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A systematic methodology to assess the impact of human factors in ship design

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Abstract

Evaluating ship layout for human factors (HF) issues using simulation software such as maritimeEXODUS can be a long and complex process. The analysis requires the identification of relevant evaluation scenarios; encompassing evacuation and normal operations; the development of appropriate measures which can be used to gauge the performance of crew and vessel and finally; the interpretation of considerable simulation data. Currently, the only agreed guidelines for evaluating HFs performance of ship design relate to evacuation 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. Equally, it can be extremely difficult for fleet operators to set HFs design objectives for new vessel concepts. The challenge for naval architects is to develop a procedure that allows both accurate and rapid assessment of HFs issues associated with vessel layout and crew operating procedures. In this paper we present a systematic and transparent methodology for assessing the HF performance of ship design which is both discriminating and diagnostic. The methodology is demonstrated using two variants of a hypothetical naval ship.

Keywords: Evacuation analysis; Evacuation simulation; Human factors; Naval architecture; Ship design; Pedestrian dynamics

1. Introduction

Modifications to ship configuration such as hull form, length, beam, size and location of internal compartments have a direct impact on ship performance in terms of stability, powering, seakeeping and strength. These traditional design parameters are well understood and can be determined in a relatively straight forward manner. Equally, when modifying the internal configuration of a ship, it is also important to determine what, if any, human factors (HF) benefits or disbenefits may result. How these aspects can be assessed is less well defined. In this paper we present a novel mathematical procedure, based on computer simulation of evacuation and normal operations (NOP), for assessing the HF performance of ship design.

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Making modifications to the internal layout of a ship or its operating procedures will have HF implications for crew and passengers, which in turn will have an impact on overall levels of safety under emergency conditions and efficiency of operation in normal conditions. The procedures employed to undertake a specific task such as evacuation or preparing the vessel for action may be modified to improve the efficiency in undertaking these tasks. Equally, changing the location of cabins, public facilities, corridor systems, stairs, assembly locations etc will have a direct impact on the ability of crew and passengers to safely and efficiently evacuate the vessel under emergency conditions. Furthermore, for passenger vessels, size, location and configuration of public spaces such as restaurants, cinemas, bars, etc will influence the ease with which they can be accessed, filled and emptied under NOP. This will in turn impact the operational characteristics of the vessel. For naval vessels, the location and distribution of compartments may have an impact on the time required by crew to go from one state to another, it may also have an impact on the minimum number of crew required to safely and efficiently operate the vessel under a variety of different conditions. These factors will have an impact on the vessels overall operating efficiency, ability to fulfil the assigned mission and lifetime costs associated with crewing requirements.

It should also be noted that changes to configuration that lead to improvements in one aspect of human performance e.g. assembly time, may have a negative impact on other aspects of human performance e.g. ease of access of public spaces.

Advanced ship evacuation models such as maritimeEXODUS can be used to determine the performance of personnel under emergency conditions for both passenger [1–4] and naval vessels [5] as well as the normal circulation of personnel for both passenger and naval vessels [5,6]. Common to this type of model is the capability to represent the population as a collection of unique interacting individuals, the ability to represent the detail of the space in which the individuals interact (i.e. the model should have a discretised representation of space) and the ability to assign individuals or groups of individuals specific tasks to complete as part of the scenario (see [7,8] for a review of model types). These models produce a wide variety of simulation outputs, such as time to assemble, levels of congestion experienced, time required to undertake specific tasks, number of operations performed in completing specific tasks, distance travelled by individuals in achieving goals, number of likely fatalities resulting from fire, likely injury levels sustained from fire, etc. As the number of different scenarios investigated increases, so does the volume of output data. It therefore becomes increasingly difficult to consistently assess changes in HF performance associated with changes in vessel configuration across a wide range of scenarios and performance requirements.

The challenge therefore is to develop a procedure that allows accurate and rapid assessment of the large-scale model outputs produced by HF simulation models and to determine if specified modifications to vessel layout or operating procedures generate improvements in human performance across a range of potentially competing requirements.

In this paper we explore a methodology to assess changes in HF performance resulting from changes to vessel configuration and/or crew procedures. Furthermore, the methodology is intended to determine whether or not a net benefit results from imposed changes to the configuration/procedures and identify specific areas where performance may be improved. The approach is therefore intended to be both diagnostic and discriminating. The identified methodology is being developed as part of a collaborative project between the authors and the Design Research Centre (DRC) of University College London, funded by the UK EPSRC with support from MoD [9]. While the proposed methodology is generic in nature, the development focuses on naval vessels to demonstrate proof of concept on a demanding set of ship operations. The methodology is similar in some respects to weighted point schemes used to rank fire safety provision in buildings, where points are awarded for the presence or absences of certain fire safety measures and the relative importance of the particular measure is represented by the assigned weight [10]. These types of schemes are common in quantitative fire risk assessment and are sometimes called "Indexing Schemes" [11]. A key difference between these schemes and the proposed methodology is that the performance measures are determined directly from detailed computer simulation of selected scenarios and not from experience of past performance or from expert judgement.

2. Methodology for assessing human factors performance

In order to gauge the HF performance of the vessel it is essential to define a range of relevant evaluation scenarios (ES) against which the vessel will be tested. These scenarios are intended to define the scope of the challenges the vessel will be subjected to. In order to gauge vessel performance across a range of criteria, the ES are made up of both evacuation and NOP scenarios.

Relevant evacuation scenarios may include those required by MSC Circular 1033 [12] and include the IMO night and day scenarios or their naval equivalent [13]. The NOP scenarios are dependent on the nature and class of vessel. For example, a cruise ship application may require the time to empty the cinema is minimised while a naval vessel may require watch changes to be completed within set period of time.

In addition to defining the ES, a range of performance measures (PM) must be defined that measure various aspects of personnel performance in undertaking the tasks associated with the ES. PM for passenger ship evacuation scenarios may include the time required to complete the assembly process while for a naval vessel NOP scenario, the total number of water tight doors (WTD) opened and closed may be relevant. The suitability of the vessel layout will be evaluated for fitness of purpose through some combination of the PM resulting from the execution of the ES.

Collectively the particular combination of ES and PM that results in a meaningful measure of the performance of the crew and vessel are described as the human performance metric (HPM). Clearly, the HPM will be specific to the type and class of vessel being investigated thus, an aircraft carrier will have a different HPM to a submarine. However, the underlying concept of the HPM will be common to all types of vessels and some components that make up the HPM may be similar across different vessel types. The HPM works by systematically evaluating one layout design against another, whether this is two variants of the same design or two completely different designs.

In this paper we will focus on applications involving naval vessels and in particular frigate type surface combatants.

2.1. The components of the human performance metric

To demonstrate the concept of the HPM we define the key components of the HPM for a naval surface combatant (i.e. a frigate class vessel).

2.1.1. Evaluation scenarios

To gauge vessel performance across a range of criteria, the ES consist of evacuation and NOP scenarios as shown in Table 1. NOP scenarios represent situations where the ships crew move around the vessel carrying out specific tasks. An example of a NOP scenario for a naval vessel is the 'State 1 preps'. In this ES the naval vessel is prepared for a war fighting situation. This scenario disregards the normal non essential tasks and brings the organisation of personnel, equipment, machinery and water tight (WT) integrity to the highest state of preparedness and readiness to deal with any emergency that might occur. Some examples of the activities that the crew undertake during this scenario might be to check all the fire fighting equipment is present and operational, close all the water tight doors and secure all loose items. Another example of a NOP scenario is the Blanket Search. In this scenario the ships company search every compartment onboard the vessel for potential damage.

Table 1
Example list of evaluation scenarios

Evaluation scenario identifier	Scenario
	Naval evacuation scenarios
ES_1	Action stations
ES_2	Normal day cruising
ES_3	Normal night cruising
	NOP scenarios
ES_4	State 1 preps
ES_5	Blanket search
...	...
ES_n	*Scenario N*
...	...

The evacuation scenarios involve the population preparing to abandon the vessel. In many cases the population are expected to gather at an emergency station prior to abandoning the vessel. NATO navies are developing regulations which set a standard for the evacuation of naval vessels [13], much like the IMO MSc Circular 1033 [12]. In essence these are several different scenarios which test the suitability of the vessel for evacuation efficiency. The scenarios vary in the starting locations of the ships complement and in the WT integrity conditions. A naval vessel has three levels of WT integrity; *X*, *Y* and *Z*. A WT integrity condition of *X* indicates that all WTD can be left unlocked and open. This is usually the condition when the vessel is in safe waters. WT integrity condition *Y* allows for some of the WTD to be in the open condition. Finally, in WT integrity condition *Z*, all WTD are shut.

The draft 'Naval Ship Code' [13] recommends that evacuation analysis be undertaken with the crew initially located in three different states, 'normal day cruising', 'normal night cruising' and 'action stations'. In the 'normal day cruising' scenario the crew locations are not necessarily known due to the relaxed nature of the vessel, although they would generally be within a particular region for example within a certain water tight zone. Only half the complement would be on watch, the other half could be in their cabins, mess room or anywhere else onboard the vessel. In the naval based evacuation scenarios, when an alarm is sounded the crew move to their emergency stations and await the command to abandon the vessel.

Presented in Table 1 are a selection of ES that may be used as part of the HPM to assess the performance of naval surface combatants. In this paper we will present an example application which employs one evacuation and one NOP ES. The evacuation scenario is based on the Naval Ship Code 'Normal day cruising' scenario while the NOP ES is the 'State 1 Preps' scenario.

2.1.2. Functional groups

As members of the ships complement may be involved in undertaking different tasks during a particular ES, the ships complement is divided into subgroups. Membership of each subgroup is determined by the nature of the tasks undertaken by the individuals in the particular ES, with each subgroup being made up of people undertaking a common set of tasks. These subgroups are labelled Functional Groups (FG). The introduction of FGs allows the analysis to focus on the performance of important subgroups of the crew whose contribution may swamp that of other FGs or be swamped by other FGs when considering the overall performance of the vessel.

An example of a FG is the 'damage control and fire fighting' group. This FG has the responsibility of maintaining the operational ability of the vessel in the event of damage. Each member of the damage control and fire fighting group are fully trained in tasks which involve fighting fires, repairing damage to the structure of the vessel, dealing with floods, checking all fire fighting equipment such as mobile pumps are fully operational, checking communications etc. The damage control and fire fighting FG is a prime example of a FG which is used in circulation ES.

In addition to the FGs defined by specific sub-populations, a special FG, identified as Ships Company, is included in all ES. Unlike other FG which identify particular sub-populations, this FG is used to represent the entire population of the vessel. It is used to provide an overall measure of the performance of the ships personnel when taken as a whole.

In practise there may be many FG on board the vessel whose performance must be evaluated. Every ES must have at least one FG and each ES may make use of different FG. Crew can be in different FGs in different ES, for example, crew members could be in the 'damage control and fire fighting' FG for a circulation scenario and then be in the evacuating FG during the evacuation scenario. Presented in Table 2 are a selection of possible FG that can be found on board naval combatants. This paper will make use of the FG; 'Ships company' and 'Damage control and fire fighting'.

2.1.3. Performance measures

To assess the performance of each FG in each ES, a set of performance measures (PM) have been defined, each of which uniquely assesses a particular aspect of the scenario, whether it be how far individuals travel in order to fulfil their duties or how long it takes to complete an assigned task such as close all WTDs. Each of the PMs returns a value determined from the computer simulation of the ES which is then used in part to complete the HPM. The higher the value of the PM, the poorer the performance of the FG in the ES. Collectively,

Table 2
Example list of functional groups

Functional group identifier	Function group
FG_1	Entire ships company
FG_2	Damage control and fire fighting
FG_3	Warfare
FG_4	Flight
...	...
FG_n	*Group N*
...	...

the PMs provide insight into the performance of the vessel and a method to discriminate one design against another.

Some 31 PM have been defined which assess many aspects of crew performance for a frigate. These PM were defined in conjunction with our project collaborators in the Royal Navy and are considered to represent relevant performance indicators for the type of vessel under consideration. The PM may be dimensional or non-dimensional parameters. Dimensional parameters are measured using SI units, such as 'distance travelled' while non-dimensional parameters simply return numerical parameters such as 'number of WTD doors used'. Most PMs are related by a particular theme and so are categorised into groups. Currently, six PM groups have been identified covering the following criteria; congestion, environmental, procedural, population, geometric and general. A selection of the PM used in the analysis presented in this paper are presented below and summarised in Table 3.

2.1.3.1. Congestion criteria. This group currently contains two PMs extracted from the IMO Circ. 1033 [12] relating to the level of congestion experienced by FG during an ES. These criteria can be used to identify possible bottlenecks and other causes of congestion.

- $\mathbf{C}_1$: 'The number of locations in which the population density exceeds 4 p/m^2 for more than 10% of the overall scenario time' [12]. As part of IMO Circ. 1033 [12], this is a pass/fail criterion. In an evacuation scenario, if this measure is exceeded at any single location, the vessel is deemed to fail to meet the evacuation standard.
- $\mathbf{C}_2$: 'The maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time' [12]. This measure shows the severity of the worst congested region in the vessel exceeding the maximum limit. This PM will return a percentage value and as such is treated as a non-dimensional PM.

2.1.3.2. General criteria. This group currently contains five PMs which assess the performance of the FGs in completing general activities associated with the ES. These PMs are $\mathbf{G}_1$: average of the time required by each individual to complete all of their assigned tasks; $\mathbf{G}_2$: average of the time spent in transition; $\mathbf{G}_3$: time to reach final state; $\mathbf{G}_4$: average time spent in congestion and $\mathbf{G}_5$: average distance travelled.

2.1.3.3. Procedural criteria. This group currently contains three PMs which assess the performance of the FGs in completing specific tasks associated with the ES. Several of the PMs in this group will be described.

- $\mathbf{P}_2$: 'The average number of operations completed per member of the FG' is a measure of the average number of tasks performed by each member of the FG in order to complete the ES. It is determined by adding all the tasks completed by each member of the FG and dividing by the number of crew in the FG.
- $\mathbf{P}_3$: 'The average time per task to complete the FGs assigned tasks' is a measure of the average time required for the FG to complete all its assigned tasks. It is determined by summing the times required to complete each of the tasks required of the FG and dividing by the number of tasks.

Table 3
Example list of performance measures

Specific performance measure	Description
	Congestion criteria
C_1	The number of locations in which the population density exceeded 4 p/m^2 for more than 10% of the overall scenario time
C_2	The maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time
...	...
	Environmental criteria
E_1	The number of fatalities
...	...
	General criteria
G_1	Average of the time required by each individual to complete all of their assigned tasks
G_2	Average of the time spent in transition for each individual; i.e. moving from one location to another
G_3	Time to reach final state
G_4	Average time spent in congestion
G_5	Average distance travelled
...	...
	Procedural criteria
P_1	The total number of operations completed by the FG
P_2	The average number of operations completed per active member of FG
P_3	The average time per task to complete the FGs assigned tasks'
...	...
	Population criteria
U_1	The FG population size
U_2	Percentage of inactive population compared to the FG population size
...	...
	Geometric criteria
M_1	The number of WTD used during the scenario
M_2	The number of hatches used during the scenario
M_3	The number of times the FG moved between decks
M_4	Average number of components used by each crew member in FG during the ES
M_5	The most number of times a WTD was operated
M_6	The most number of times a hatch was operated
...	...

2.1.3.4. Population criteria. This group currently contains two PMs which assess factors associated with the number of crew involved in various activities associated with the ES. These PMs are $\mathbf{U}_1$: FG population size and $\mathbf{U}_2$: size of the inactive population expressed as a percentage of the number of inactive to the total number of people in the FG.

2.1.3.5. Geometric criteria. This group currently contains 14 PMs which assess the performance of the FGs in navigating through various components of the vessel. Individual components of the vessel may be more difficult to traverse than others, for example climbing a ladder is more time consuming than walking the same distance on a deck. Furthermore, all components which require members of the FG to stop and operate them will incur a time penalty which will slow the performance of the FG and lengthen the time required to complete the ES. These PMs include: $\mathbf{M}_1$: the number of WTD used in the ES and $\mathbf{M}_3$: the number of times the FG moved between decks.

2.2. Defining the human performance metric

The HPM is used to compare the human performance capabilities of competing vessel designs X_1, X_2, $X_3, \ldots, X_n$. These alternative designs may simply be different design iterations of a particular vessel or competing

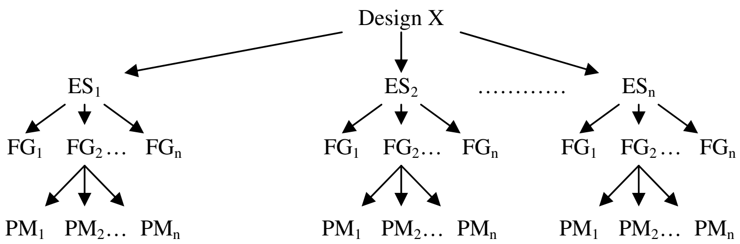

Fig. 1. Tree diagram setting out the relationship between the various components of the HPM.

design options. To assess the performance of the vessels, a set of evaluation scenarios ES_1, ES_2, ... ES_n are selected (see Table 1) which are relevant to the intended operation of the vessel.

The design alternatives are then crewed with the required number of personnel and the crew assigned to their functional groups FG_1, FG_2....FG_n (see Table 2). The number and type of FG may differ between design alternatives for each ES. Finally, each functional group FG_i, has a set of performance measures PM_1, PM_2,...,PM_n defining the performance of the FG (see Table 3). The relationship between the various components of the HPM is illustrated in Fig. 1.

2.2.1. Constructing the HPM

To complete the HPM, performance scores, $a_{i,j}$ (PM_k), associated with each PM must be determined. The PM score is simply its value derived from the execution of the simulation software for each FG within each ES. Thus,

$$a_{i,j}(\mathrm{PM}_k) = \text{Performance score derived from the simulation software for evaluation scenario } \mathrm{ES}_i, \\ \text{functional group } \mathrm{FG_j}\text{and performance measure } \mathrm{PM_k}.$$

Each page in the HPM is made up of a collection of these raw scores as shown in Table 4.

In their present state the performance scores $a_{i,j}$ (PM_k), represent a mix of dimensional and non-dimensional numbers. It is thus not possible to make a meaningful comparison between scores. To allow a meaningful comparison between performance scores, each score, with the exception of the PM G_3 ('time to reach final state') in evacuation ES, is normalised using the largest performance score from the competing design variants as shown in Eq. (1).

$$\bar{a}_{\mathrm{i,j}}(\mathrm{PM_k}). = a_{\mathrm{i,j}}(\mathrm{PM_k})/\mathrm{max_{i,j}}(\mathrm{PM_k}), \tag{1}$$

where $\max_{i,j}(PM_k)$ is the maximum value of $a_{i,j}(PM_k)$ across the designs variants X_1, X_2, X_3,...,X_n.

Using this approach, all the HPM entries will be less than or equal to 1.0. The larger the performance score, the worse the performance of the FG in that particular PM. Normalised performance scores equal to 1.0 indicate that the vessel achieved the worst performance of all the variants in this particular PM. Normalised performance scores close to or equal to 1.0 indicate an area of concern in the design.

In evacuation evaluation scenarios (ESs), the performance measure (PM) G_3 is normalised using the regulatory defined maximum value which is a function of the number of WT zones [12]. Thus, a value of

Table 4
HPM page of raw data associated with ES_n describing the PM scores associated with each FG for a particular design variant

ES_n Functional Group	PM_1	PM_2	...	PM_n	...
FG_1	$a_{n,1}(PM_1)$	$a_{n,1}(PM_2)$	...	$a_{n,1}(PM_n)$	...
FG_2	$a_{n,2}(PM_1)$	$a_{n,2}(PM_2)$	...	$a_{n,2}(PM_n)$	...
⋮	⋮	⋮	...	⋮	...
			...		...
FG_n	$a_{n,n}(PM_1)$	$a_{n,n}(PM_2)$	...	$a_{n,n}(PM_n)$	...
⋮	⋮	⋮	...	⋮	...

1.0 indicates that the vessel's performance equals the regulatory maximum, a value less than one indicates that the vessel is outperforming the regulatory requirement and a value greater than one indicates the vessel has failed the regulatory requirement.

An overall score can be determined for each FG representing the performance of the particular FG in the particular ES. This is calculated by taking a weighted sum of the normalised PM scores achieved by the FG across all the PMs. As not all PMs are considered of equal importance, a weighting is introduced to differentiate between various PMs. For example, the PM 'Number of fatalities' is considerably more important than the PM 'average distance travelled'. However, weighting of the PM is somewhat arbitrary and may depend on the nature of the ES and the FG being considered and the priorities of the assessor. Ideally, the weights should be set in consultation with the client so that their priorities are appropriately represented within the analysis (see Section 3.6). Alternatively, appropriate weights could be determined through canvassing expert opinion using the Delphi method [14].

Thus, each normalised score $\bar{a}_{i,j}(PM_k)$ will have a weight associated with it $A_{i,j,k}$, where subscript i refers to evaluation scenario ES_i, the j subscript refers to the functional group FG_j and the k subscript refers to the performance measure PM_k. Thus, the functional group score $\acute{\alpha}_{i,j}$ is given by Eq. (2).

$$\acute{\alpha}_{i,j} = (A_{i,j,1} \times \bar{a}_{\mathrm{i,j}}(\mathrm{PM}_1)) + (A_{i,j,2} \times \bar{a}_{\mathrm{i,j}}(\mathrm{PM}_2)) + \cdots + (A_{i,j,n} \times \bar{a}_{\mathrm{i,j}}(\mathrm{PM}_n)) + \cdots \quad (2)$$

The HPM with functional group score are presented in Table 5.

An overall score can also be determined for each ES representing the performance of all the FGs in the particular ES. This is calculated by taking a weighted sum of the FG scores achieved in the ES. The weighting is introduced to represent the fact that not all FGs are equally important. For example, the FG 'flight' may not be considered as significant as the damage control and fire fighting FG during the ES 'state 1 preps'. For this reason, each FG score has a weight applied to it where a high valued weight represents an important FG and a low valued weight represents a FG of little significance to that scenario. As with the PM weights, weighting of the FG is somewhat arbitrary and may depend on the nature of the ES being considered and the priorities of the assessor.

Thus, each function group score $\acute{\alpha}_{i,j}$ will have a weight associated with it, $B_{i,j}$ where subscript i refers to evaluation scenario ES_i, the j subscript refers to the functional group FG_j. Thus, the evaluation Scenario Score SS_i for ES_i is given by Eq. (3).

$$\mathrm{SS}_i = (\mathrm{B}_{i,1} \times \acute{\alpha}_{i,1}) + (\mathrm{B}_{i,2} \times \acute{\alpha}_{i,2}) + \cdots + (B_{i,n} \times \acute{\alpha}_{i,n}) + \cdots \quad (3)$$

As crew can be members of more than one function group (e.g. by definition, all crew are members of FG_1 however, crew can also be members of a specialist function group such as the damage control and fire fighting group (FG_2)), so as not to double count the performance of crew in a particular ES, weights assigned to the various FGs must sum to 1.0. Thus, in ES involving only FG_1 i.e. the entire ships company, the weight given to this FG is 1.0. The performance of the entire ships company in a particular ES is considered to be the most important component of vessel performance as it represents the overall performance of the vessel. Thus, in ES involving FG_1 and other FGs, a weight of 0.5 is given to FG_1 and the weights of the other FGs should add to 0.5, i.e.:

Table 5
HPM page of normalised data together with function group weights and function group scores associated with ES_n for a particular design variant

ES_n Functional Group	PM_1		PM_2		⋯	PM_n		⋯	Functional group score
FG_1	A_{n11}	$\bar{a}_{n1}(PM_1)$	A_{n12}	$\bar{a}_{n1}(PM_2)$	⋯	A_{n1n}	$\bar{a}_{n1}(PM_n)$	⋯	$\acute{\alpha}_{n1}$
FG_2	A_{n21}	$\bar{a}_{n2}(PM_1)$	A_{n22}	$\bar{a}_{n2}(PM_2)$	⋯	A_{n2n}	$\bar{a}_{n2}(PM_n)$	⋯	$\acute{\alpha}_{n2}$
⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋯	⋮
FG_n	A_{nn1}	$\bar{a}_{nn}(PM_1)$	A_{nn2}	$\bar{a}_{nn}(PM_2)$	⋯	A_{nnn}	$\bar{a}_{nn}(PM_n)$	⋯	$\acute{\alpha}_{nn}$
⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋯	⋮

Table 6
General HPM for design X showing individual weights

Evaluation scenario	Functional groups								Scenario score	Scenario weight
	FG$_1$		FG$_2$		⋯	FG$_n$		⋯		
ES$_1$	B_{11}	$\acute{\alpha}_{1,1}$	B_{12}	$\acute{\alpha}_{1,2}$	⋯	B_{1n}	$\acute{\alpha}_{1,n}$	⋯	SS$_1$	C_1
ES$_2$	B_{21}	$\acute{\alpha}_{2,1}$	B_{22}	$\acute{\alpha}_{2,2}$	⋯	B_{2n}	$\acute{\alpha}_{2,n}$	⋯	SS$_2$	C_2
⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋯	⋯	⋯
ES$_n$	B_{n1}	$\acute{\alpha}_{n,1}$	B_{n2}	$\acute{\alpha}_{n,2}$	⋯	B_{nn}	$\acute{\alpha}_{n,n}$	⋯	SS$_n$	C_n
⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋯	⋯	⋯
Overall functional group scores	SFG$_1$		SFG$_2$		⋯	SFG$_n$		⋯		
			Overall design performance						VP$_{\text{DESIGN}(X)}$	

$$\begin{aligned} & \mathrm{B}_{i,1} = 0.5 \\ & \sum \mathrm{B}_{i,j} = 0.5 \quad \text{where } j > 1. \end{aligned} \tag{4}$$

Finally, an overall performance measure can be determined for the design iteration X representing its performance across all the ESs. This is calculated by taking a weighted sum of the ES scores. The weighting is introduced to represent the fact that not all ESs are equally important. For example, the ES ‘State 1 preps’ may be considered more important than the ‘blanket search’ scenario and so should be weighted differently.

Thus, each evaluation scenario Score $\mathrm{SS_i}$ will have a weight associated with it $\mathrm{C_i}$, where subscript i refers to evaluation scenario $\mathrm{ES_i}$. Hence the overall vessel performance VP_x for design X is given by Eq. (5).

$$\mathrm{VP}_x = (C_1 \times \mathrm{SS}_1) + (C_2 \times \mathrm{SS}_2) + \cdots + (C_n \times \mathrm{SS}_n) + \cdots \tag{5}$$

It may also be useful to determine an overall performance score for each FG for a given design. This could be of use when investigating why one design performed better than another. This score can be calculated by summing the product of each FG score with its respective function group weight and scenario weight as shown in Eq. (6).

$$\mathrm{SFG}_1 = (\acute{\alpha}_{1,1} \times B_{11} \times C_1) + (\acute{\alpha}_{2,1} \times B_{21} \times C_2) + \cdots + (\acute{\alpha}_{n,1} \times B_{n1} \times C_n) + \cdots \tag{6}$$

The HPM with scenario and design score along with the all the associated individual scores and weights are presented in Table 6.

The overall vessel performance, VP for design X can then be compared against the VP score for all other designs to determine which design produced the best overall performance. The matrix is also diagnostic in that it allows the identification of which measures contributed to the poor performance of a failed vessel design, or which PM could be improved in a winning design.

3. Example application of the human performance metric

The use of the HPM concept in evaluating the relative performance of two designs of a hypothetical naval vessel will be demonstrated in this section. For simplicity, only two ESs are considered, one evacuation and one NOP. The aim of this analysis is to determine which design variant is the most efficient in terms of its HF performance and whether any improvements to the winning design can be identified.

3.1. The geometry

The baseline vessel design (variant 1) consists of 61 compartments spread over two decks with 27 compartments plus a passageway on the lower deck and 34 compartments plus a passageway on the upper deck. The two decks are connected via three ladders; two located in the aft and one in the forward of the vessel. The vessel has two emergency stations, one at either end of the vessel. The first variant design (variant 1) has a single 1.0 m wide passageway which runs centrally from the aft to the forward end of the vessel on both decks (see Fig. 2a and c). The second variant design (variant 2) consists of the same number of compartments spread over the two decks as in variant 1, with 27 compartments on the lower deck and 34 compartments on the

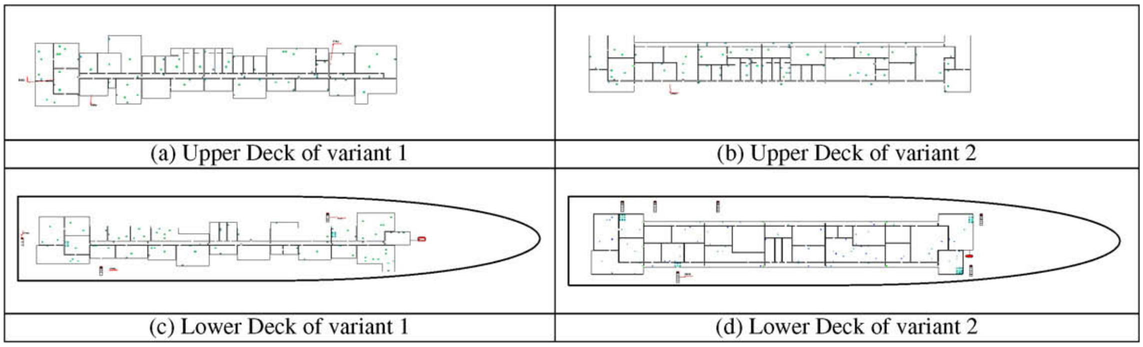

Fig. 2. Layout of variant 1 [(a) and (c)] and variant 2 [(b) and (d)].

upper deck. The key difference between the two designs is that variant 2 has two passageways running in parallel from the aft to the forward end of the vessel on both decks (see Fig. 2).

3.2. The scenarios

Each vessel has a complement of 150. For simplicity, the crew are initially scattered randomly throughout the vessel. In this example each variant is assessed using two ESs. These are the naval evacuation ‘normal day cruising’ and NOP ‘State 1 Preps’ (ES_2 and ES_4, respectively, in Table 1) scenarios.

The NOP scenario (ES_4) involves the entire complement moving to designated locations across the vessel and changing into appropriate battle gear. In addition, two teams of five fire fighters in the damage control and fire fighting FG (FG_2) move to their appropriate fire stations where they check all the fire fighting equipment and dress in full fearnought clothing. At the same time, two crew members from FG_2 close all WTD on the vessel bringing it to condition Z. Of the rest of the crew, five people search all the compartments and secure all loose items. In both designs, the same crew carry out the same tasks in the same compartments and they initially start in the same locations in both designs. This means that the results produced from the HPM will be a direct result of the change in structure between the single passageway baseline design and the double passageway variant design. The evacuation scenario (ES_2) involves the complement moving towards their designated emergency stations ready for the call to abandon ship.

In both scenarios, crew were given response times as stipulated in the draft Naval Ship code [13,15]. Finally, it must be noted that the scenarios used in this demonstration are not intended to accurately represent actual naval operations, but are used simply to demonstrate the HPM concept.

3.3. The software and methodology

The ship evacuation model maritimeEXODUS [1–6] was used to perform the simulations. The software has been described in detail in many publications [1–6] and so only a brief description of the software will be presented here.

EXODUS is suite of software to simulate the evacuation and circulation of large numbers of people within a variety of complex enclosures. maritimeEXODUS is the ship version of the software. The software takes into consideration people–people, people–fire and people–structure interactions. It comprises five core interacting sub-models: the Passenger, Movement, Behaviour, Toxicity and Hazard sub-models (see Fig. 3). The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. Many of the rules are stochastic in nature and thus if a simulation is repeated without any change in its parameters a slightly different set of results will be generated. It is therefore necessary to run the software a number of times as part of any analysis. The key components of these sub-models will be briefly described.

The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock. The spatial grid maps out the geometry of the structure, locating exits, internal

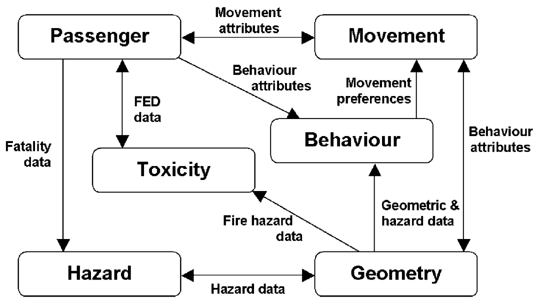

Fig. 3. EXODUS sub-model interaction.

compartments, obstacles, etc. and can involve multiple decks, which are connected by stairs or ladders. The structure layout can be specified automatically using a DXF file produced by a CAD package or manually using the interactive tools provided. Internally the entire space of the geometry is covered in a mesh of nodes that are *typically* spaced at 0.5 m intervals. Each node represents a region of space typically occupied by a single passenger. In addition to the representation of the structure itself, the abandonment system can also be explicitly represented within the model.

The HAZARD SUB-MODEL controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke concentration and toxic fire gas concentration throughout the atmosphere and controls the availability of exits (i.e. opening and closing times of exits). While the thermal and toxic environment is determined by the Hazard sub-model, EXODUS does not predict these hazards but distributes them through time and space. EXODUS will accept hazard data either from experimental measurements or numerical data from other models including a direct software link to the CFAST [16] fire zone model and the CFD fire field model SMARTFIRE [17]. The TOXICITY SUB-MODEL determines the effects on an individual exposed to toxic products distributed by the hazard sub-model. These effects are communicated to the behaviour sub-model, which in turn, feeds through to the movement of the individual. To determine the effect of the fire hazards on occupants, EXODUS uses a fractional effective dose (FED) toxicity model [18]. This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, irritant (e.g. HCl) and narcotic (e.g. CO) fire gases and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour.

The BEHAVIOUR SUB-MODEL is the most complex module, and incorporates adaptive capabilities that include, structural knowledge, reaction to communication, affiliative behaviour, occupant motivation, interaction with signage and reaction to fire hazards. The Behaviour Sub-model determines the passenger's response to the current situation, and passes its decision on to the Movement Sub-model. Social relationships, group behaviour and hierarchical structures are modelled through the use of a "gene" concept [19], where group members are identified through the sharing of social "genes". With regard to the environmental conditions, passengers will stagger through smoke filled environments. Furthermore, as the smoke concentration increases and visibility decreases, the travel speed of the occupants is reduced according to experimental data [20]. Another important aspect of human behaviour is the manner in which passengers react to the ship orientation and movement. Their movement rates in corridors on stairs and through doorways at various static angles of heel and under conditions of dynamic motion is represented within the model and based on data generated from large-scale trials [4,6]. In addition, data specific to naval personnel using equipment found on naval vessels such as; watertight doors, vertical ladders, hatches and 60 degree stairs have also been collected and incorporated within maritimeEXODUS [5].

Another feature of the Behaviour sub-model is the ability to assign passengers and crew a list of tasks to perform. This feature can be used when simulating emergency or normal operations conditions. As part of the current project, the software's capabilities has been extended through the inclusion of a number of new task capabilities required for normal operations scenarios and include; a 'terminate' command, used in the normal operations scenarios allowing crew to stay at their last location once all their tasks have been completed; a 'repeat' command, used to allow crew to repeat predefined set of tasks a number of times as is required in the patrol task; a 'search compartment' command which instructs crew to enter a list of assigned compartments to undertake a search as part of the blanket search scenario. In addition, a separate utility program has been developed (the Human Performance Metric Analyser) which automatically constructs the matrix of human performance scores from maritimeEXODUS output that are used in the evaluation of the vessel design.

Each scenario was repeated 50 times for each vessel design as specified in the IMO guidelines [12]. Once the simulations had been run, a representative output file was selected for detailed analysis. For the evacuation scenario (ES_2), the IMO guidelines [12] were used to select the representative simulation while for the NOP scenario (ES_4), the representative scenario was considered to be the scenario producing the maximum simulation time.

3.4. HPM structure

In this section we define the constituent components of the HPM. As there are two design variants, the HPM will consist of two pages, one for variant 1 (single passageway case) and one for variant 2 (two passageway case).

3.4.1. The evacuation evaluation scenario ES_2

The evacuation evaluation scenario (ES_2) consists of a single functional group, FG_1. This ES is concerned with getting the ship's complement to the emergency stations as quickly and efficiently as possible. The PMs considered important for this case are congestion (C_1, C_2, G_4); general performance of the crew (G_1, G_2, G_3 and G_5) and structural interaction (M_1, M_3 and M_5). It is also necessary to define a set of PM weights. The PM weights are intended to allow a meaningful comparison to be made between the various PMs and to allow the more important PMs to be given priority. The weights are based on a scale of 0 to 10 where a weight of 10 indicates an important PM and 0 indicates a PM of no relevance to the FG in that ES. It must be emphasised here that all the weights provided in this paper are based solely on the interpretation of the authors. In real applications of the technique the weights would be determined in consultation with the client so as to reflect the performance factors which are of importance to the client or by a community of experts using the Delphi method.

In evacuation scenarios, the PMs C_1, C_2 and G_3 are pass/fail criteria and so are given a very high weighting of 8. The PM relating to the average time for each individual to complete their tasks (G_1) is also quite important since it could have a major impact on the final time to complete the scenario (G_3) and so is given a weighting of 4. The PM assessing the average distance the crew travels to reach the emergency stations (G_5) could have a significant impact on the final time to complete the scenario, since the further a person must travel, the longer it will take them to arrive at their destination and therefore this PM has been set a weighting of 4. The PMs related to the geometric components are considered to be of little importance in this scenario and have been given relatively low weightings. The final array of weightings used for evaluation scenario ES_2 is displayed in Table 7.

3.4.2. The NOP evaluation scenario ES_4

The NOP evaluation scenario (ES_4) requires two functional groups, FG_1 and FG_2. As in ES_2, this scenario must be completed in as little time as possible and so the same PMs as those found in ES_2 are used in this scenario. However, in addition, the various FGs must perform various tasks and so the PMs related to completing tasks (P_1, P_2, and P3) are also used. For this ES, the main PM of interest is that which assesses the final time to complete the scenario (G_3), therefore this PM has been set a high weighting of 8. The level of congestion is not a pass/fail criteria in this ES and therefore C_1 and C_2 are given a relatively low weighting of 3. However, congestion is still of importance and so the average congestion experienced PM G_4 is given a weighting of 6.

For simplicity, the same set of weights have been applied to both the FGs in this scenario. The final array of weightings used for evaluation scenario ES_4 is displayed in Table 7.

3.4.3. The overall HPM

The time required to prepare a naval vessel for action (the 'state 1 preps') is considered one of the most important routine tasks that the crew will ever undertake. For this reason the NOPs scenario (ES_4) is given

Table 7
Weightings for the PMs associated with scenarios ES_2 and ES_4

Performance measure	Evaluation scenario ES_2	Evaluation scenario ES_4	
	FG_1	FG_1	FG_2
C_1	8	3	0
C_2	8	3	0
G_1	4	6	6
G_2	3	5	5
G_3	8	8	8
G_4	3	6	6
G_5	4	2	2
P_1	0	3	3
P_2	0	3	3
P_3	0	4	4
M_1	2	4	4
M_3	4	4	4
M_5	1	3	3

a higher scenario weight than the evacuation scenario (ES_2). This does not mean that the evacuation scenario is not important but merely that it could be perceived as less important to a naval vessel than NOPs. The relative weightings for ES_2 and ES_4 used in this analysis are 1.0 and 1.5, respectively. In evaluation scenario ES_4 the damage control and fire fighting group (FG_2) are considered the most important FG as they are performing tasks essential to the safety of the vessel. For this reason FG_2 will be assessed in addition to the entire population (FG_1).

3.5. Results and analysis

The two evaluation scenarios (i.e. ES_2 and ES_4) were each run 50 times and two representative simulation result files were selected to construct the HPM for each variant. The PMs for each variant were then determined and the final HPM constructed for each variant (see Tables 8 and 9).

Table 8
Human performance matrix for variant 1

Evaluation scenario	Functional groups				Scenario score	Scenario weight
	FG_1		FG_2			
	Weight	Score	Weight	Score		
ES_2	1	34.26	0	0	34.26	1
ES_4	0.5	51.26	0.5	43.59	47.43	1.5
Overall functional group scores	72.71		32.69			
	Overall vessel performance				105.4	

Table 9
Human performance matrix for variant 2

Evaluation scenario	Functional groups				Scenario score	Scenario weight
	FG_1		FG_2			
	Weight	Score	Weight	Score		
ES_2	1	19.31	0	0	19.31	1
ES_4	0.5	40.95	0.5	37.18	39.07	1.5
Overall functional group scores	50.02		27.89			
	Overall vessel performance				77.9	

As can be seen from Tables 8 and 9, variant 2 produces a VP score of 77.9 while variant 1 produces a VP score of 105.4. Thus, it can be concluded that variant 2 is the more favourable design in terms of its human factors performance according to the measures we have identified, producing an overall vessel performance that is some 26% better than variant 1. Furthermore, we note that variant 2 outperformed variant 1 in both evaluation scenarios, returning a 44% and 18% better performance than variant 1 in the evacuation and normal operations scenarios, respectively. In addition, each function group in variant 2 outperformed the corresponding function group in variant 1 across each scenario. Thus, variant 2 appears to outperform variant 1 in each broad assessment category. These results also suggest that the performance of variant 2 in the normal operations scenario, while considerably better (i.e. 18% better) than that of variant 1, returned approximately half the improved performance of the evacuation scenario (i.e. 44%) and so this aspect of the vessels performance may provide scope for further improvement. In particular the performance of FG_2 could be examined more closely.

However, it must be emphasised that this conclusion is based on the particular evaluation scenarios, performance measures and weights that have been used in the analysis. If the factors used to measure crew/vessel performance (i.e. the performance measures) or the particular scenarios that are used to challenge the vessel (i.e. the evaluation scenarios) are changed, it is possible that a different result would be obtained.

To better understand why variant 2 has out performed variant 1 and to identify potential areas in which variant 2 can be further improved it is necessary to delve into the sub-components of the HPM.

As the performance of FG_2 in variant 2 for the NOP scenario ES_4 was not much better than that of variant 1, we explore this aspect of the HPM to determine if there is any scope to improve the performance of variant 2. From Table 10, we note that variant 2 performed better than variant 1 in six of the 11 PMs (G_1, G_3, G_4, P_3, M_3 and M_4). These six PM all performed better (i.e. more than 15%) than the respective variant 1 PM, with G_4 (average time spent in congestion) returning 86% and G_3 (time to complete simulation) returning 16% better performance. However, five of the PMs (G_2, G_5, P_1, P_2 and M_1) returned poorer performance than in the first variant. These PMs returned values which were at least 12% worse in variant 2 than in variant 1. The poorest performance was achieved by M_1 (number of WTD used) and P_2 (average number of operations performed per active FG member) which returned 57% and 15% worse performance.

The poor return produced for M_1 is due to the dual corridor system having some eight more WT doors than the single corridor variant. The increase in the number of WTDs is due to the requirement to maintain water tight integrity and so is dictated by a design constraint which cannot be violated. This in turn results in an increase in P_1 (total number of tasks completed) and P_2 (the average number of tasks completed) due to the need to close the additional WTDs. However, it should be noted that even with these additional tasks, variant 2 is able to complete the scenario in a shorter period of time as measured by G_3. We also note that in variant 2, crew members must travel some 14% further (as measured by G_5) in order to complete their tasks.

Table 10
Comparison of results for FG_2 in ES_4 between Variant 1 and Variant 2

Performance measure	FG_2				
	Weight	Variant 1		Variant 2	
		PM Value	Normalised PM value	PM Value	Normalised PM value
G_1	6	604.4	1	491.9	0.81
G_2	5	379.4	0.88	432.9	1
G_3	8	791	1	584.3	0.74
G_4	6	111.5	1	15.8	0.14
G_5	2	87.7	0.86	102.0	1
P_1	3	42	0.84	50	1
P_2	3	3	0.75	4	1
P_3	4	61.9	1	51.9	0.84
M_1	4	6	0.43	14	1
M_3	4	15	1	11	0.73
M_5	3	4	1	3	0.75
Variant Scenario Score			43.59		37.18

Table 11
Comparison of results for FG_2 in ES_4 between Variant 1 and Variant 2

Performance measure	FG_1				
	Weight	Variant 1		Variant 2	
		PM value	Normalised PM value	PM Value	Normalised PM value
C_1	8	3	1	0	0
C_2	8	55.99	1	0.00	0
G_1	4	134.33	0.88	153.04	1
G_2	3	36.36	0.40	90.95	1
G_3	8	316.75	0.11	195.75	0.07
G_4	3	29.71	1	9.96	0.34
G_5	4	26.28	0.98	26.78	1
M_1	2	5	0.42	12	1
M_3	4	76	0.99	77	1
M_9	1	9	1	7	0.78
Variant Scenario Score			34.26		19.31

This additional distance is reflected in the time spent traversing the geometry which is 12% longer in the second variant (as measured by G_2). It should be noted that the time spent travelling is affected by factors such as the walking speeds of the individuals, the type of terrain they pass through (e.g. ladders, corridors, stairs, etc) and the congestion they experience on the way. We note that in the second variant, the average time spent in congestion (as measured by G_4) was some 86% less than in variant 1. This significant reduction in congestion results in variant 2 being able to complete scenario much quicker than variant 1.

This analysis suggests that it is difficult to further improve the performance of variant 2 FG_2 further. This is primarily due to the requirement for additional WTDs in variant 2.

From Table 11, we note that variant 2 performed better than variant 1 in five of the 10 PMs (C_1, C_2, G_3, G_4, and M_9). These five PM all performed better (i.e. more than 12%) than the respective variant 1 PM, with C_1 and C_2 (congestion criteria) returning 100% and G_4 (average time spent in congestion) returning 66% better performance. However, five of the PMs (G_1, G_2, G_5, M_1, and M_3) returned poorer performance in the first variant. These PMs returned values which were at least 1% worse in variant 2 than in variant 1. The worst performance was achieved by G_2 (average time spent in transition) and M_1 (number of WT doors used) which returned 60% and 58% worse performance.

We note from Table 11 a serious failing of variant 1 is that it does not meet the Naval Ship Code [8,9] concerning regions of critical congestion, with three regions displaying serious congestion as measured by unnormalised value for C_1. However, both vessels pass the assembly time criteria as measured by G_3, with variant 2 being some 36% quicker than variant 1 and some 93% quicker than the maximum allowed time.

While variant 2 produces a shorter assembly time than variant 1 (as measured by G_3), the average assembly time as measured by G_1 is some 12% greater in the second variant. This difference is not due to the distance the crew have to travel (G_5) which shows that the average crew member had to travel just 2% further in variant 2. Neither is this difference due to the average level of congestion experienced (G_4), which in variant 2 is a third of the value experience in variant 1. However we note that the average time spent travelling to the emergency stations (G_2) is 150% larger in variant 2 than in variant 1. This is why it takes the average crew member longer to evacuate in variant 2 than variant 1. This increase in the travel time can largely be accounted for by the additional eight WTDs in variant 2 which must be operated. In using a closed WTD, a person must stop, open the door, pass through and close the WTD. This can be a time consuming process which can add significantly to the average traversal time.

As described previously, the increase in the number of WTDs is a result of a requirement to maintain water tight integrity and so is dictated by a design constraint which cannot be violated. In this case it is unlikely that the performance in this scenario can be further improved.

In summary it has been demonstrated that introducing double passageways significantly reduces congestion which reduces the overall time for the vessel to complete each ES. However, by having two passageways, the number of required WTDs is increased in order to maintain water tight integrity and this increases the number of tasks that must be performed to complete state 1 preps.

3.6. Weight sensitivity analysis

To examine the sensitivity of the HPM concept to changes in the relative weights used in the analysis, the results from the example application are re-examined using different weightings. The analysis involves setting the ES weights, FG weights and PM weights each to 1.0 in turn.

With each ES given equal importance, the VP for variant 1 and 2 become 81.7 and 58.4, respectively. Thus, it is clear that variant 2 is still the preferred design. Furthermore, variant 2 is some 29% better than variant 1 which is equivalent to the difference noted in the original analysis. As only the ES weights have changed all other values in the HPM remain unchanged. In this example, changing the scenario weights does not produce a change in the outcome. However, in this example, results produced for both ESs were better for variant 2 than variant 1. Had variant 1 produced a better performance in one of the ESs the conclusions could well be reversed by setting the ES weights to 1.0. Thus, it is clear that a thoughtful setting of the scenario weights is necessary and furthermore, in drawing conclusions from the analysis, a knowledge of the relative ESs weights is essential if meaningful conclusions are to be drawn.

With the FG weights all set to 1.0, the VP for variant 1 and 2 are 176.6 and 136.5, respectively. Once again it is clear that variant 2 is still the preferred design and variant 2 returns a performance which is some 23% better than variant 1. However, with all the PM weights set to 1.0, the scenario score for ES_4 doubles relative to the original values. While this has not made a significant change in this case, it is possible that the contribution from one ES could swamp that of another if all the weights were set to 1.0.

With the PM weights all set to 1.0, the VP for variant 1 and 2 are 24.3 and 20.2, respectively. Once again it is clear that variant 2 is the preferred design and variant 2 is some 17% better than variant 1. Setting the PM weights to 1.0 has produced the most significant change as the degree to which variant 2 is better than variant 1 has decreased. Furthermore, if we examine the FG scores we find for the evacuation scenario, setting all the PM weights to 1.0 results in FG_1 in variant 2 outperforming FG_1 in variant 1 by 20%, while using the original weight distribution, variant 2 outperforms variant 1 by some 44%. Thus, it is clear that an appropriate setting of the weights can amplify the performance differences between variants. Thus, in setting the PM weights a clear understanding of ones priorities in evaluating the designs is essential. Furthermore, in drawing conclusions from the analysis, a knowledge of the relative PM weights is essential if meaningful conclusions are to be drawn. Ideally, the weights could initially be set through expert opinion derived from a Delphi analysis and then fine tuned in discussion with the client so that their priorities are appropriately represented within the analysis.

4. Concluding comments

This paper has laid out and demonstrated a general methodology, the Human Performance Metric (HPM), for evaluating HF performance of competing ship designs. The use of the methodology was demonstrated using two hypothetical variants of a surface naval combatant, one variant involving a single longitudinal passageway and a competing variant involving two longitudinal passageways. Using the methodology the dual passageway variant was identified as the superior design on the basis of two evaluation scenarios, one evacuation scenario (normal day cruising) and one NOP scenario (State 1 Preps). The approach also identified why the winning design was superior and was used to suggest how the performance of the vessel could be improved even further.

While the approach has been demonstrated for a naval surface combatant, it can be applied to any class of vessel, civilian or naval. The approach is both systematic and transparent allowing user priorities to be clearly stated as part of the methodology. The user priorities can be identified through the selection of appropriate evaluation scenarios and the weights assigned to the various components of the HPM. Furthermore, in drawing conclusions from the analysis, knowledge of the relative weights is essential if meaningful conclusions are to be drawn.

By selecting the variant design that produces the smallest vessel performance (VP) score, the methodology is capable of discriminating between competing designs and by studying the various components of the HPM it is possible to identify areas which can be improved providing the technique with a diagnostic element. The methodology is intended to be used as a comparative tool, where the performance of one variant is compared with the performance of an alternative variant. The alternative variant may have its structural layout altered or the personnel procedures employed in the various scenarios may be altered.

For a given class of vessel, it is possible to define a set of standards representing the desired or minimum acceptable performance of candidate vessels across a range of ES and PMs. By defining this standard it is possible to evaluate a one-off design, not against another contender vessel, but against the specified standard. This is a useful concept as it allows fleet owners to define the precise performance levels they expect from candidate vessels and also provide a means of measuring the performance of potential candidates. The standards can simply be defined on the basis of the existing best performer in class.

Finally, the HPM methodology has application not just to ship design, but also to the design of buildings.

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