating Ergonomics into Ship Design", CETENA Human Factors Conference, Genoa, October 2005, Proceedings on CD; copy held by UCL.
3. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S, Lawrence, P, Gwynne, S and Boxall, P, "Integrating Ship Design and Personnel Simulation", INEC, IMarEST WMTC, London, 6 - 10 March 2006, Proceedings on CD, ISBN 1-902536-54-1.
4. Andrews, D J, Casarosa, L and Pawling, R, "Integrating the Simulation of Operations Into Preliminary Ship Design", NAV 2006; International Conference on Ship and Shipping Research, Genoa, 21 - 23 June 2006, Vol. 1, pp 4.3.1-4.3.12.
5. Andrews, D J, "Simulation and the Design Building Block approach in the design of ships and other complex systems", 2006 Proc. R. Soc. Vol. 462, pp 3407-3433.
6. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S and Lawrence, P, "Integrating Personnel Movement Simulation into Preliminary Ship Design", RINA Int. Conf. on Human Factors in Ship Design, London, 21-22 March 2007, pp 117-128.
7. Andrews, D J, Pawling, R, Casarosa, L, Galea, E R, Deere, S and Lawrence, P, "Integrating Personnel Movement Simulation into Preliminary Ship Design", RINA IJME, to be published Vol. 150 Part A1 2008.
8. Galea, E R, "The next step in the rise of maritime human factors simulation models : Optimising vessel layout using human factors simulation", Key Note Address, The Rise of Maritime Simulation, Ocean Innovation 2007, Halifax, Canada, 21-24 Oct 2007. (http://www.oceaninnovation.ca/OI-2007_guide_low%20res.pdf)
9. Deere, S J, Galea, E R and Lawrence, P, "A Systematic Methodology to Assess the Impact of Human Factors in Ship Design", Applied Mathematical Modelling, to appear 2008.
10. Deere, S J, Galea, E R and Lawrence, P, "Optimising Vessel Layout using human factors simulation", Pedestrian and Evacuation Dynamics 2008, 27-29 Feb 2008 Wuppertal, Germany, To appear in conference proceedings 2008.

Reports from Project Partners

A letter from MoD (DES SESea) is included.