Ship Design with the Human Factor:

Evacuation and Normal Operations Modelling

in the Ship Design Process

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Declaration

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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Abstract

This thesis addresses the modelling of human factors and how they can impact ship design. Two different but related applications areas are considered; passenger ship evacuation analysis and naval vessel normal operations and evacuation analysis.

In the first instance, this thesis investigates the impact of the current regulatory specified passenger response time distributions upon evacuation analysis and then recommends a more realistic passenger response time distribution which should be implemented when performing an evacuation analysis of a passenger RO-RO vessel. This realistic passenger response time distribution is based upon the results of sea trials. The results of this analysis have been adopted by the IMO and form part of the new guideline document, IMO MSC 1238.

In addition, this thesis addresses the analysis of the human factors' performance of a naval vessel. Naval vessels are built primarily for undertaking assigned missions in times of war and conflict. While the safety of those on board is important, the ability of the vessel to function and complete its assigned mission is of paramount importance. This thesis utilises an evacuation model, maritimeEXODUS, which was extended to incorporate the functionality of modelling non-evacuation scenarios, to assess the human factors' performance of a naval vessel during both normal operations and evacuation scenarios.

This thesis develops a methodology for simultaneously assessing the human factors' performance of both a range of normal operation scenarios and evacuation scenario on board a naval vessel. The methodology, called the Human Performance Metric (HPM), is discriminating, diagnostic, systematic, transparent and reproducible in nature.

This thesis then implements the HPM methodology into the early stages of the design cycle for a new naval vessel. The thesis presents the software modifications required to implement the methodology in to the design cycle as well as presenting a demonstration of the new system.

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Glossary

CSV	Comma Separated Values
CWT	Cumulative Wait Time
CG	Correspondence Group (created by the IMO)
DXF	Data eXchange File (autoCAD drawing data file)
DRC	Design Research Centre (UCL)
EGO	EPSRC funded project on the Guidance on the Design of ships for Enhanced Escape and Evacuation
EPSRC	Engineering and Physical Sciences Research Council
ES	Evaluation Scenarios
FG	Functional Group
FRPP	Fire, Repair Party Post
FST	Final Simulation Time
FSEG	Fire Safety Engineering Group (UoG)
GPSS	General Purpose Simulation System
HF	Human Factors
HPM	Human Performance Metric / Human Performance Matrix
IMO	International Maritime Organization
LSA	Life Saving Appliance
MTA	Meta ASCII formatted maritimeEXODUS Model file
MSC	Maritime Safety Committee (IMO)
MoD	Ministry of Defence (UK)
NBCD	Nuclear Biological Chemical Defence
NOP	Nornal OPerations
PET	Personal Elapsed Time / Personal Evacuation Time
PM	Performance Measure
RTD	Response Time Distribution
UoG	University of Greenwich
UCL	University College London

WT	Watertight
WTD	Watertight Door

Chapter 1

Introduction

1.1 Introduction

This thesis addresses the modelling of human factors and how they can impact ship design. Two different but related applications areas are considered; passenger ship evacuation analysis and naval vessel normal operations and evacuation analysis.

Modelling of human factors has become more prominent over the past few decades in the design and regulation of maritime vessels, especially in the field of evacuation simulation. Research has led to development of ship based evacuation models which has enabled an improvement in our ability to accurately predict how a population will evacuate from a given vessel layout. In response to these developments, the International Maritime Organization (IMO) through its Maritime Safety Committee (MSC) developed guidelines as to how these ship evacuation models should be used in the analysis of passenger ship evacuation. When research for this thesis began, these guidelines were enshrined in MSC Circ 1033 (IMO, 2002). The first issue addressed in thesis is how the guidelines can be made more reliable.

The second issue concerns naval vessels and is the main focus of this thesis. Naval vessels are designed and built primarily for undertaking assigned missions in times of war and conflict. While the safety of those on board naval vessels is important, the ability of the vessel to function and complete its assigned mission is of paramount importance. Issues associated with evacuation, while important, are not the primary driver when it comes to designing the vessel for human factors considerations. Evacuation of naval vessels is carried out as a very last resort; only once the vessel is deemed to have been lost. Therefore, analysis of non-emergency normal operational scenarios is of considerable importance to a naval architect and their client while designing a naval vessel. A challenge addressed in this thesis is determining whether evacuation modelling software can be used to address normal operations scenarios in addition to evacuation scenarios and how the requirements of the two can be addressed in coherent and systematic manner.

The design cycle of a naval vessel has evolved quite dramatically over the past few decades. This is due in most part to the invention of the computer. As computing power has increased, so has the ability to solve complicated calculations quickly. In the past naval architects would use complex mathematical equations along with history and experience of ship building to design the vessel. Nowadays, computers cannot only help design the vessel but can also be used to simulate how the final design will behave in its intended environment. Ship stability simulations, roll and pitch analysis and modelling of flooding can all be performed by a computer in the early stages of the design cycle.

Analysis of ‘human factors performance’ can be performed on a vessel design. However, this analysis is carried out at a much later stage in the design cycle, once the vessel design has been finalised. At this stage it is too late to make any structural changes to the design. If problems or inefficiencies in the design are found, they have to be resolved with procedural changes, which may in fact lead to further inefficiencies in the operation of the vessel. Therefore, another challenge addressed by this thesis is to develop a methodology that brings human factors performance analysis into the early stages of the design cycle for a naval vessel.

1.2 Research aims and objectives

This PhD has two main research motivations:

1. To make passenger ship evacuation analysis more reliable for evacuation modelling
2. To introduce human factor’s analysis into the early stages of naval ship design for evacuation and normal operation scenarios.

The International Maritime Organization (IMO) produced the MSC Circ 1033 guidelines (IMO, 2002) to help govern the evacuation analysis of passenger Ro-Ro (Roll-on Roll-off) vessels. The guidelines contain criteria which every sea going passenger vessel must abide by in order to satisfy a certain level of safety. The guidelines also contain information required to set up and run an evacuation of a passenger vessel. This information includes such data as passenger response time distributions, travel speeds and population demographics (for example age and gender distribution). This thesis will address the validity of the IMO MSC Circ 1033 (IMO, 2002) specified response time distribution for use in the evacuation analysis of a passenger vessel.

In 2006, the NATO navies set up a specialist team on Naval Ship Safety and Classification. This specialist team created the Naval Ship Code (NATO, 2006) as a means of achieving a minimum standard of safety on board naval vessels. The Naval Ship Code identifies the need to model the evacuation procedures onboard a naval vessel during the early stages of the design cycle. The code defines the scenarios which need to be simulated and the criteria the vessel must satisfy.

However, the Naval Ship Code does not take into consideration human factors (HF) performance during Normal OPerational (NOP) scenarios on board naval vessels. However, this is a key concern in the design of a naval vessel. NOP scenarios are performed significantly more often than an evacuation scenario onboard a naval vessel, and in some instances are a daily routine. Thus assessing a designs' ability to complete NOP scenarios may identify inefficiencies which help produce a better design in terms of its HF performance. However, this raises the question of whether an evacuation model can be used to simulate NOP scenarios. Furthermore, can the HF performance of the vessel and crew in both NOP and evacuation scenarios be considered in a single analysis to determine the overall HF performance capabilities of the vessel.

The research questions which this thesis intends to address are listed below.

1) How realistic is the IMO 1033 passenger response time distribution?
    a) What is the IMO specified response time distribution based on?
    b) Does the IMO specified response time distribution represent reality?
    c) Can knowledge of response time distributions derived from the building industry be of use in the passenger ship application?
    d) Can we develop a more realistic response time distribution for passenger ships?

   e) What impact would this have on predicted evacuation times?

2) How is the evacuation analysis of a naval vessel governed?
   a) What problems are there with the Naval Ship Code with regard to evacuation analysis of a naval vessel?
   b) Can work carried out in the passenger shipping industry fulfil the requirements of the Naval Ship Code in terms of the evacuation analysis of naval vessels?
3) How can we assess human factors associated with normal operations (NOP) of a naval vessel?
   a) What types of NOP scenarios are relevant to a naval vessel?
   b) What specific human factor aspects of these scenarios are relevant?
   c) How can the end-user (customer) exercise their requirements on the relative importance of these scenarios and human factors criteria?
   d) Are these scenarios and criteria applicable to all types of naval vessel?
      i. Can the technique be easily adapted to address these differences?
   e) Can ship evacuation models be used to assess NOP scenarios?
      i. What changes to the human factors capabilities of these software tools are required?
      ii. What changes to the modelling capabilities of these software tools are required?
4) Can we establish a combined assessment methodology that simultaneously takes into consideration human factors associated with evacuation and normal operations on naval vessels?
   a) How sensitive is the technique to small changes in user requirements or vessel design?
   b) Can the methodology be used to not only assess human factors performance but to suggest improvements in ship design and operational procedures, making the approach both discriminating and diagnostic?
   c) Can the approach be designed so that the assessment is both transparent and reproducible?
5) How can we introduce human factors associated with normal operations into naval ship design assessment?

1.2.1 Evacuation modelling

History has presented us with many maritime tragedies, such as, human error causing the sinking of the Herald of Free Enterprise (Sheen, 1987), the equipment failure causing the loss of the Estonia (JAICE, 1997), the fire on the Scandinavian Star (NOR, 1991) and the grounding of the Saint Malo Ferry. More recently the BBC news website (2009) reported on tragedies in Indonesia where several vessels have sunk killing the majority of people on board. The BBC (2009) also reported how in July 2005 about 200 people died as a ferry sank off eastern Indonesia and in December 2006 over 400 people lost their lives as a ferry sunk while making a routine trip between Borneo and Java. In February 2007 42 people died as a ferry caught fire; in July 2007 another passenger ferry sank off eastern Indonesia killing 70 people on board and most recently in January 2009 a passenger ferry carrying over 250 people sank in heavy storms. In all of these Indonesian cases the seaworthiness of the vessels was called into question. Perhaps, the most famous of all maritime disasters is that of the Titanic (Roberts, 2001). This disaster in 1912 resulted in the deaths of 1,517 people when it hit an iceberg and sank.

Throughout history, major disasters, such as the Titanic, have been followed by the developments of regulations to safeguard the sea going public. These retrospective regulative measures include having sufficient life saving appliances for everyone on board, improved fire prevention and extinguishing systems and better training for crew. Unfortunately, how ever many precautions are taken, disasters can still occur.

In the past 50 years, as a means to make vessel designs safer, many evacuation models have been developed which aim at predicting how individuals evacuate from a structure. Among other factors, they aim to assess how long it would take to evacuate people from the structure. In addition to the evacuation time, these models aim to identify the level of congestion which could occur in an evacuation scenario; this would also include identifying possible bottlenecks. Further to these factors, routes commonly used by passengers can be calculated, as well as the average distance travelled by the occupants and the average time taken by each occupant to evacuate.

By performing evacuation analysis, disasters will not necessarily be avoided but the chances of safely evacuating the population in the event of an emergency situation should increase. These mathematical models, such as maritimeEXODUS (Galea, 2001) , can predict regions where congestion may occur as well as commonly used paths taken to life boats.

One means of enforcing tighter safety requirements and procedures is through regulation. Regulative bodies such as the International Maritime Organization (IMO) and the naval equivalent, NATO's specialist team, Naval Ship Safety and Classification, have developed a number of guidelines and regulative documents aimed at improving the safety of vessels, both during their design phase and while the vessel is in service.

One area of expertise of the IMO is in regulating the safety of passenger vessels. The first document developed in relation to setting guidelines for simulating ship evacuation, MSC Circ 909, was published in June 1999. This document, entitled 'INTERIM GUIDELINES FOR A SIMPLIFIED EVACUATION ANALYSIS ON RO-RO PASSENGER SHIPS' (IMO, 1999), presented a first attempt at producing a guideline for simulating evacuation scenarios using a simplistic hydraulic network method. The guidelines made the assumption that the entire population is in a very good state of health with no disabilities and they can move unhindered. The regulations do not take into account ship movement or effects of smoke and fire on the population and assumes all escape routes are available.

These guidelines were superseded in June 2002 by the MSC/Circ 1033. This document was entitled 'INTERIM GUIDELINES FOR EVACUATION ANALYSES FOR NEW AND EXISTING PASSENGER SHIPS' (IMO, 2002) and introduced an advanced method of evacuation simulation. This document contains the same methodology as in the MSC/Circ 909 except the simplified method has four scenarios to simulate; a day time case, night time case and a repeat of these two scenarios with either 50% of the stairwells out of action or 50% of the population in the identified main vertical zone having to move to an adjacent zone. In addition to this simplistic methodology, these guidelines introduce an advanced method of simulation. This method is designed for agent based simulations whereby each individual in the simulation is modelled as a separate entity. The regulations set out the distributions for individual's speed over flat terrain, up and down stairs; it also stipulated the population demographics in terms of age and gender. Both the simplified and the advanced methods of simulation have the same aims, to identify, and as far as possible eliminate congestion regions and to show suitable flexibility of escape routes to cope with the unavailability of Life Saving Appliances (LSA), muster stations and escape routes.

In October 2007, the IMO agreed to make modifications to the MSC/Circ 1033 to include more realistic human factor performance analysis of a vessel design. One of the significant modifications involved the change in response time distribution. In the MSC/Circ 909 and MSC/Circ. 1033, the response time distribution took the form of a random uniform distribution, however following research activities carried out in this thesis, it was considered more realistic to employ a log normal curve. The modifications were incorporated in to the revised circular ‘MSC.1/Cric 1238’.

To comply with these regulations, a design must be able to evacuate within a set time limit and have no areas of severe congestion in all four scenarios. Areas of severe congestion are defined in the MSC/Circ 1033 as regions where the population density exceeds 4 persons per metre^2 for longer than 10% of the overall evacuation time. These are key areas of compliance when assessing a design’s ability to evacuate, however they are by no means the only factors to evaluate. There are other factors which can impact on the time to evacuate a vessel which are not currently included in the regulations nor included in many evacuation simulation models. For example how far a person has to travel, and the number of stairs or doors a passenger has to utilize in order to evacuate.

Although the aforementioned human factors are not necessarily pass / fail criteria, they do have a large impact on the design’s ability to evacuate. As such they should be considered in some capacity.

There are limitations related to simulating evacuation scenarios. The first issue is related to the accuracy of the modelling software. Many evacuation simulation software products are available on the market today which perform simulations of emergency scenarios. However, there is currently no accepted industry standard of accuracy and therefore it is not known whether the results produced from these models accurately resemble real life. The only way to validate these models is to compare the results of real life trials of non-emergency situations where the movement and behaviour of the participants can be captured and analysed. The same non emergency situation can then be simulated within the evacuation model and compared against the real life trial results. Unfortunately, the data from real life trials is very scarce, however there have been some large scale evacuation trials performed on marine vessels. One of note, labelled the FIRE-EXIT project, was a large multinational EU funded project which consisted of a number of trials aimed at collecting a range of data for validating evacuation models.

The FIRE-EXIT project (EU FP5, 2002) has made an important contribution to the development of our understanding of human behaviour within the maritime environment through the collection of human performance data in laboratory-scale trials relating to movement rates of passengers under a variety of conditions, including; static adverse angles of orientation, dynamic ship motion, a combination of dynamic motion and reduced visibility due to smoke and the time required to board a variety of Life Safety Appliances (LSA). In addition to these laboratory scale experiments, two full-scale trials at sea using an operational passenger vessel and actual passengers were conducted as part of the FIRE-EXIT project. The primary purpose of this work was to collect data relating to the response time of passengers involved in assembly trials.

The second issue identified relating to the modelling of an emergency evacuation scenario regards the response time distribution assigned to the population within the simulated scenario. Understanding how people behaviour in emergency situations within maritime settings is vital if we are to; design and develop evacuation efficient vessels and crew evacuation procedures, train crew in the management of evacuation situations and regulate the design and operation of vessels. An essential component of this understanding is the collection and characterisation of human performance data such as the response time distribution.

The response time distribution specified by the International Maritime Organization (IMO) in their regulatory document MSC/Circ. 1033 (IMO, 2002) takes the form of a random uniform distribution. The shape of this distribution suggests that the same number of people will react at each point in time within the range of the distribution. This is an extremely unlikely scenario and quite unrealistic. This thesis, in Chapter 4, will attempt to investigate the suitability of the existing regulatory specified response time for simulating both ‘day’ and ‘night’ scenarios.

1.2.2 Modelling naval vessels

Naval vessels are very different to passenger vessels; passenger vessels are designed to transport civilians from one place to another as safely as possible, whereas a naval vessel is designed for combat. On passenger vessels, the safety of the passengers is of the utmost importance, whereas the survivability and functionality of the naval vessel is considered the most important factor to the Royal Navy. For these reasons, the IMO regulations would not apply directly to naval vessels, although the same principles for assessing a vessel's ability to evacuate would apply. However, no naval equivalent to the IMO MSC/Circ 1033 exists.

The NATO Navies recognised that there was no naval equivalent to the work carried out by the International Maritime Organization (IMO). In response they developed a framework for naval vessels which is based upon the conventions and resolutions created by IMO. This framework has been named the 'Naval Ship Code' (NATO, 2006). Chapter 7 of this code concerns the simulation of escape and evacuation. Within the Naval Ship Code, escape is defined as being "*the movement of people to a position of relative safety on board the vessel*" and evacuation is defined as "*the movement of people to a position of relative safety away from the vessel*".

If the escape and evacuation analysis is to be performed in the early stages of the design cycle, it is necessary to ascertain what level of detail will exist in the design, and what level of detail will be required in order for human simulation software to simulate emergency and non emergency scenarios. Chapter 10 will aim to address this issue.

In addition to the need to analyse the human factors performance of a design in its abilities to evacuate the population, vessel owners, operators and designers alike are also interested in analysing a population's ability to complete normal operational scenarios. These non-emergency normal operational scenarios are carried out on a day to day basis whereas an evacuation of a vessel would occur very rarely in the ship's life.

With regards to passenger vessels, ship operators / owners are very interested in analysing how a population moves about the vessel, in order to identify ways to improve the design and potentially maximise profits. Assessing a population's ability to fill and empty a restaurant or a cinema is one example of a way a vessel operator could maximise their profits. The more efficient this process, the greater the throughput of paying customers. Furthermore, if ship operators could simulate the population's general movement about their vessel, then they could identify the optimal position to place such facilities as for example a casino. By placing a casino next to the majority of passenger cabins for example, there would be a greater chance of passengers walking past the casino and as such a greater chance of enticing them in. In this example, the ship operator would improve the profitability of the vessel.

For a naval vessel, the navy would be extremely interested in analysing the human factors performance of a vessel design in terms of the population's ability to complete normal operational scenarios. A naval vessel's ability to complete a scenario as quickly as possible can mean the difference between life and death. If a vessel becomes under attack, it needs to be able to defend itself in the most efficient manner and retaliate as quickly as possible if need be. This may require the crew to move about the vessel quickly. Analysis of this type of scenario may identify ways of modifying the design in order to get a crew member from A to B more efficiently. This may include such alterations as moving doors or even removing doors, moving compartments around to shorten the distance between two commonly used locations or even inserting additional ladders.

One of the largest costs in the life cycle of a naval vessel is the manning costs. Over the life of a naval vessel, this expense far exceeds the cost to design and build the vessel. As such, it would be of a particular interest to a navy to make their vessels as efficient as possible in terms of human factors performance, so that fewer crew are required to man the vessel. This could result in a large cost saving to the navy.

Being interested in simulating *Normal OPerational (NOP)* scenarios brings into the equation the question of how to simulate them in conjunction with evacuation scenarios. Emergency and non-emergency scenarios are quite different to model. During evacuation scenarios, the entire population are moving towards a small number of locations (exits) and all have the same aim of getting out of the structure and to a place of relative safe haven. In contrast, during normal operational scenarios, possibly only a few people have the same aims and itineraries. The tasks which the individuals need to carry out can vary greatly; from drinking tea in a restaurant to checking compartments for damage.

There are few models which have the capabilities to model normal operational scenarios. As such, an existing egress model would have to be extended in order to possess the capabilities to model NOP. The alternative would be to build a new model from scratch to simulate both emergency and non emergency scenarios.

After obtaining a human simulation model to assess both evacuation and NOP scenarios, a decision needs to be made as to how both types of scenarios are assessed in conjunction with each other. At present, as previously mentioned, there are regulative documents and guidelines as to how a vessel design should perform in an evacuation, however there are no standards as to how NOP scenarios should perform. This is mainly due to the vast number of different possibilities which can be assessed.

Due to the broad variety of NOP scenarios, it would be extremely difficult to create any guidelines as to how they should perform. This causes a problem when assessing NOP. A solution to this would be to use a comparative technique. This could mean comparing the performance of a new design against the performance of a recognised ‘good’ design.

1.3 Structure of Thesis

This thesis is structured into five main sections. The first section introduces the work carried out (Chapter 1) and reviews the work already carried out in this field (Chapter 2). In addition to the review of the state of the art, Chapter 3 reviews the two software tools selected for use in this thesis. Following this, the second section of this thesis (Chapter 4) evaluates the accuracy of evacuation models in assessing human factors performance. The key focus of this chapter is the response time distribution assigned to the population. The chapter assesses the regulatory specified response time distribution and compares it to other known distributions. The chapter also suggests a more realistic response time distribution which should be used throughout this PhD thesis.

The third section of this thesis (Chapters 5 – 9) addresses how to evaluate human factors performance in both evacuation and normal operations scenarios alongside each other. The solution described in this section consists of the development of the Human Performance Metric (HPM) concept. This takes a weighted sum approach to make a comparison of human factors performance between two or more competing designs. The resulting methodology is both discriminating and diagnostic in nature. This section of the thesis also presents the use of maritimeEXODUS as a suitable tool to use in the assessment of the human factors performance of a given design and discusses the software modifications and developments needed to implement the HPM methodology. A demonstration of these developments and methodology is carried out using an example of a Royal Navy Type 22 Batch III frigate.

The fourth section of this thesis (Chapter 10 – 11) is focused on incorporating human factors and the HPM concept into the early stage of the design cycle for a naval vessel. This is achieved by creating a link between the ship design software tool PARAMARINE and the human factors simulation tool maritimeEXODUS. This involved translating the outputs from one tool into the inputs of the other tool, and vice versa. The work also required a lot of development within maritimeEXODUS in order to automate much of the process of modelling the human factors of a design. In addition to this, two utility tools were created to help develop the link between the two software tools as well as make the process of setting up a model and analysing the results more efficient. These tools are labelled the Scenario Generator and the HPM Analyser.

Finally conclusions are presented in Chapter 12 and recommendations for further work is provided in Chapter 13.

The detailed structure of this thesis is as follows:

Chapter 1 (Introduction) provides an introduction to the work provided in this thesis.

Chapter 2 (Literature Review) reviews human simulation tools and their limitations. This chapter presents a review of the regulations governing the simulation of human factors. Within this chapter there is a summary of the design cycle used to create new naval vessels and also presented is a brief review of the software tools which can be used for designing a new naval vessel

Chapter 3 (A Model Review) provides a greater detailed analysis looking at the software tools selected for use during this work; maritimeEXODUS and PARAMARINE. The chapter identifies the strengths and weaknesses of these software tools, with particular emphasis on the maritimeEXODUS tool.

Chapter 4 (Proposal of a Realistic Response Time Distribution) presents extensive work carried out examining the regulatory specified response time distribution (RTD) used in the simulation of human movement and behaviour during an evacuation scenario. The chapter demonstrates the effect of different RTD using distributions obtained from the built environment, alongside the regulatory specified RTD and then proposes a more realistic response time distribution which was then adopted by the regulators. This work was required in order to improve the accuracy of modelling of human behaviour.

Chapter 5 (Development of the Human Performance Metric) introduces the concept of the Human Performance Metric (HPM). This chapter introduces the components which make up the HPM and define its structure. The implementation and application of the methodology is presented as well as how to analyze the results produced and identifies how sensitive the concept is to changes in the design's structure or procedures employed by the population.

Chapter 6 (Defining a HPM for a Naval Vessel) aims to define a Human Performance Metric for a naval surface combatant. It defines the scenarios and performance measures required to effectively assess the human factors performance for the vessel type in question.

Chapter 7 (Software developments required for the implementation of the HPM methodology) discusses the software developments that were necessary in order to employ the newly developed HPM methodology. This includes relevant changes made to the maritimeEXODUS software tool as well as the development of two new utility tools required to setup and analyse the results from the model.

Chapter 8 (Demonstration of newly implemented maritimeEXODUS features) provides a useful demonstration of the newly implemented software developments presented in Chapter 7.

Chapter 9 (Demonstration of the HPM technique as a stand alone system) demonstrates the capabilities of the new HPM concept with the use of a hypothetical naval vessel and a geometry based on the UK Royal Navy's Type 22 Batch III surface combatant.

Chapter 10 (Integration of HPM into early stages of the design cycle) depicts the necessary software changes required to insert the new HPM concept into the early stages of the design cycle for a naval vessel. Highlighted in this chapter are the difficulties encountered in the integration of human factors analysis into the early stages of a design cycle and how these were overcome.

Chapter 11 (Demonstration application of the human performance metric implemented into the early stages of the design cycle for a new naval vessel) provides a demonstration of the novel HPM methodology as implemented in the early stages of a design cycle. This makes use of a UK Royal Navy's Type 22 Batch III frigate in an example application which will demonstrate the new capabilities of all the software tools needed for the integrated design cycle.

Chapter 12 (Conclusions) lists the achievements and conclusions drawn from the work carried out in this thesis along with some discussion.

Chapter 13 (Recommendations for further work) presents ideas for work which could follow on from this PhD thesis.

Chapter 2

Literature Review

2.1 Introduction

This chapter provides a comprehensive review of the subject field which this work is based upon. It provides critical analysis of the current state of the art and suggests where work needs to be carried out.

The chapter provides an introduction to the concept of modelling human factors followed by a review of human factors modelling software and a review of the regulations governing the modelling of human behaviour. The chapter discusses the validation of human behaviour models. The chapter then presents an introduction to decision making techniques in design selection and an introduction to the design cycle of a new naval vessel.

2.2 Modelling human factors

Evacuation models are used to enable ship designers to test ship designs for safety and to ensure they comply with regulations before the vessels are built. This allows the geometry to be tested without building physical prototypes which are expensive and difficult to configure, as well as introducing ethical issues (Gwynne, 1999). Computer based evacuation models are cheaper and more efficient to build, and can simulate many different evacuation scenarios easily.

The most significant developments in computer based evacuation modelling technology have occurred in the building industry. This has been the driving force behind much of the development in evacuation modelling despite not being the first sector to pioneer the technology. One of the first computer based evacuation models to appear in literature was an aircraft evacuation model using GPSS (Folk, 1972) (Garner, 1978) in the 1970's. It is generally accepted that Predtechenskii & Milinksii (1969) and Fruin (1971) pioneered the work in this field and have influenced the development of evacuation models quantifying the movement of people.

Evacuation models (often called egress models), use 'agents' to represent humans. Many evacuation models represent each agent individually, as separate entities which have their own attributes such as height, weight, age, gender, travel speeds and agility. In these models, the agents can move independently to one another or as groups and can move in counter flow to one another.

2.2.1 Assessing human factors

Traditionally when assessing a design, whether for example it is a building, marine vessel or an aeroplane, in terms of its human factors performance, the key factor which is always desired, is the overall time required for the population to complete a scenario. This is the major pass/fail criteria for all regulations which incorporate some kind of human analysis. Some regulations / standards do go further than dictating the overall simulation time. For example, the International Maritime Organization regulations for the evacuation of a marine vessel (IMO, 2007) states that there should be 'no locations of severe congestion within the geometry'. Similarly, within building regulations, there is a criteria that each member of the population should 'not have to travel more than 100 metres in order to reach a location of safe haven'.

The common human factors (HF) that are assessed and the impact they have are listed below. Some of these are inputs into the model and some are the outputs.

- Final simulation time

The ultimate factor, showing the HF performance of a design. The lower this value, the quicker the scenario is completed and therefore, the more efficient the design. This value represents the time for every individual agent to complete all of their itinerary tasks.

- Individual simulation time

  This value represents the time for an individual agent to complete all of their assigned tasks.

- Congestion

  This represents the amount of time an agent spends stationary due to obstructions caused by other agents in their way

- Distance

  This value represents how far an agent has to travel in order to complete their part of the scenario. The shorter this distance, the quicker the agent will complete their tasks.

- Response time

  This value represents the time it takes from the signal of alarm to the time when the agents begin purposeful movement towards the completion of their tasks. This time could be anywhere between 0 seconds and 10 minutes, depending on the nature of the enclosure, the environment and the activities being performed prior to starting the scenario. For example, the agent maybe finishing their dinner, waking up and / or getting dressed.

- Travel speeds

  This value represents how far an agent can move in a second. Different travel speeds will be applied for different activities, for example, walking on flat terrain, walking up or down stairs and can be applied to simulate varying ages/disabilities.

- Weight / age / height

  These values apply restrictions to the agents to simulate realistic populations.

- Structural components which require operation by the agent (for example doors, Watertight (WT) doors, stairs / ladders etc)

  Operating these components, such as opening a door or climbing a ladder, will slow an agents' progress towards completing their tasks. The more components that require operation, the longer it will take an agent to complete their itinerary.

- Congestion regions

  Bottlenecks caused by obstructions or bad design can lead to high levels of congestion. These congested regions will slow all agents in this area. These regions of congestion should be avoided, either by changing the design or implementing procedures which disperse the agents more efficiently.

2.2.2 Computer based evacuation models.

Evacuation models have existed for many years but really developed with the invention of the computer. Evacuation models refer to the simulation of a population exiting a structure. Initially, evacuation models consisted of hydraulic systems which used complicated mathematical equations to predict a structures' ability to evacuate. These models were performed using hand calculations prior to the invention of the computer and took a long time to calculate but with little reliability or confidence in the results. There was also a low level of detail in the results produced and essentially the only result obtained was an estimation of the final evacuation time of a structure.

With the invention of the computer, more complex simulations have become feasible. It is now possible to model individuals moving independently of one another in their bid to exit the structure. This provides a greater level of detail to be produced from the analysis, for example, it allows for the assessment of the level of congestion that builds up in a simulation and to identify common routes taken by the population.

There are many different evacuation models in use at the present time, most of which have been included in comprehensive studies of egress models, such as the 28 egress models examined in a report written by Erica Kuligowski (2004). There have been many other reviews carried out through the years, for example, by Sharp (2003b), Santos & Aguirre (2004), Okazaki & Matsushita (1993), Watts (1987) and most recently by Muhdi (2006). Rogsch did a study in 2009 which ran the same high rise building model in four different commercial software tools and compared the results to a real evacuation of the building in question. He found that while all four evacuation models obtained similar evacuation times as the real building evacuation, there were large differences in the clearance of each floor and in other behaviours observed during the simulated models.

There are three classifications of evacuation models: Microscopic, Macroscopic and Mesoscopic (Kim. H et al, 2004).

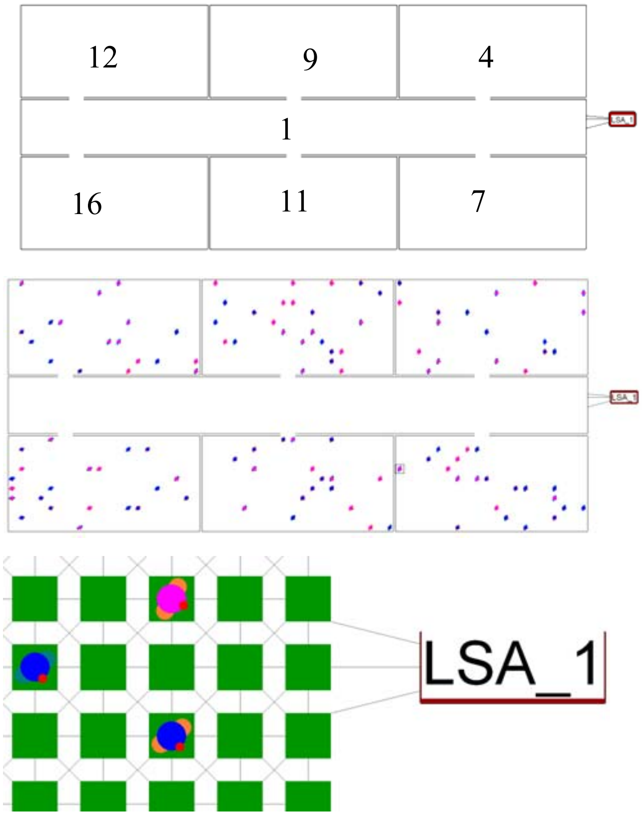
Microscopic evacuation models (Meyer-Konig, 2001) simulate each person individually. Although this requires more computing power than the two other models, it is appropriate to investigate the effect of each evacuation factor.

Macroscopic models (Gilmore, 1997), often called ball bearing models, simulate agents exiting a structure similar in nature to a fluid dynamics model. Macroscopic models simulate agents flowing through a structure towards the exits much like a fluid does. These types of models do not simulate each person individually but rather as a group of people moving together. Since the population are not simulated individually much less computing power is required, however, with this comes the disadvantage of not being able to assign itineraries to individuals, nor modelling counter flow or being able to appreciate the level of congestion which may build up during a scenario.

Mesoscopic models are half way between macroscopic and microscopic. These models simulate each person individually but each agent does not have the complexity in behaviour or movement as is the case with a microscopic model.

Computer simulated evacuation models must contain two different components within the model, the agent and the geometry. The agent represents a human in the model. The agent will move through the mesh (geometry) to their destination (usually the exit).

To enable the evacuation model to pinpoint the location of an agent, to move an agent within the simulation and to calculate the distance that an agent travels within the structure, it is necessary to overlay a grid or ‘mesh’ within the geometry. There are three types of mesh that can be used by an egress model; fine, coarse and continuous (Chooramun et al, 2010).



(a) A coarse mesh

(b) A continuous mesh

(c) A fine mesh

Figure 2.2-1 - illustrative difference between Coarse, continuous and fine mesh models

In the coarse mesh approach (Figure 2.2-1(a)), each compartment and corridor is represented by a single node and there are no spaces between each node. Each node can contain a number of occupants but the movement of each occupant is not simulated through an individual space. In general it appears that evacuation models which employ a coarse mesh simply display the number of occupants on each node rather than displaying the movement of the agents. For this reason, these are generally the least computer processing intensive type of model to use but are the least accurate at modelling human movement. EVACNET4 is an example of an evacuation model utilising a coarse nodal mesh.

The continuous mesh (Figure 2.2-1(b)) represents the space in which the agents can move using vectors. With this type of mesh agents can freely move in any direction that they desire. This is the most computing intensive type of model to use but also the most accurate. An example of a model using the continuous mesh is EVI (PennyCott & Hifi, 2010)

The fine mesh (Figure 2.2-1(c)) consists of a number of small nodes which will generally accept a single occupant. Each node is connected to the rest of the mesh via arcs. These arcs effectively represent an occupant taking a step from one node to the next. This type of mesh is easy to set up and produces reasonably accurate results. EXODUS (Galea, 2001) is an example of an evacuation simulation model that uses this type of mesh.

A list of current computer based evacuation models are shown in Table 2.2-1. Some of these models are no longer being developed, some of the models perform evacuation models on buildings only, some are designed for maritime structures, some for aircraft, some (like EXODUS) can simulate evacuations for many different types of structures.

Table 2.2-1 - a List of available evacuation models

AENEAS	EPT (Evacuation Planning Tool)	Helios	S-Cape (external PDF)
ALLSAFE	E-Scape	Legion	SGEM
ASERI	ESM	MA&D (Micro Analysis & Design)	SimPed
BFires V1 / BFires-II	EVACNET4 / EVACNET+	Magnetic Model	Simulex
BGRAF	EVACSIM	MASCM	SimWalk
BuildGEM	EvacuationNZ	MASSEgress	SMART Move
BUMMPEE	Evi	MASSIVE Software	SpaceSensor
Cube Avenue	EXIT89	MASSMotion	STEPS
CRISP	EXITT	Musse & Thalmann	Takahashi's Fluid Model
DBES (Distributed Building Evacuation Simulator)	Exodus	Myriad II	TIMTEX
EARM	F.A.S.T	Nomad	TSEA: Transient

			Simplified Egress Analysis
EESCAPE	FDS+Evac	PathFinder	VSSIM
EGRESS	Firescap	PEDFLOW	WayOut
Egress Complexity Model	FlowTech	PedGo	ZET
EgressPro	FPETool	PedRoute / Paxport	WayOut
ENTROPY	GridFlow	PedSim	ZET

The table below shows four of the more developed maritime based computer evacuation models and the features available for each.

Table 2.2-2 - Comparison between evacuation models

	maritimeEXODUS	EVI	ANEANUS	SimWalk
Define itineraries	✓	✓		
Import CAD drawings	✓	✓	✓	✓
Simulate individual agents	✓	✓	✓	✓
Output travel distances	✓	✓	✓	✓
Output itinerary task data	✓	✓		
Accessibility to source code	✓			
Capable of modelling passenger vessel evacuations	✓	✓	✓	
Capable of modelling naval vessel evacuations	✓			
Simulate non-emergency naval scenarios				
Simulate group behaviour	✓	✓	✓	✓
Stochastic distribution of results	✓	✓	✓	✓

maritimeEXODUS has been demonstrated and proven to have the ability to successfully model ship evacuations (Galea, 2002b), and more importantly, has demonstrated the ability to simulate naval vessels (Boxall, 2004). There is no literature which demonstrates any other evacuation model being able to model naval vessels. Since the source code of the evacuation model maritimeEXODUS is available to the author of this thesis, the software has the capabilities to be extended to enable it to model normal operational scenarios. For these reasons maritimeEXODUS becomes the model of choice for the work carried out in this thesis

A more detailed analysis of the limitations and capabilities of the maritimeEXODUS software will be presented in Chapter 3.

2.2.3 Validation of human simulation models

Many evacuation models exist in the market which can visually represent humans moving to exits within a design, such as EVI. However, to have confidence in the results of the simulation it is necessary to ensure that the evacuation model has been validated in some way, despite the limitations implicit with performing announced trials with members of the public, this method produces the most realistic approximation to 'real-world' human behaviour and is used to validate human simulation models (Galea, 2010a, b).

Because of the large number of variables in the exploitation simulation (for example the routes that could be taken by an agent) the same simulation can be repeated but a slightly different result will be produced. Using this approach, a number of simulations need to be performed in order to build up a distribution of results, which, whilst not covering every possible permutation, more accurately represents the likely outcome. For instance, a fire could break out in so many different locations and contain many variations of toxic gases. It would take thousands, if not millions, of simulations to cover the numerous fire scenarios in ships.

In order to validate these models, it is necessary to compare their results to a real life occurrence of a scenario. This is rather difficult to do on a full scale, would require a means of videoing an entire scenario (in reality), ensuring the capture of the initial locations of people and their paths to the destination. In the maritime field large multinational projects have been funded which aim to collect much of the data required to properly validate maritime evacuation models.

The FIRE-EXIT project (EU FP5, 2002), for example, was a large multinational project funded by the EU which aimed at collecting this type of data on human response times and routes to assembly stations. The semi-unannounced assembly drill was performed at sea using full fee paying passengers. The passengers response times and assembly times were captured using a series of video cameras.

In Japan, a full scale trial was performed on a passenger vessel with 356 school children and teachers (Yoshida et al, 2001). This trial was performed while the vessel was moored and the participants were aware they were in an evacuation drill. During this trial, when the alarm was sounded, the passengers returned to their cabins, donned life vests and moved to the assembly stations. Video cameras were used to track the movement of passengers.

Another major project is currently studying the performance of humans in the event of an evacuation (at time of writing this thesis). This project entitled SAFEGUARD (EU FP7, 2009), plans to carry out six full scale assembly exercises on board three separate types of passenger vessel. The three vessel types in question are passenger ferries with cabins (i.e. ferries performing over night journeys), ferries without cabins and cruise liners. The aim of the project is to collect the response times and paths taken to the assembly stations by each of the passengers as well as the time taken for the passenger to arrive at the assembly station. The data collected from these 6 assembly exercises will then form three separate validation data sets (one for each type of vessel) the recommendation will be that future evacuation models are validated using these data sets, thus making evacuation modelling more accurate and trustworthy. Each passenger will be tracked as they move through the structure using novel person tracking technology. This technology involves a series of Infra-Red (IR) beacons positioned throughout the vessel and each passenger wearing an IR tag. As a passenger walks through an IR field produced by an IR beacon, the IR tag logs the beacon ID and time. Then after the assembly exercise, each passenger's path and assembly time can be extracted from the IR tags.

Very few simulation models available in the current market are suitable for use in military applications. In fact, there is only one proven model for simulating evacuation based scenarios on board UK naval vessels, which is maritimeEXODUS (Boxall, 2004). This is because, to perform an evacuation simulation on a naval vessel, the model must be able to simulate the use of 60 degree stairs, ladders and watertight (WT) doors; none of which are considered to be used by passengers on a civilian vessel during an evacuation. Similarly, the Royal Navy are less interested in their vessels' ability to evacuate, since abandoning the ship is the very last resort. Instead, the Royal Navy are far more interested in their vessel's ability to carry out various tasks, such as change of watch or preparation for battle. This is not to say that the safety of Naval personnel is not a consideration, as the Royal Navy still requires the modelling of the emergency egress scenario during several different ship states (i.e. state 1, state 2 and state 3) (NATO, 2006)

2.3 Decision making techniques

There are many frameworks, models and methodologies in existence to assist in the decision making process. To a greater or lesser degree these models have an element of subjective input which greatly affects the outcome of the analysis performed. Examples of some of these are explained and examined below

Decisions are always being made in every day life, from something very simple, like what channel to watch on the TV to less frequent and more involved decisions such as, for example, what car to buy. The following section discusses some frequently used 'decision making' techniques and their use in industry.

Companies may carry out a cost / benefit analysis before making a decision to embark on an investment. A simplified explanation of this analysis is to quantify the value of the benefits of a course of action, and subtract the costs associated with it. This is a frequently used business tool employed to help make strategic decisions (Götze, 2010).

The limitations with this decision making framework include the inherent difficulty in accurately calculating the discount rate of future costs and benefits, in estimating potential benefits and calculating indirect impacts.

Another useful tool for making decisions is the 'Kepner-Tregoe Matrix' technique. Developed by Charles Kepner and Benjamin Tregoe during the 1960s, this technique requires all the possible solutions to a problem to be defined. Then a list of 'must have' criteria is defined to test each solution against. Each 'must have' criterion is then given a weight by ranking them into order of importance. Each 'must have' criterion is given a score depending on how well the solution satisfies it. Once a set of 'must have' criteria has been defined and assigned a rank, a score given to each criterion for each solution, then the score is multiplied by the rank.

This technique was designed as a business tool to help managers make decisions as to how the business should proceed. The technique makes use of criteria, which could take the form of any measurement, which could be human performance criteria.

This technique of evaluating solutions provides a systematic approach, and if applied to vessel design could highlight areas of a design's HF performance which may need some attention. The disadvantage to this method is that the relevant importance of each criterion is subjective. This can be a disadvantage since one person's opinion as to what the rank is can be completely different to another person's opinion.

'Pareto analysis' is a method of identifying the most important areas where resources should be focused to obtain the maximum benefit (Das, 1997). Firstly the problem areas are identified with the root cause of each problem. Then the problems are 'scored' depending on their strategic importance and are grouped together by their root cause. Lastly the scores are analysed and action taken to address the problems with the highest scores.

The technique involves ranking solutions into an order of importance. The solution ranked as the most important would be the one which would be the most effective. This is not necessarily the best or most optimal solution, but the most effective suggested solution. The aim of the Pareto analysis was to generate an 80% improvement from carrying out just 20% of the work and was created by Joseph M. Juran and named after Italian economist / philosopher Vilfredo Pareto.

In the fire safety industry decisions must be made as to how safe a structure is for the occupants and whether the fire safety precautions in place are sufficient.

In Hong Kong, fire risk assessments for high rise non residential buildings are carried out using a ranking system (Lo, 1999) to determine whether or not the fire safety provisions are sufficient.

The methodology employed here consists of a 15 point fire safety ranking system which acts as a check list. The system is designed to assess a high rise building's fire safety system. Each of the 15 items on the check list carries a score and a weight. Buildings score '1' if the building has the item and '0' if it does not. In some cases there is a '0' for an item being in good condition and '-1' if the item is not in good condition.

Some of the 15 points in the check list include; fire alarm system, sprinkler system, building height (for example is it below 50 metres?), evacuation routes (for example are the number of exits greater than the building department's requirements?). The weights are determined via consultation with a group of experts in the field. The result will be between -15 and 15 (excluding weights). The higher the score the more the high rise building satisfies fire safety standards. If a low score is achieved then the items with zero or negative score need to be addressed.

The good aspect about this methodology is the approach to assigning values to the points. Acting as a check list, effectively means that each point has pass / fail criteria whereby if the building passes those criteria then it gets a point and if it fails it gets zero points. This is useful since all the values will be of the same magnitude and have the same meaning. This makes the final result intuitive to interpret. The methodology also makes it easy to identify how to improve a high rise building's fire safety precautions. Limitations with this methodology are with the subjectivity of the assignment of weights and with the difficulty in obtaining complete agreement within the expert group as to the setting of weights. There is also no mention of how to compare the final result or perform a sensitivity analysis. However it could be assumed that a final score would be compared against a similar building which is considered to have an acceptable fire safety system.

2.3.1 Risk analysis

Presented by Dr Hakan Frantzich (Frantzich, 2008a) was an approach to assessing the fire safety precautions of a structure, utilizing two methods of risk assessment to evaluate the risk that occupants would face if a fire broke out in the building. It demonstrates a standard Quantitative Risk Assessment (QRA) and an extended QRA.

The standard QRA method focuses on the combined effect of frequency and consequences of a possible accident. The methodology builds up a system of scenarios whereby each scenario has a probability (frequency) of it occurring and a consequence such as the number of fatalities or injuries.

The standard QRA calculates the average societal risk (ASR), also known as the potential loss of life (PLL). The ASR value conveys the potential number of fatalities in the scenario considered. This methodology makes use of a decision making tree, referred to as an 'event tree'. Within this event tree, several sub scenarios make up an overall scenario. For example the scenario may start with the outbreak of a fire. The sub scenarios to this could then be that the sprinkler system fails or the alarm system does not work. Each branch of the event tree represents a sub scenario which has an assigned probability of occurrence and consequence. The ASR value is calculated by multiplying the probability of each scenario occurring against the consequence of the scenario.

An example application for this approach is of a sprinkler system in a hospital ward (Frantzich, 2008b). It was calculated that 2.7×10^{-4} persons per year would be affected by a fire if a sprinkler system is implemented and 2.2×10^{-3} persons per year would be affected by a fire if a sprinkler system is not implemented. Unfortunately the calculations used in this approach are not presented and therefore it is not possible to critically evaluate the merits of this approach fully.

The extended QRA takes into account the issue of uncertainty. In practise the probability and consequence of a scenario occurring will not be a fixed value but rather will fall within a range of values. This method will then use the mean values for the probability and consequence values in order to calculate the ASR.

A strength of this methodology is in the assignment of weights. In this case the probability or frequency of a scenario is used. This means that human judgement is taken out of the equation and provides a more scientific method.

However, the foreseen problem with this methodology would be in obtaining the values for the probability and consequences for every defined scenario. The methodology is also very dependent on the validity of these probability and consequence values. In some cases the probability of an event occurring may be known, possibly from historical records of the structure in question or from the history of similar structures. However, for some scenarios the data may be limited or unknown.

Common to all of these decision making techniques are a set of criteria which need to be evaluated. Many of these techniques also allocate a weight to each of the criterions as a method of assigning a level of importance.

Having a set of criteria and weights describes an area of mathematics known as multi-criteria decision making (Stadler 1984, 1998) or multi-objective optimisation (Jahn, 2004). There are many methods which have been devised which solve different applications of multi-criteria decision making which include the weighted sum approach. This seems to be the most common method of decision making. Although there are many other techniques, all designed for specific applications.

The weighted sum approach is formed of a set of criteria with each criterion being assigned a level of importance. This level of importance is multiplied to the criterion in the form of a weight. The method then adds up all the values of the weighted criteria to produce a number for that set, which can be compared against another set.

While developing a system to assess the HF performance of a design, many different approaches were tried and tested, especially in relation to populating the criteria, assigning weights to the criteria and if necessary, normalising the criteria. These areas will now be briefly discussed.

2.3.2 Populating the criteria

In order to make any decisions about a designs' efficiency in terms of its human factors' performance, data has to be collected to assess the design by. The following sections look at different methods of populating the criteria. The use of a checklist is explored, as well as a points scale system, and finally using the raw data values from an evacuation model is analysed.

2.3.2.1 Checklist approach

Firstly a checklist approach (Chow, 2002) could be taken, whereby criterion would have a set performance standard which, if the design meets certain standards it will receive points but if the design fails it will lose points. For instance a criterion could be 'to have less than 20 seconds of congestion experienced on average by the population'. If the average level of congestion experienced in design 1 is 15 seconds then it will comply with the standard and thus receive 2 points; if design 2 experiences 30 seconds of congestion on average then it will fail to meet the standard set in the criterion and as such lose 2 points. Employing this method would mean that all criterion values are integers with no dimension and as such would be directly comparable against one another. Then the weighted sum of the criterion values can be calculated to produce a HF performance score for the design.

The advantage of this method of assessing the HF performance of a design is that as long as the same criteria are used with the same performance standards then new designs can be added to the analysis with very little effort. This would be a very simple method to implement.

However, the disadvantage of this implementation is the lack of detail in the results. It may be possible to use this method for a quick and easy assessment of the HF issues related to a design however a fuller analysis of the human factors is not possible using this method. For instance, two designs may complete a scenario within the standard set by the criterion and as such receive the same amount of points, but design 1 may complete the scenario twice as fast as design 2. This would make design 1 more favourable; but this fact would be omitted thus suggesting that the two designs complete the scenario in an equal amount of time.

2.3.2.2 A Points Scale approach

An alternative approach to populating the criteria is to use a points scale system. In this approach, a score could be assigned to a criterion depending on how well it performed. The performance of each criterion would be compared to a table of classification which will assign an appropriate score to it.

An example of a points scale system was presented by Chow & Lui (2001), in this instance the criteria would be given a score depending on how well the design performs. If the design returns a good performance from the simulations then it can be given a larger score of, for example, 5. While, if the design returns a poor performance from the simulation then the criterion would be given a low score of 1. See Table 2.3-1 for an example break down of the points rewarded to the criterion measuring the average level of congestion experienced by the population during a scenario.

Table 2.3-1 - Example points score for the average level of congestion experience during the scenario

Performance	score
Less than 10 seconds	5
10 – 19 seconds	4
20 – 29 seconds	3
30 – 39 seconds	2
Greater than 40 seconds	1

Employing this method of applying values to the criterion would, much like the checklist approach, mean that all values are integers between 1 and 5 with no dimension and as such would be directly comparable against one another. With this in mind, the assessor would merely have to take the weighted sum of the criterion values to get a HF performance score for the design.

This method would be far more accurate than the checklist approach since it has categories for each design's performance, enabling a more accurate comparison to be made between designs. The more categories that are defined the more accurate a comparison can be made.

As with the previous method of implementation, the disadvantage of this method is the lack of accuracy in the HPM. It may be possible to use this method for a quick and easy assessment of the HF issues related to a design however for a fuller analysis of the human factors this method loses the detail. For instance using the 'average level of congestion experienced' criterion from Table 2.3-1, the population in design 1 may experience 20 seconds of congestion compared to 29 seconds in design 2. This is a 45% increase in the average level of congestion but looking at the points rewarded to the criteria both designs would have a score of 3. Thus this significant increase in the level of congestion is lost in the analysis. This inaccuracy can be reduced by introducing more categories.

In addition to this, how are the range of values classified for each criterion? It will be acceptable to use scientific reasoning to select the bands of values but in the majority of cases, these bands will be subjectively defined.

2.3.2.3 Using the raw data values

The disadvantages to the previous two approaches, checklist and points system, has been the loss of accuracy when classifying a design's performance in a specific criterion. The obvious solution to this is not to classify the performance of a design in a criterion, but instead use the raw data value from the model. By using the raw value produced by a model, a better comparison can be made between designs.

However, the disadvantage to using the raw data values from a model is the range of possible values. The values for some criteria will be dimensional thus some will be measured in metres, others in seconds and others in frequency. Additionally, some of the values will be very small and others very large. These cause a problem since producing a single HF performance score for the design becomes complicated. There is no simple way of adding 923 seconds to 5 metres, for example, and obtaining a meaningful result which could be used to assess a design's HF performance.

The solution to this problem is to normalise the raw data values. This will remove all units of measurement and bring all the values of the criteria into the same range. This will then mean that all the criteria could be compared against each other and the weighted sum approach could still be used to produce a single HF performance score for a design.

Due to the accuracy obtained from this approach of populating the criteria, this is the approach that is adopted in this thesis. Methods of normalisation will now be analysed to find the technique best suited for the work in this thesis.

2.3.2.4 Normalisation

As described above, once a model has been run and the criteria populated, there will be a wide range of values, ranging from tiny decimal numbers up to large integer values, all of which will have different units of measure. Some of these values will be measured in time, others in distance or frequency of occurrence. It would be very difficult to compare these values and get an overall sense of how well the human factors performed in the design, Therefore a means of normalising all the values was required. This would remove all units of measurement as well as bring all the values into the same range.

One approach for normalisation involved comparing a base case to the other design alternatives. With this approach, the first design variant from a set would be labelled the 'base case' and all of its criterion values became the 'normalising factors'. Then the raw values for the criterion in all other designs would be divided by the respective normalising value from the base case. In this instance, when the weighted sum of the criteria is calculated the vessel performance score would indicate whether other designs were more or less efficient than the base case design and by how much.

This was intuitive since it would be easy to identify those designs which are more efficient than the base case (as having a negative score) and those which are not (i.e. had a positive score). In addition, if another design was added to the analysis then the criteria for each design would not have to be renormalized since as long as the base case design does not change then the normalising factors would not change either.

The problem with this method would be that of a normalising factor of zero. If the raw data value of a criterion in the base case design was zero then trying to divide the respective criterion value in the other design alternatives would produce an error. A zero divide cannot work! Many attempts were made at trying to accommodate this but with little success.

One idea to solve this zero divide problem was to have the zero as the normalised criterion score in the base case and the normalised values for all the design alternatives would simply be the value of the criterion raw data value. This would work but then the normalised values for the design alternatives would be of a different magnitude. The normalised values for most of the criteria would be in the range of 0 and 1, but if the normalising factor is zero then the normalised values for the criterions in the other designs could take any value, typically below 100 but more than likely above 1. This could then have a significant impact on the overall HF performance score of a design, even if the criteria is seen as unimportant.

Another attempt to resolve the zero divide problem involved adding one to the normalising factor. Since all of the criteria would be written such that they could not have a negative value then adding one to the normalising factor would always produce a factor greater than one. In addition, since the normalising factor was always the raw data value from the base case design plus one, all of the criteria would be affected equally. The disadvantage to this resolution is that adding the value one to the denominator introduces an error. As the denominator gets larger, the error becomes smaller but nonetheless there is an error which when multiplied by the criterion weight will be magnified. This produces an unwanted inaccuracy to the value of the HF performance score of a design.

Additional attempts were made to reduce this error, for instance the dominator could have been the square root of the raw data value from the base case criteria plus 1 or a very small value such as 0.00000001 could have been added to the normalising factor. However in every case there would still be an error. For this reason the idea of having a base case, for which all design alternatives were compared against, was discarded.

This led to the idea of taking the highest criterion value from all the design alternatives as the normalising factor which all the criteria are divided by. This eradicated the problem of a zero normalising factor, since the highest criterion value was used. Since all the criteria had been designed such that they would never have a negative value, if the maximum value for a criterion across all the designs was zero then all the designs must have a zero value for that criterion. In this instance all the designs would have a normalised value of 0 for that criterion. The method also allows the direct comparison between designs

Using this approach, the normalised values for every criterion were within the range of 0 and 1 with a maximum of 2 decimal places. Since no criterion's raw data value could have a negative value the lowest possible normalised value would be 0. Since the highest raw criterion value was the normalising value, in the normalisation it would be divided by itself (the normalising factor) thus producing a value of 1.

In this fashion, all the criterions had a normalised value relative to the worst performing criterion. As such, a normalised criterion value of 0.4 meant that it was 60% better performing than the worst performing design for that criterion.

The downfall to the chosen method is the annoyance of having to renormalize every criterion in every design if an additional design is added. This has to be done since the new design may have the highest value for some of the criterion and as such these values would become the normalising factors.

Since this downfall is just a time constraint, this method of normalisation is considered favourable since it maintains a high level of accuracy. As such this is the method adopted in this PhD thesis (see Chapter 5).

2.3.3 Assignment of weights

In addition to assessing different methods of populating and normalising the criteria, it was also important to identify a suitable method assigning weights to the criteria. Unfortunately there really is just one method which is appropriate for the work in this thesis, and this method is of a very subjective nature.

The method implemented involved obtaining the opinion of the client, i.e. the person(s) who is paying for the design to be built. This is one person's opinion as to what the weights should be and will represent their priorities. Due to the nature of the weights, representing the level of importance, it should be easy for an individual to justify their selection of weights since they can point to a criterion and say that it is more or less important than another.

However, in certain circumstances there may be a group of individuals who each want to select the weights assigned to the criteria. In this instance, one person's opinion may be quite different to another's. Therefore there needs to be a procedure for selecting the weights. There exists a developed approach to this, known as the Delphi method (Harmathy, 1982).

The Delphi method was first developed in the early 1950's by the RAND corporation and sponsored by the U.S. air force. Its purpose then was to make forecasts on future developments. Since then the method has been adapted to suit many different applications but with the underlying technique of giving a series of questionnaires to a group of experts, with the results of the previous round of questionnaires being summarised and added to the next round of questionnaires. With this approach, each expert can voice their opinion on setting the values of the weights. The questionnaires would then be collated and summarised, with the results updating the questionnaire. The next questionnaire would then be issued to the experts who can agree / disagree with the set of values and provide feedback. The questionnaire can then be further updated with the new set of values along with feedback. This process will continue until a set of values has been agreed upon.

This is a useful and established approach to obtaining a set of values with the input from a group of experts, all of whom may have quite different views. This will collate all of their views however this may well take many iterations which could be very time consuming and does not necessarily mean that a set of values will be produced which everyone can agree upon.

Fulop (2005) also presents a summary of the group decision making process which follows the same principles of the Delphi method.

2.3.4 Weights Scale

The scale of the weights should also be assigned appropriately. The adopted scale was an integer between 0 and 10, but equally a scale of 0 to 1 or 0 to 100 could have been used. A scale of 0 to 1 was immediately disregarded since this would involve decimals and this would introduce issues of precision. The use of weights with a high precision has the potential of making the weighted criterion score very small, especially with values less than 0.001. This range could be considerably narrowed by reducing the precision and as such a precision of 1d.p for the weights would produce a possible range of 0.001 to 1. At the opposite end of the spectrum, a scale of 0 to 100 could also produce a large range of numbers.

2.4 Ship Design Process

The design process of a naval vessel has evolved greatly through the decades, especially in the past 50 years with the introduction of computers. Computers can do vast amounts of calculations within seconds which leads to complex computer simulation tools which can help designers build and test a new vessel in a matter of hours or at most a few days.

The focus of this thesis is on the early stages of the design cycle. Much of the work discussed in this section is taken from Richard Pawling' Ph.D. thesis (2007) and many of the papers which were authored / co authored by Richard Pawling and Professor Andrews from University College London.

The general procedure adopted in producing a new ship design study, as specified by Pawling (2007), is as follows:

1. An outline requirement is identified and a design style proposed;
2. A series of Design Building Blocks are defined or selected, containing geometric and technical attributes;
3. Design Building Blocks are located as required within the configurational space;
4. Overall weight and space balance and performance (e.g. stability, powering) of the design are assessed;
5. The configuration is then manipulated until the designer is satisfied;
6. Decomposition of the building blocks to greater levels of detail is undertaken as required, and balance / performance maintained at the required level.

The Design Building Block approach to designing new naval vessels will be described in much greater detail in Chapter 3, when reviewing the ship design software tool PARAMARINE.

Figure 2.4-1 illustrates the process of designing a new naval vessel according to Pawling (2007). It can be seen from this figure how once the brief is issued ('radical idea' in the figure), the first step is to define the overall space of the vessel ("Space Definition"), for example the hull form, required compartments such as engine room. With the hull defined, the internal space is divided into smaller spaces which will later define the compartments on board. These smaller spaces can go through several iterations of being rearranged in order to fit the purpose of the specification. This iteration can be seen between "General Arrangement" and "Detailed Layout" in Figure 2.4-1. Once the initial arrangement of the design is satisfied, the design will go through a number of analytical assessments which will determine the designs suitability for sea; this is performed at the "Geometric Definition" stage of Figure 2.4-1, and involves such assessments as stability analysis and manoeuvring analysis. If the design satisfies these assessments then the structure is finalised and the fixture and fittings will be added and the crewing of the vessel will also be considered at this stage, this is done at the "Weight Module" stage in the design cycle presented in Figure 2.4-1.

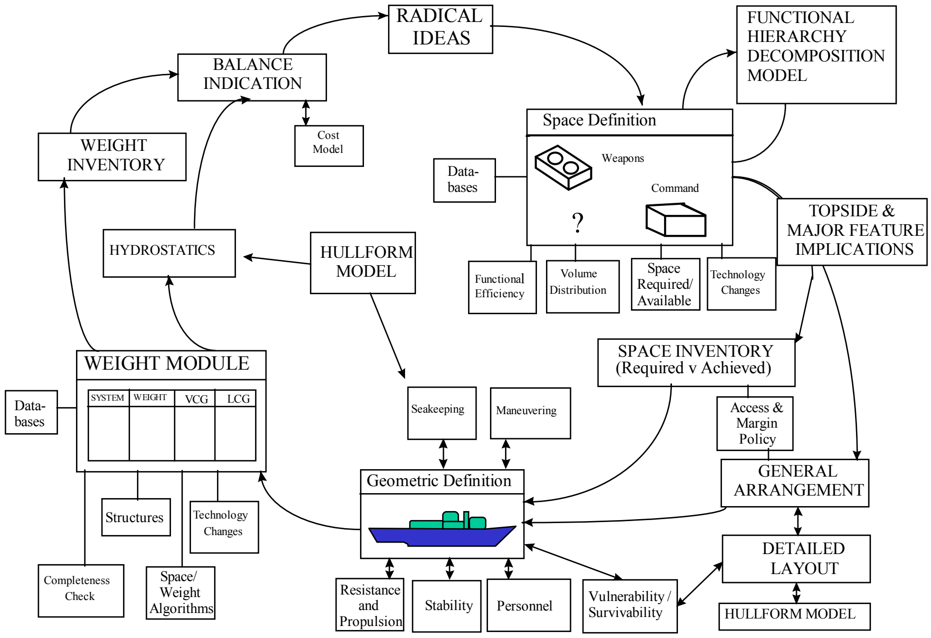


Figure 2.4-1 - The ship design cycle as illustrated by Pawling (2007)

2.4.1 Ship Design Software

There are a number of software tools which are used to assist in the design of naval vessels. The majority of these are able to design the vessel from the initial stages of the design process to the final product. Below is a list of some of the more popular software tools.

- PARAMARINE (Forrest, 2008)

  Software tool created by Graphic Research Corporation (GRC). This organization was originally a part of the UK MoD but later split to form a private company. In recent times the company has been taken over by Qinetiq which has a lot of associations with the UK MoD. During the early stages of the design process, PARAMARINE uses a building block approach to designing a new vessel, this methodology was designed by UCL's Design Research Centre (DRC)
- Foran (Grupo Sener, 2008)

  Developed by SENER
- ShipConstructor (ShipConstructor Software Inc, 2011)

Created by ShipConstructor software Inc, which is a Canadian shipbuilding software developer company. Development on the ShipConstructor began in 1988 with a simple DOS based program which then grew into a suite of software capable of designing a naval vessel from scratch through to the final design.

- AutoShip (Autoship Systems Corporation, 2011)

  Development of the AutoShip suite of software tools began in 1980 by the Autoship Systems Design.

- NAPA (NAPA, 2011)

  Development of the NAPA software began in the 1970's in a shipyard in Helsinki, Finland. A company (NAPA Oy) was formed in 1989 where the software was developed for commercial use. This software was released in 1992 and is still considered a leading naval architectural software tool.

- SmartMarine (Intergraph corporation, 2011)

  Developed by Integraph Corporation

PARAMARINE was selected for use in this work, since it is used by the UK MoD to design new naval vessels and is quoted from the Qinetiq (2011) website as "One of the main tools used by the UK Royal Navy to model its ships and submarines and the only endorsed UK MoD tool for ship and submarine stability analysis". In addition, the users and designers of the software (UCL DRC) were partners on the EPRSC project 'EGO' (2004), on which this thesis is based.

2.4.2 Naval Terminology

Naval vessels, much like passenger vessels, are split into watertight (WT) zones and then into WT compartments. The compartmentalisation of a ship enables areas of the vessel to be isolated in the event of a breach of the hull. This effectively contains the flooding to sections of the vessel. That is to say if the WT integrity of a compartment is breached it may still be contained in the WT Zone thus keeping the ship afloat.

Naval vessels have 3 different states of awareness; State 1 (Action), State 2 (Defence) and State 3 (cruise). These states are discussed further in Chapter 6. Along with the three ship states, there are three watertight integrity conditions: X, Y and Z. These relate to the number of WT doors and hatches that can be open. WT integrity Z is the highest state of readiness and in this case all WT doors must remain shut at all times. This ensures the vessel is most prepared to take on board damage and contain that damage as much as possible. WT integrity X is the most relaxed of the three and many WT doors and hatches can remain open. WT integrity Y requires essential WT doors and hatches remain closed but others can remain open.

Along with these differences there are some components which are used on a naval vessel which are not required during the evacuation analysis of a passenger ship, where only the passenger areas are modelled., elements such as:

- Watertight doors
- Hatches
- Ladders (including wire ladders)
- 60 degree stairs

These components are found on passenger ships, but not in areas which passengers occupy.

For both naval vessels and civilian passenger vessels the various parts of the ship are referred to as follows:

- Bow

  The front of the vessel. In this thesis, the bow is always on the right of the displayed design
- Stern

  The rear of the vessel. In this thesis, the stern is always on the left of the displayed design
- Midships

  The middle of the vessel, centre part of the deck
- Fore section of the ship

The section of the ship between midships and the bow.

- Aft section of the ship

  The section of the ship between midships and the stern.

- Starboard

  Right hand side of the vessel. In this thesis, the starboard side is always at the upper part of the displayed design.

- Portside

  Left hand side of the vessel. In this thesis, the portside is always at the lower part of the displayed design.

2.5 Regulative bodies and regulations

Two main regulatory bodies are referred to in this thesis. The first of which is the regulatory body that is concerned with recommendations and guidelines for civilian passenger vessels, this is set by the International Maritime Organization (IMO) The second regulatory body discussed in this thesis is that of a NATO specialist team on Naval Ship Safety and Classification.

The Correspondence Group on Recommendations on Evacuation Analysis for New and Existing Passenger Ships of the Fire Protection Subcommittee (FP46) of the International Maritime Organization (IMO) produced an interim regulatory framework in an attempt to address the development and application of evacuation models within the maritime environment. These regulations are described in the document entitled 'Interim Guidelines for Evacuation Analysis for New and Existing Passenger Ships', which is referred to as the Maritime Safety Committee Circular 1033 'MSC/Circ. 1033' (IMO, 2002), Lee (2003) provides a good introduction to the simplified evacuation analysis provided in the MSC/Circ 1033 document..

2.5.1 MSC/Circ. 1033

In February 2002, a methodology was presented to FP46, which was intended to cover the analysis of ***all new build*** passenger ships with a recommendation that it be applied to all passenger ships. The methodology outlined covered both simplified (i.e. hydraulic evacuation analysis) and advanced (i.e. the use of evacuation modelling tools) techniques for the simulation of evacuation. This approach was accepted by FP46 and in the 75th Session of MSC (in May 2002) was formally adopted as the Interim Guidelines for evacuation analysis of new and existing passenger ships including RO-RO (Roll-On Roll-Off) passenger ships.

These guidelines define two benchmark scenarios (along with two variants) that must be simulated as part of the certification process. These are defined as the “night” and “day” scenarios. While arbitrarily defined, they established a baseline performance for the vessel and crew, allowing comparison with both the set target time and alternative designs. The scenarios only address the mustering or assembly phase of the evacuation in calm conditions (i.e. zero list, heel and roll) and do not *explicitly* take into consideration the impact of fire. The guidelines also set out validation/verification requirements that the software must satisfy before it is considered suitable for use in certification applications. These include 11 test cases and software documentation requirements. The documentation is intended to demonstrate the credibility and appropriateness of the approach adopted and furthermore, allow easy verification and reproduction of the submitted results. The document includes reference to two distinct methods for approved evacuation analysis: a *Simplified method* and an *Advanced Method.* For the purpose of the work carried out in this PhD thesis, the advanced method was used and will be further explored.

Response times for the simplified method were arbitrarily fixed at 300 and 600 seconds for day and night scenarios respectively, and were arbitrarily fixed at 210 – 390 seconds and 420 – 600 seconds for the advanced method of analysis. The response distributions in the advanced method are implemented as a random uniform curve. This means that the same number of people will respond at every time period, for example 10 people will respond every second. These response time distributions were defined by a panel of experts in the field of evacuation modelling based on opinion as opposed to validated data, which was not available at the time. Clearly the same number of people responding at each time slice is not representative of real life, however due to an unavailability of validated data the random uniform distribution was considered a step in the right direction.

The main differences in the requirements of the two methods are in defining the population. In the simplified method, the population is assumed to have the same parameters such as travel speed and the time to commence movement, whereas the advanced method allows populations to be defined by age, sex, walking speeds, response time and mobility.

Both methods only consider the time to assemble and assume that the vessel is stationary with no list, trim or fire conditions. In addition, both have inclusion of safety factors to compensate for assumptions made within the analysis.

The circular also states the performance requirements that the analysis must meet and is ship type specific; i.e. for all types of passenger vessels including RO-RO vessels with no more than three vertical fire zones, the total evacuation time should not exceed 60 minutes. For passenger vessels (other than RO-RO vessels) which have more than three vertical zones, the total evacuation time is increased to 80 minutes.

There is a requirement within the circular that congestion is to be avoided and where present, should be reduced to an acceptable level. The unacceptable level is defined as a region where the local population density exceeds 4 person/m^2 for a time period greater than 10% of the overall assembly time.

2.5.1.1 The Advanced Method

Advanced evacuation analysis may be used as part of this methodology in order to calculate what is termed as the 'travel time' (the speed at which an individual moves within the simulation). In this context, advanced evacuation analysis is

"taken to mean a computer-based simulation that represents each occupant as an individual that has a detailed representation of the layout of a ship and represents the interaction between the occupants and the layout."

(MSC/Circ 1033, ANNEX 2, page 1)

The evacuation model in this context is used to calculate the travel time component of the evacuation. A number of assumptions are required during the advanced method of analysis. These include the assumption that passengers and crew respond on an *individual* basis and that they evacuate via the main escape route. The assumption is also made that the ship motion, the impact of signage, the impact of smoke, the location of crew, and group behaviour is accounted for by a safety factor and that, unlike the Simplified Method, the *Awareness time* (or time taken for an individual within the simulation to respond and actively disengage from their activity and purposefully move towards the assembly station) is an integral part of calculation (averaging 10 minutes for night and 5 minutes for day scenarios). Embarkation and launching times are then added separately and the population demographics are stipulated as are starting locations. Lastly, the guidelines specify that each case is run a minimum of 50 times with at least 10 different populations (i.e. 10 populations, each of which are simulated 5 times). The 95th percentile results produced during these 50 runs are accepted as representing the time to assemble.

It was assumed that 50 simulation runs was sufficient to produce a suitable distribution of results from which to select a representative case from. However, due to the random nature of many evacuation models, the severity of congestion or worst case scenarios may be missed and therefore there may be a need to produce significantly more simulation runs. However, this is not specified in the regulations.

In addition to these assumptions certain requirements are made of the models themselves: each person must be represented as an agent and the movement of each person should be recorded. The individuals are determined according to a set of parameters, a sub-set of which are probabilistic and the values of which will vary throughout the population; the basic behavioural algorithm is shared by the entire population and each time step should be less than or equal to one second. In addition to these factors a number of restrictions and requirements are placed upon the model in terms of the configurational, procedural, environmental and population-based representation.

The guidelines present the characteristics of just one population to be used during the evacuation analysis of a passenger vessel. This is very limiting since every population on board a passenger vessel will be different, some vessel owners may market their vessels towards older people thus the population which should be used during an evacuation analysis should contain a larger proportion of agents exhibiting characteristics attributed to older people. This population also assumes that all the crew are young able bodied people whereas in fact many crew members on a passenger vessel may be older experienced crew. In addition to this, the guideline assumes there are 50% male crew and 50% female crew on board the vessel. Although this may be the case in some instances, in the majority of the cases, there will be a larger proportion of one gender or the other. This can make a difference since different age groups and different genders are assigned different travel speeds. Therefore having a population which are predominantly young males will evacuate a vessel much more quickly than a population of older women according to the guidelines. This is not a concern for this thesis, but should be a consideration for further work.

These guidelines define two benchmark scenarios (along with two variants) that must be simulated as part of the certification process. These are defined as the “day” and “night” scenarios. In addition to these two benchmark scenarios, a variation of these two scenarios must be simulated. There are two possible variations suggested in the regulation which both involve modifying the way in which the population evacuates from the identified main vertical fire zone. The main vertical fire zone is selected as the fire zone which contains the person who produces the longest assembly time. As such the guidelines recommend that a minimum of four separate cases should be examined in order to determine the evacuation potential of the vessel; these are similar to those identified previously although require the provision of additional detail due to increased flexibility provided by the advanced method.

In Case 1 *(primary evacuation case, night)* passengers and 2/3 of crew members are assumed to be in their cabins with maximum berthing capacity fully occupied. Of the remaining 1/3 of crew members, 50% should be initially located in service spaces and behave as passengers, 25% should be located at their emergency stations and should not be explicitly modelled, whilst 25% should be initially located at the assembly stations and should proceed towards passenger cabins in counter-flow with evacuees, returning to the assembly stations once they have reached the passenger cabins (to simulate searching of cabins).

In Case 2 (*primary evacuation case, day*), passengers are distributed around the public spaces, which should be occupied to 3/4 of their maximum capacity. 25% of the crew should be located at their emergency stations and should not be explicitly modelled; 25% should be initially located at the assembly stations and should proceed towards passenger cabins in counter-flow with evacuees, returning to the assembly stations once they have reached the passenger cabins; the remaining 50% of the crew will behave as passengers (1/3 initially distributed in public spaces, 1/3 in service spaces and 1/3 in accommodation spaces).

In cases 3 and 4 (secondary evacuation case, night and day) only the main vertical zone, which generates the longest assembly time, is further investigated. Two alternatives exist for this analysis: removing 50% of the stairway capacity previously used within the identified main vertical zone, or the introduction of 50% of the persons in one of the vertical zones neighbouring the identified main vertical zone.

These are just benchmark cases and do not cover every eventuality which could occur on a vessel during an evacuation. However, is it realistic to expect all passengers to be located in their cabins during the night scenarios? Many Ro-Ro vessels do not have cabins on board, or if they do, very few vessels have sufficient cabin space to accommodate all of the passengers. Therefore, where should these passengers be located? These benchmark scenarios may not be sufficient to accurately represent the vessel design during an evacuation scenario. However, these questions are not for the work presented in this thesis but could be considered for further work.

Using the *Advanced method*, the total evacuation time is then calculated according to the following formulae:

$$\textit{total evacuation time} = T + 2/3\,(E + L) \leq n$$

$$\text{where } E + L \leq 30 \text{ minutes}$$

where ***(T)*** is the travel time (in minutes) including the response of the individuals which is an integral part of the calculation (set as a distribution of between 210 – 390 seconds and 420 – 780 seconds for the day and night cases respectively), ***(E)*** is the embarkation time and ***(L)*** is launching time. ***(n)*** is the maximum time allowed for the whole process. This value is set to 60 minutes for RO-RO passenger ship and passenger ships with no more than 3 main vertical zones, and 80 minutes for passenger ships other than RO-RO vessels which have more than 3 main vertical zones. The travel time is calculated using the evacuation model chosen. The final value reached is then extended by a safety factor and counter-flow factor such that

$$T = t + \Delta$$

where Δ is the safety factor to be taken as equal to 600 seconds for the primary night and day scenarios (cases 1 and 2) and 200 seconds for the secondary night and day scenarios (for cases 3 and 4).

All of these factors are then combined as specified in Figure 2.5-1. The embarkation and launching time should be calculated separately either from manufacturer or trial data, or in the event that this data is not available these two factors combined can be assumed to equal 30 minutes. A third of the combined total of the embarkation and launching time must be discounted from the overall time, it being assumed to occur simultaneously with some portion of the travel time of the passengers.

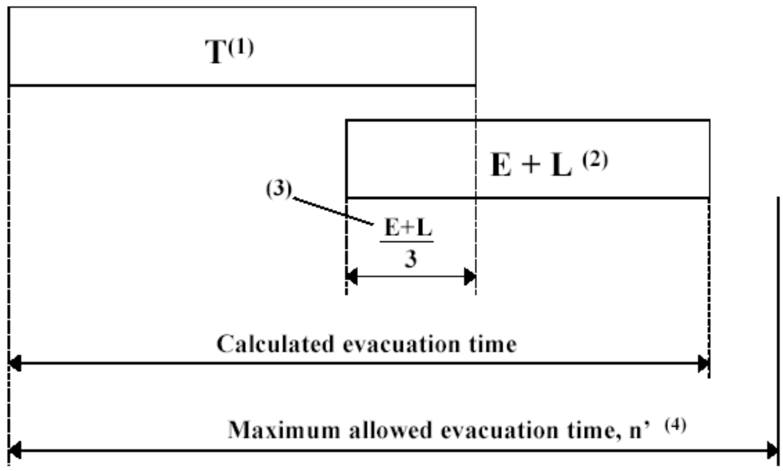


Figure 2.5-1 - Schematic of the overall evacuation calculation for the advanced analysis as specified in IMO MCA Circ. 1033 (IMO, 2002).

In addition to these quantitative factors, the conditions during the cases must also be monitored (implicitly indicating the necessity of the model to be able to generate and monitor the specified conditions) to determine whether the congestion during the evacuation reaches intolerable levels. If the congestion levels reach or exceed 4 persons / m^2 for longer than 10% of the assembly time then the evacuation will be deemed not to meet the requirements of the regulatory framework. This again provides an indication of the type of capabilities that are required within an evacuation model that is intended to examine the potential of a vessel to be evacuated.

2.5.2 MSC/Circ. 1238

In October 2007 at the 83rd session of the Maritime Safety Committee on the recommendations of the Fire Protection Subcommittee (FP46) accepted alterations to the MSC / Circ.1033. The modified MSC / Circ 1033 then became the MSC.1 / Circ 1238 documents (IMO, 2007). The newly formed regulatory document kept the same name as its predecessor with the exception that the word 'interim' was removed from the title. Therefore the title of the MSC.1 / Circ 1238 was 'Guidelines for Evacuation Analysis for New and Existing Passenger Ships'. The main change saw the shape of the response time distribution curve change. On the recommendations of two papers written and co-authored by the author of this PhD thesis (Deere et al, 2006) and (Galea et al, 2007) and discussed in detail in chapter 4, the response curve was changed to match a log normal distribution. This curve is more indicative of real life. The previous random uniform curve suggested that the same number of people would respond to an event during every time period which simply was not reasonable, whereas the proposed response curve suggested that more people would respond early on and as time progressed less people would respond. The suggested curve was obtained from trials carried out on board a passenger ferry (Galea et al, 2007) and as such was representative of a population on a marine vessel.

Another major change to the method of assessing a design's ability to evacuate is that the safety margin of 600 seconds (for primary evacuation scenarios) and 300 seconds (for secondary evacuation scenarios) were removed from the calculation of the final evacuation time, instead of adding a safety factor to the travel time, the travel time is multiplied by a 1.25 safety factor. Figure 2.5-1 then becomes Figure 2.5-2 with the implementation of the safety factor.

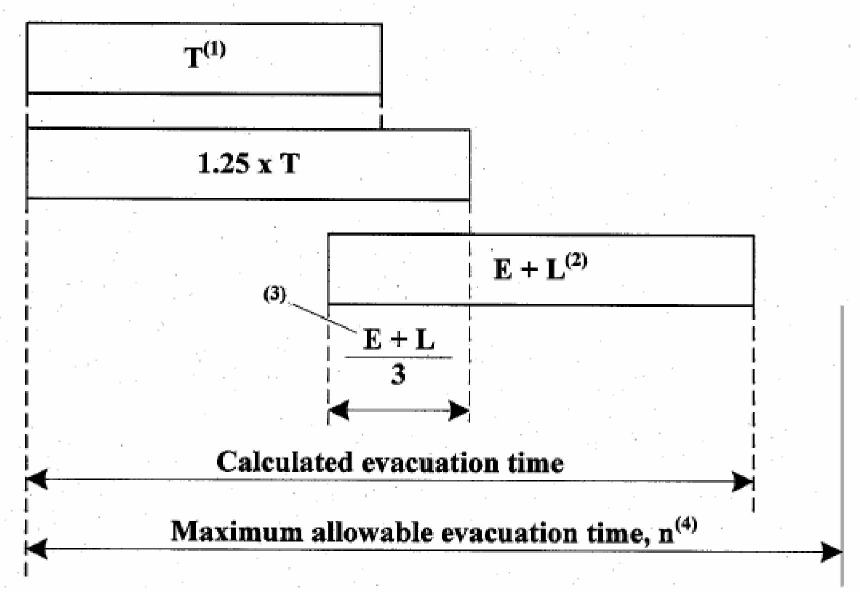


Figure 2.5-2 - Schematic of the overall evacuation calculation for the advanced analysis as specified in IMO MSC.1 Circ. 1238 (IMO, 2007).

2.5.2.1 Naval Ship Code

The second regulatory body referred to in this thesis is the Specialist Team on Naval Ship Safety and Classification. Recognising that there was no naval body equivalent to IMO and that naval ships are not embraced by the work of IMO, the NATO navies established a Specialist Team on Naval Ship Safety and Classification.

In addition to Navies, Classification Societies through the Naval Ship Classification Association (NSCA) have a standing invitation to attend the meetings of the Specialist Team as active participants. The Specialist Team is tasked with the development of a Naval Ship Code that will provide a cost-effective framework for a naval surface ship safety management system based on and benchmarked against IMO conventions and resolutions.

The Specialist Team has established a Goal Based Approach to the development of the '**Naval Ship Code**' (NATO, 2006) and is now developing each chapter in turn. The naval ship code covers the areas of general provisions, structure, buoyancy and stability, machinery installations, electrical installations, fire safety, escape evacuation and rescue, radio communications, safety of navigations and carriage of dangerous goods through ten separate chapters. However, the only chapter relevant to this work is Chapter 7, escape, evacuation and rescue. As such when the naval ship code is referenced, it is only Chapter 7 that is considered.

This chapter largely follows the philosophy of the IMO MSC/Circ 1238, the difference being that the Naval Ship Code is applied to naval vessels and as such require additional factors to be considered which are not usually present on civilian passenger vessels.

Chapter 7 is split in to twenty seven clearly definable sections with escape, evacuation and rescue being the three main categories. Escape is defined in the regulations as the '*movement of persons to a place of relative safety on board the vessel following an emergency*', which in terms of modelling means the movement of the crew to their assigned muster stations. Evacuation is defined in the regulations as the '*movement of persons to a place of relative safety away from the damaged vessel'*. In terms of modelling, this means the movement of the crew to the LSA's from the muster stations. Rescue is defined in the regulations as 'the survival and recovery of persons to a safe haven, which offers an equivalent or higher level of safety than that prior to the incident.

In this PhD thesis, the main aspect of the Naval Ship Code which is of concern is regulation 3 of Chapter 7. It is entitled '*Escape and Evacuation Analysis and Demonstration'*. This regulation deals with the modelling of a vessel's ability to evacuate.

This regulation assumes the design in question is undamaged and in normal seagoing conditions, with 0° heel and trim. All machinery and equipment are considered to be operating in normal sea going conditions and all survival craft should initially be in their stowed positions.

The regulations however do not specify the response times, travel speeds or the population demographic to be used during the evacuation analysis of a naval vessel. Therefore it is not known how quickly the naval personnel can move about the vessel. This is vital if an evacuation analysis is to be performed. However, the escape and evacuation analysis for compliance with the Naval Ship Code should follow the philosophy outlined in the IMO MSC Circ. 1033 with some modifications. This suggests that the data from the IMO MSC Circ

1033 can be used to bridge the gap between the Naval Ship Code and the evacuation analysis of a naval vessel.

The regulations state that the evacuation process should not exceed 30 minutes. The combined escape and evacuation process should not exceed 60 minutes for vessels with RO-RO spaces or less than three vertical fire zones; otherwise the process should not exceed 80 minutes. This analysis is to be carried out early in the design process so that any identified problems can be resolved through changing the structure and investigate possible improvements to the escape and evacuation process.

The escape and evacuation analysis should only be carried out once on the first of a class of vessel or where the escape and evacuation measures significantly differ. If the escape and evacuation process is considerably altered during its life then the naval administration may enforce the escape and evacuation analysis to be carried out again.

The escape and evacuation analysis has to satisfy the naval administration. They have the right to enforce more stringent / flexible performance requirements or to adjust the scenarios to be performed

The Naval Ship Code considers six scenarios to be analysed as part of the evacuation analysis of a naval vessel. This is to accommodate a naval ship's range of ship states and watertight integrity.

Case 1 is labelled as *normal night cruising*. During this scenario, the vessel design in question is consider to be at state 3 (cruise) whereby there is no imminent threat of attack without prior notice and as such most WT doors can assume to be opened. Since this scenario is set during the night, most of the ship's complement are considered to be in their cabins and asleep. There would generally only be one team on watch and they would be at their state 3 (cruise) locations. The exact location of the complement and the procedures employed for this scenario would very much depend on the nature of the vessel's operations. For the work carried out in this thesis, after the identification of an incident, the ship's complement would move to their emergency stations from where an NBCD (Nuclear Biological Chemical Defence) effort can be launched in order to tackle the incident. The incident would commonly come under the guise of a fire or flood. If the NBCD effort was then to fail and the severity of the incident over runs the vessel, the call to abandon ship maybe given. At which point all crew members would move to the muster stations where they would receive any vital life saving equipment such as life jackets or personal thermal protection suits. They would then disembark the vessel by any means possible, be that via a life craft, platform (ramp to land if the vessel is moored up in a harbour) or by jumping over the side into the sea.

Case 2a is entitled *normal day cruising*. This scenario is very similar to the normal night scenario, except for being set during the day. As such the vessel would still be at state 3 (cruise) with most WT doors assumed to be open. The main difference between the two scenarios is that generally there would be two teams on watch. As with the normal night cruising scenario, the exact location of the crew and the procedures employed for the scenario would vary depending on the nature of the vessel's operations. After the identification of an incident, the starting point for the scenario, the crew would move to their emergency stations where an NBCD effort would be commenced. If the NBCD efforts fail and the call is given to abandon ship, then the complement would move to the muster stations prior to disembarking.

Case 2b is entitled *action stations*. This scenario differs quite significantly to the previous two cases. With this scenario the vessel is considered to be in state 1 (action) whereby an attack is imminent without warning. In this ship state, all WT doors would be closed and the vessel would be at its highest state of preparedness and readiness to deal with any emergency that might occur. Therefore all crew would be on watch and at their state 1 location. If an incident is identified then the NBCD team would already be in place. Therefore this scenario starts once (and if) the NBCD effort fails. At which point the call to abandon ship is given and the complement move from their state 1 location to the muster stations where they will receive vital life saving equipment prior to disembarking. En route to the muster stations, the crew will have to encounter closed WT doors which will slow their progress towards the muster stations. As with the previous two cases, the exact location of the crew and the procedures employed will differ depending on the nature of the vessel's operations.

Cases 1, 2a and 2b are the primary evacuation scenarios, in line with the IMO MSC 1238. The Naval Ship Code then requires a variation of these scenarios to be considered as secondary evacuation scenarios. The Naval Ship Code provides two possible alternatives which could be used for the secondary evacuation scenario. These are the same as the secondary evacuation scenarios as defined in the IMO MSC 1238. The first alternative involves 50% of all the deck connections being unavailable in the main vertical fire zone. Where the main vertical fire zone is the zone identified as containing the person who produces the longest simulation time. The other alternative provided by the regulations involves 50% of the population from a neighbouring vertical fire zone being forced to move into the main vertical fire zone before proceeding to the muster stations.

Unlike the IMO MSC 1238, the Naval Ship Code is only interested in the worst case scenario. Therefore although 50 simulations are still required to be performed for each scenario, the output file selected to represent the design is the one with the highest simulation time. This is in contrast to the IMO MSC 1238 which selects the simulation file which when all the simulation output files are ranked into order, is the 95% file.

2.6 Summary

This chapter has presented a foundation with which to build the work of this PhD thesis upon.

The chapter has discussed issues with evacuation modelling tools and their validity as well as their strengths. The chapter suggested maritimeEXODUS as the best choice evacuation software tool to use during this PhD thesis, due to the availability of the source code and the level of support which can be provided. maritimeEXODUS has also been demonstrated as having the abilities to perform an evacuation analysis on a naval vessel.

The chapter discussed the guidelines governing the evacuation analysis of both passenger and naval vessels. It stated that the IMO guideline governing the evacuation of passenger vessels uses an unrealistic random uniform response time distribution, which does not mimic the real world.

Also discussed was the ship design software tools, of which PARAMARINE was selected as the tool of choice for this thesis. This was chosen as it is the preferred choice of ship configuration tool used by the UK MoD.

Decision making techniques have been discussed in this chapter. Many different techniques were discussed, detailing their strengths and weaknesses, however, they all had common attributes; criteria and weights. The weighted sum approach was selected as the technique of choice for its simplicity.

Chapter 3

A Model Review

3.1 Introduction

Within this chapter the models selected for use in this thesis will be scrutinised more closely. The features required for the work will be discussed as too will the limitations in the programs. This will help to identify some of the work required to fulfil the PhD and some of the restrictions.

The two programs selected for use within this thesis are maritimeEXODUS and PARAMARINE.

maritimeEXODUS is an evacuation model which models human movement and behaviour during the assembly and abandonment scenarios within a marine structure. maritimeEXODUS is part of a suite of software called EXODUS, which is a product of the Fire Safety Engineering Group (FSEG) based at the University Of Greenwich. The EXODUS software suite also features buildingEXODUS, airEXODUS and railEXODUS.

maritimeEXODUS uses a discretized mesh of nodes (representing floor spaces) within which agents (representing humans) move along in their quest to fulfil their tasks (i.e. evacuate). The model takes into account people–people, people–structure and people-fire interactions.

PARAMARINE is a naval architecture software tool used in the early stages of naval vessel design. PARAMARINE uses a ‘design building block’ approach (Pawlings, 2007) to create the design of a naval vessel. PARAMARINE has a number of subcomponents, one of which is called SURFCON. PARAMARINE is a product of Graphics Research Corporation LTD (GRC).

3.2 A review of the maritimeEXODUS model

3.2.1 Introduction to maritimeEXODUS

EXODUS is suite of software, developed by the Fire Safety Engineering Group of the University of Greenwich, designed to simulate the evacuation and circulation of large numbers of people within a variety of complex enclosures. maritimeEXODUS is the ship version of the EXODUS software. The software takes into consideration the interactions of people with other people, with the structure and with fire. The software comprises of six core interacting sub-models: the Passenger, Geometry, Movement, Behaviour, Toxicity and Hazard sub-models (see Figure 3.2-1). 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 these 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. This will build up a distribution of results, from which a representative simulation run can be selected. The key components of these sub-models will be briefly described in the following sections.

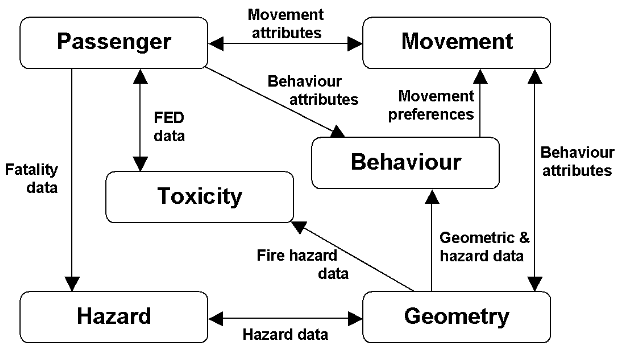


Figure 3.2-1 - EXODUS Sub-model Interaction (Galea et al, 2001)

3.2.2 The Geometry Sub-Model

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 compartments, obstacles, etc. and can involve multiple decks connected by staircases and ladders. The structural 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 0.5m intervals. Each node represents a region of space which could be occupied by a single passenger.

Within maritimeEXODUS there are several types of node used to represent different aspects of a geometry. These include freespace, door, mega, attractor and discharge nodes, chair, stair, redirection node and LSA (Life Saving Appliance).

Freespace node is the most common and basic of all the nodes. This node represents a floor space of 0.5 m^2 which one agent can occupy. With these dimensions, it is possible to achieve a population density of 4 persons / $metre^2$. This is calculated since there can be a maximum of 4 nodes in a square metre and since an agent can only occupy one node at a time then the maximum density is 4 persons / $metre^2$.

The door node, as the name suggests, represents a door in the structure. A door node can be open or shut and can be opened or closed by any agent. A door can also be active or inactive, meaning that during the scenario the status of the door can be changed. I.e. if the door is locked then it cannot be opened (without a key) and therefore the door can be closed and inactive to represent this.

There are several door types that exist in EXODUS, these are a standard door, a watertight (WT) door or a user defined door. The difference between types of door relate to the flow rate of that category of door i.e. how many people can pass through it during a set period of time (usually a second). For instance with a WT door, the agent has to step over a raised threshold which typically slows their progress through the component. There are additional delays associated with different types of doors which relate to the opening / closing of the door. WT doors are typically much heavier than a standard door and have clips which must be released before the door can open. A WT door requires two door nodes to be present in the model, since maritimeEXODUS needs to know which side of the door an individual is opening / closing it from. This can make quite a difference to the delay time imposed on the individual, since pushing the WT door away from the agent can take significantly less time than pulling the heavy door towards the agent.

The mega node represents the connectivity between decks of a vessel. This type of node is utilised to represent ladders and 60 degree stairs. The node allows a hatch to be added to the component, this acts as a door at the top of the ladder / 60 degree stairs. maritimeEXODUS allows the width of the stairs to be specified since in some instances two or more people may be able to use the stairs in counter flow. The mega node can be represented at any angle to coincide with the angle of the component in the design. This can make a difference, firstly with the 3D representation of the component within vrEXODUS (the EXODUS utility tool for representing simulation runs in 3D virtual reality), and secondly if the simulated scenario has a heel and trim other than 0 degrees. If the scenario includes heel and trim then the individual's ability to traverse the components can be severely affected i.e. the effect of heel and trim can throw the agent from side to side, as well as speed them up or slow them down.

Another type of node is the external exit. This represents the LSA (Life Saving Appliance). These represent a means for how the agents get out of the structure and can take the form of life boats, life rafts, chutes or TIRR (Totally Inflatable Rescue Raft). When an agent arrives at this node, they experience a delay which represents them entering the LSA and where appropriate moving about the LSA. After which time, they are considered to have evacuated the structure, their parameters (such as personal evacuation time and amount of congestion experienced) are recorded and are removed from the simulation.

In relation to creating the mesh of nodes within the maritimeEXODUS geometry, there is a tool labelled 'node flood' which will firstly place a freespace node wherever the user clicks in the geometry, and then it will place freespace nodes around that node. It will then place freespace nodes around the second node created and then around the third node created and so on in a circular motion. The node flood operation will continue to create nodes until it has filled the geometry. The node flood will continue to spread out in all directions until it finds a boundary line (created from a DXF file (see next section) or line created within maritimeEXODUS). The limitation with this feature is that if there are no boundary lines or if there is a hole in the lines then maritimeEXODUS will continue to insert nodes indefinitely.

3.2.3 The Passenger sub-model

The PASSENGER sub-model, models each individual person in the geometry as a separate agent which can interact with other agents, the structure and with smoke / fire. The agents are defined by a range of attributes such as age, height, weight, travel speed, response time and patience.

3.2.4 The Behaviour sub-model

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 in maritimeEXODUS' sister tool buildingEXODUS through the use of a "gene" concept, where group members are identified through sharing a social "gene". Although this capability does exist in maritimeEXODUS, it is very limited in its functionality and under developed. At the start of this PhD thesis, the group behaviour involved making faster moving agents stop and wait for slower agents to catch up.

Another important aspect of human behaviour is the manner in which passengers react to the heel and trim motion of a ship. 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 (Caldeira-Saraiva et al, 2004). In addition, data specific to the interaction between naval personnel and various types of equipment found on naval vessels such as; watertight doors, vertical ladders, hatches and 60 degree stairs have also been collected and incorporated within maritimeEXODUS (Boxall et al, 2005).

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 operational conditions. Prior to the work carried out in this project, the tasks which could be performed by a crew member were limited. The first of these is the ‘delay’ task. This task enforced a time delay on an agent effectively restricting them to the node they occupied and represented the individual carrying out a task, for example changing clothing, cooking food, working at a desk etc. This simple task had no built-in intelligence and as such would not be sufficient in a more complex scenario. The main limitation with the ‘delay’ task is that it is associated with a node (a specific location within a space). In some designs, especially in the early stages of a design cycle,, it may not be known exactly where an agent has to go and therefore would be advantageous to assign a delay to a compartment, rather than a node. In the early stage of the design cycle, it may be necessary to move compartments around a design in order to satisfy requirements of the design, such as stability analysis. If this is the case, having the ‘delay‘ task assigned to a compartment would mean the model could update itself automatically (i.e. the task would follow the compartment around the vessel) whereas with the task assigned to a specific location the user would have to change the location of the task when they move the compartments around the design.

A larger problem with carrying out this task on a specific node is the fact that the individual has to actually stand on the node in order to carry out the task. As a result if there is someone else on that node then the individual has to wait for them to move off before they can stand on it and carry out their task. This can cause the simulation to be artificially longer than it should be. In more complex scenarios there may be a need for a number of people to carry out the same task at a certain location such as man a gun or operate machinery. In these cases only one person would be able to stand on the specified node but everyone assigned the task would need to carry out their tasks at the same time.

Other tasks which were implemented in maritimeEXODUS prior to this work included ‘muster’, ‘evacuate’, ‘wait’ and ‘collect vest‘. Agents could be given the command to ‘muster’, whereby the individual would move to the specified muster station and wait there (within a defined muster region) until a scenario completion condition is met. If an individual was not given any itinerary tasks by the user then they would, by default, be given the command 'evacuate' whereby they would move towards their nearest exit.

maritimeEXODUS has a setting which allows the simulation to end once every individual has arrived at the muster stations, this flag is called 'terminate when mustered'. This is a useful setting since frequently, for regulatory purposes, it is only necessary to model the evacuation of a vessel up to the point where the entire population have reached the muster stations. The IMO regulations (IMO, 2002) provide a default value for the movement of passengers from the muster stations to the LSA and the embarkation onto and launching of the LSAs.

3.2.5 The Hazard Sub-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 (Peacock et al, 1993) fire zone model and the CFD fire field model SMARTFIRE (Ewer et al, 2010).

3.2.6 The Toxicity Sub-Model

The TOXICITY sub-model determines the effects on an agent 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 agent. To determine the effect of the fire hazards on occupants, EXODUS uses a Fractional Effective Dose (FED) toxicity model (Purser 1996). This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, irritant (e.g. HCl) and narcotic fire gases (e.g. CO) 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.

3.2.7 Validation of the model

Key to using any simulation software tools is having confidence in the numbers being produced by the model. Evacuation modelling is no different. There have been numerous papers written about the validation of the maritimeEXODUS software tool (Gwynne et al 2003a, 2003b) including work carried out to validate the software for use in naval vessels (Boxall et al, 2005). The software has been validated against one full scale trial during the FIRE EXIT project (EU FP5, 2002) which also included numerous small scale component testing (Caldeira-Saraiva et al, 2004). These component testings included gathering information about the speed and behaviour of passengers using chutes, slides, platforms and boarding life rafts and life boats. There are currently (at time of publishing) more full scale trials being carried out as part of the EU funded project SAFEGUARD (EU FP7, 2009, Galea et al, 2010a, 2010b). This level of validation is considered satisfactory to represent an evacuation through modelling with confidence in the results.

3.2.8 A review of maritimeEXODUS input files

There are three input files which maritimeEXODUS uses to load in the geometry; these are the DXF, MTA and EXO files. The DXF file is an autoCAD drawing data file which describes the structure of a design. It is primarily an ASCII based file, but can also be a binary file, which describes the lines and text to be drawn in the design. The lines are described by providing the X & Y locations of the start and end of each line. When maritimeEXODUS uses a DXF file to import a geometry, a grid of nodes needs to be created inside the lines defined by the DXF file. This grid of nodes as explained earlier is required to simulate people moving through the structure. The grid of nodes can be inserted using a feature in maritimeEXODUS called ‘node flood’. This operation allows the user to click anywhere on the screen and a node will be placed there. maritimeEXODUS will then fill out in all directions from that node, spanning the space encompassed by the lines created by the DXF file. There are functions within maritimeEXODUS which allows the user to modify the lines imported from the DXF file. The user is able to insert a new line, delete a line or resize / relocate a line. The restriction with this method of importing a geometry is that every time the DXF files are loaded in, every space has to be filled with nodes. This process can be a very time consuming and tedious task. As such it would not be recommended to load a geometry from a DXF file every time. Instead, the DXF file can be read in and filled with nodes and then saved as an EXO file.

The EXO file is a binary file written specifically for the EXODUS suite of software tools. It contains information about every node and arc in the geometry. It also contains information about the population. In essence everything required to complete a simulation is stored within the EXO file. However, the lines defined by the DXF files are not stored in the EXO file. Therefore, it is common for an EGX file to be produced along with the EXO which will contain the boundary line definitions. A problem with the EXO file format is that it is not compatible with other versions of EXODUS or even other versions of maritimeEXODUS. This is due in part to each version of maritimeEXODUS having different features, all of which may store different information in the EXO file and as such each EXO file is unique to each version of maritimeEXODUS.

There is also a third method of loading a geometry into maritimeEXODUS which acts as a half-way house between the DXF files, which only contain line information, and the EXO file, which contains information about every node, arc and person. This intermediate file is the MTA file format. This is an ASCII based file which is in an easily human readable format and can be transported between platforms. This file format can contain information about nodes, arcs and people as well as having a link to the DXF files for the line definition. Typically the MTA file would only be used for small geometries where the user would like to edit the geometry’s details / characteristics using a text editor. This ability to build / modify a geometry using a text editor allows external software to create a geometry which maritimeEXODUS can read in and use. However, in most cases it is advised that a geometry is saved as an EXO file.

Below is an excerpt from an example MTA file showing a node and an arc.

```
Node
Label:1
Title:Compartment_1
WinID:1
PositionX:1617
PositionY:775
Potential:103.476
Nodetype:FreeSpace
Obstacle:0
adjacentNodes: 2 0.7071 0
```

From the above code excerpt of the node, it can be seen that the section starts with the word 'node' which tells EXODUS that it is going to start reading in information about a node and will have to create a new instance of a node. The 'Label' tag contains a number which is the unique identifier for that node and every node has to have a 'Label' tag.

The next tag in the code excerpt is the 'Title' tag. This is an optional tag which if it is not present then maritimeEXODUS will leave empty. Quite often it is useful to provide a title for the nodes; this title appears when the node is selected and its properties displayed in the maritimeEXODUS user interface.

The 'WinID' tag tells maritimeEXODUS which window to place the node into. Each window in EXODUS represents a different floor within the geometry, although sometimes more than one floor can be modelled in the same window. The next two tags position the node within its window, 'PositionX' and 'PositionY'. They describe the X and Y location within the EXODUS window and use EXODUS units, whereby 30 EXODUS units represent one metre in the geometry.

The 'Potential' tag, which is also optional in the MTA file and is used in defining the attractiveness of door, attractor and discharge nodes. The potential value of a node determines how attractive that node is to the user, as mentioned earlier, the lower this value, the higher the chance an individual will move towards it. This is unimportant for freespace nodes since the potential value is calculated by EXODUS at the start of each simulation and as such the value in the MTA file will be replaced. However, the potential value from the MTA file is kept for the door, attractor and discharge nodes.

The 'NodeType' tag is required for every node in the MTA file since it identifies what information is required from the MTA file in order for EXODUS to use it. A freespace node only requires the X, Y and window values to be identified so that it can be positioned within the geometry. A door node requires further information relating to the type of door (standard / WT), the direction that it opens, whether it is initially open or closed and whether it is active or not i.e. during the scenario can it be opened / closed. Similarly, the same information is required by a mega node (i.e. a ladder or 60 degree stairs). However a mega node can have additional parameters such as having a hatch. The MTA file can also define the attributes for the door and mega nodes such as set the flow rate of people passing through the node or the range of times for operating the node. Without these values, EXODUS will set the default values.

The 'Obstacle' tag is used by EXODUS to slow people down as they travel across the node. This value can be used to represent the node being on a slope or the presence of debris, over which the individual would have to climb. The final tag in the code excerpt above, 'adjacentNodes', denotes the nodes to which this one is connected. The tag is followed by three numbers; the first is the node ID of the adjoining node, the second number relates to the distance between the two nodes (this is measured in metres) and the third number is a 0 and acts as a separator between sets of adjacent nodes. Using this information, it can be deduced from the above code excerpt that there is a freespace node called 'Compartment_1' with node ID 1. This node would be located in the second window (denoted by the value 1, the first window would have a winID value of 0) and would be positioned 53.9 metres to the right and 25.8 metres below the top left hand corner of the window. From the code excerpt it can also be deduced that the node is connected to another node with ID 2, which is 0.7071 meters away.

3.2.9 A review of maritimeEXODUS output files

maritimeEXODUS has the ability to produce many different possible output values as can be seen in Figure 3.2-2. The main attributes to output, as regards to the individuals, are their personal simulation times (PST – also known as personal evacuation time-PET), cumulative wait times (CWT), distance travelled, response times, ages, weights and heights. Each individual's PET, CWT and response time is measured in seconds and is accurate to 1/12th of a second. The distance each individual travels is measured in metres.

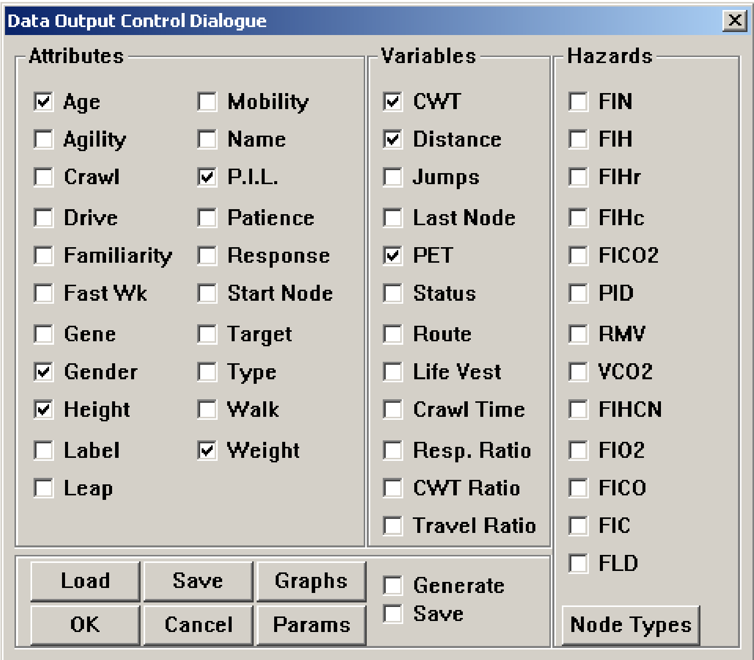


Figure 3.2-2 - maritimeEXODUS output selection screen

In respect to the overall simulation, maritimeEXODUS can produce the averages for all of the above outputs in addition to the final simulation time and number of severe congestion regions (i.e. those regions where congestion persists at the regulatory specified 4 persons/metre^2 for longer than 10% of the final simulation time). The WT door usage is also produced for each door, illustrating the average flow rate, number of people who pass through it, the time of the first usage and the last usage as well as the overall flow time i.e. how long the door was open for. The same information is also produced for ladders and census regions. Census regions allow the user to place a line in the geometry and EXODUS will then output information regarding how many individuals crossed that line and when.

All of the above outputs are contained within a SIM file which is ASCII based and human readable. The SIM file also contains information about the setup of the simulation including what version of the software was used, the number of individuals modelled and the date and time of the simulation run. It also contains information about the parameters used to set up the scenario including the radius of the catchment area for muster stations and range of times for donning life jackets. The SIM file contains information about specific behaviours / switches used within the simulation such as allowing individuals to crawl, jump over seats, avoid congested regions and maintain itinerary (even if they encounter problems such as smoke). Other behaviours which can be applied to the entire population include giving everyone a specific response time, making the population impatient or making the population pack together on stairs (i.e. leaving less space between occupants).

The VRS file is created by maritimeEXODUS for use in the virtual reality 3D visualisation software vrEXODUS. The file is an ASCII based file containing purely numbers. These numbers represent the initial X & Y location of each individual and then the time and X & Y location of every point at which each individual either changes direction or changes speed.

3.3 A review of the PARAMARINE Software

3.3.1 The Naval Architecture Software

PARAMARINE is a naval architecture software tool that is used in the development of marine vessel designs. PARAMARINE uses a building block approach (Andrews, 2006) to create the structure of a naval vessel in the early stages of design.

As mentioned before in Chapter 2, Graphics Research Corporation (GRC) created the software package PARAMARINE to aid in the designing of naval vessels. They were approached by UCL's DRC team with the proposals for a 'Lego©' brick style design approach to creating naval surface vessels at the early stages of the design cycle. GRC duly accepted the proposal and created SURFCON (Andrews & Pawling, 2003a). This tool was incorporated into PARAMARINE and made use of the ‘Design Building Block’ technique (Pawling, 2007) to design naval vessels.

The basis of the Functional Specification for SURFCON as a module within the PARAMARINE (Bole & Forest, 2005) ship design software was spelt out in the SURFCON descriptive paper (Andrews & Pawling, 2003a) and this then provides the balanced design description on which personnel simulation can be undertaken.

The design building block approach to creating a new vessel involves creating cuboids which are then manipulated (in shape and size). These cuboids are then placed together, much like a LEGO© set to form the basis of the vessel design. A variety of different analytical assessments are then performed on the design to discover its power, strength and sea keeping, to name a few characteristics of the vessel design. Once the design passes these assessments, they will be further developed by adding more detail, after which the design is built. The aim of this work was therefore to add human factors assessment as one of the analytical assessments performed on the design by PARAMARINE at the early stage of the design cycle.

A feature of the Design Building Block approach is that of the “Functional” breakdown, which breaks the ship description into “Float”, “Move”, “Fight” and “Infrastructure”. Each of these types of block have their own features and helps the designer achieve a good balance in the design. At a latter stage when more detail is to be added, it will be easier to see where objects should be placed, depending on the type of space they should go in. For example, an engine would go in a ‘Move’ type of building block.

Another feature of the building block approach is the use of the term ‘Master Building Block’ to denote how the overall aggregated attributes of the building blocks were brought together to provide the numerical description of the resultant ship design. Typical information in the Master Building Block is as follows:

- Overall requirements: Ship speed, seakeeping, stability
- Ship characteristics: weight, space, centroid
- Overall margins: weight, space, location for growth and enhancement

The incorporation of SURFCON within PARAMARINE gives access to a wide range of analytical tools to check the naval architectural viability of the design. These include:

- Stability calculations against several stability criteria;
- Powering analysis for a range of assessments using well established methods and methodical series;
- Seakeeping analysis for typical wave spectra;
- Longitudinal strength analysis;
- Ship vulnerability;
- Dynamic analysis;
- Manoeuvring.

The features incorporated in the SURFCON-PARAMARINE system enable the designer to conduct preliminary ship design studies using the Design Building Block approach The general procedure adopted in producing a new ship design study, as specified by Pawling (20007), is as follows:

1. An outline requirement is identified and a design style proposed;
2. A series of Design Building Blocks are defined or selected, containing geometric and technical attributes;
3. Design Building Blocks are located as required within the configurational space;
4. Overall weight and space balance and performance (e.g. stability, powering) of the design are assessed;
5. The configuration is then manipulated until the designer is satisfied;
6. Decomposition of the building blocks to greater levels of detail is undertaken as required, and balance / performance maintained at the required level.

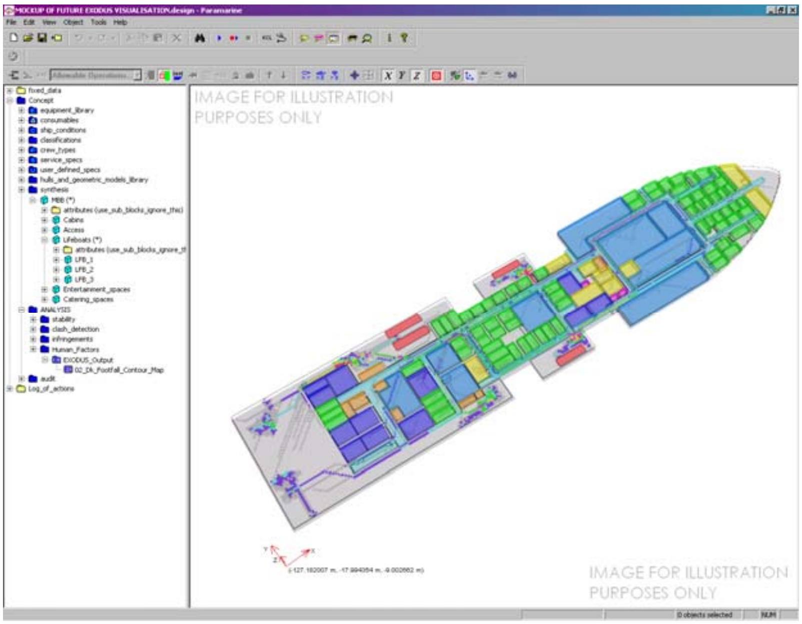


Figure 3.3-1 - Screenshot of PARAMARINE

A screenshot of the PARAMARINE system in use is shown in Figure 3.3-1. The user inserts objects in the "tree pane" on the left of the screen, which shows a logical hierarchal description of the design, whilst the graphical visualisation of the design blocks are shown in the "graphical pane" on the right of the screen. PARAMARINE does not just show a graphical layout of the design, it also contains objects for the assessment of the performance of the design across a range of design capabilities, including resistance, propulsion, stability and manoeuvring. A typical numerical analysis is shown in the top right hand box in Figure 3.3-2.

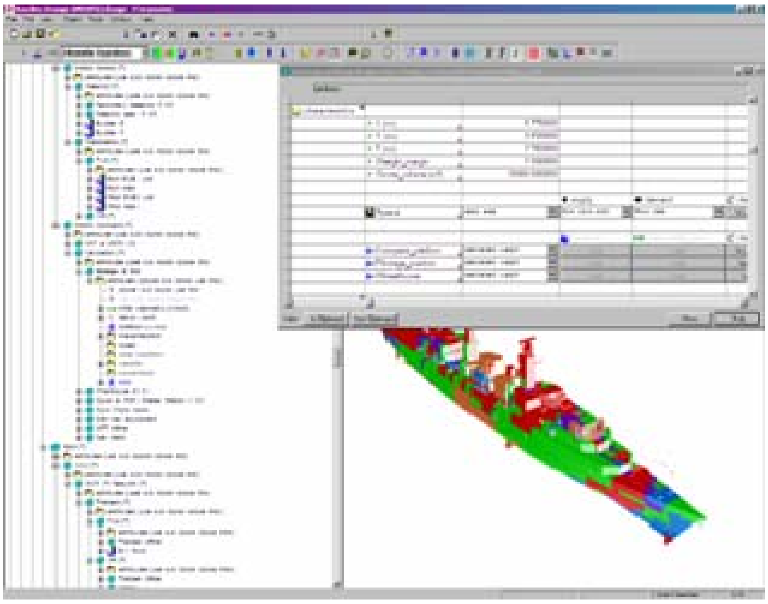


Figure 3.3-2 - Multiple views of a Design Building Block representation of a frigate using SURFCON.

The fundamental basis of SURFCON and the Design Building Block approach is the Design Building Block object. This is a placeholder or folder in the design space, which contains all descriptive information relevant to a particular function. For example, Figure 3.3-3 shows the hierarchical view of a block representing a mess deck for Junior Rates and the corresponding graphical view.

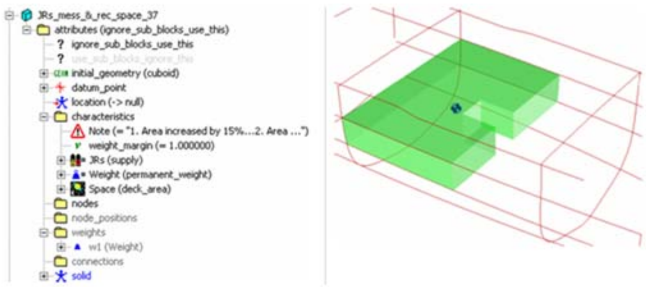


Figure 3.3-3 - Design Building Block hierarchical and graphical views of a mess deck.

3.3.2 A review of PARAMARINE input and output files

PARAMARINE has two output files; KCL and DXF. The DXF file has been discussed earlier in this chapter and contains a list of lines, some of which make polygons. The KCL (Kernal Command Language) is a macro based language which builds up the structure of the saved design. The KCL file will describe the characteristics of a placeholder for which the design is built within. After this the file will describe the characteristics of the first building block of the design. The characteristics / attributes of the building block will include the X, Y and Z coordinates of the centre of the block, along with its width, length and height. Once this building block is described, the next building block will be added, but this time the X, Y and Z coordinates of the centre of the block will be described in relation to the first building block. For example, X coordinate for centre of block 2 = X coordinate for centre of block 1 + ½ the width of block 1 + ½ the width of block 2. This is a very simplistic example to illustrate how the file format builds up the structure of the design. Even in very simple geometries, this file can be rather complex in structure. In a geometry consisting of just 10 building blocks, to find the coordinates of the 10^{th} block, one would have to ascertain the coordinates of the other 9 building blocks. In addition to calculating the centre X, Y and Z coordinates of a building block, the width, length and height of each building block can also be derived by an equation consisting of the X, Y and Z coordinates of the centre of other building blocks. In the case of a real naval frigate for example, even in the very early stages of design, there could be well over 100 building blocks. This helps to understand the complexity of the output / input file of PARAMARINE. In addition to the X, Y and Z coordinates and the width, length and height of the building bocks, there are other attributes which are saved in the KCL file, such as connectivity between blocks and type of space represented by the block (for example “Float”, “Move”, “Fight” and “Infrastructure”.).

3.4 Summary of Review

This chapter has provided an extensive review of both the ship evacuation tool, maritimeEXODUS, and the naval architecture software tool, PARAMARINE. This chapter should have provided the user sufficient understanding of the strengths and weakness of both software tools. The weaknesses described in this chapter will be addressed later in this thesis, Chapter 7 and Chapter 10.

This chapter focused particularly on maritimeEXODUS, since the majority of the PhD thesis involves this tool. This chapter has shown the complexity of the evacuation model.

Chapter 4

Proposal of a Realistic Passenger Response Time Distribution for use in Evacuation Analysis of Passenger Vessels

4.1 Introduction

The International Maritime Organization (IMO) has adopted the use of computer simulation to assist in the assessment of the assembly time for passenger ships. The guidelines specify a number of key parameters to be used in the evacuation analysis, for example travel speeds of passengers along flat terrain, up and down stairs, passenger response times, and a distribution of passenger age and gender.

These parameters are key to the accuracy of the model predictions and hence to their usability in evaluating ship designs for evacuation. A Correspondence Group (CG) was created by the IMO, to propose evacuation guidelines and define a number of these parameters. However, due to a lack of 'ship relevant' data, some parameters were set using expert opinion rather than empirical data.

One of the key parameters used in the evaluation of ship design is the passenger response time distribution. As this chapter will demonstrate, the response time distribution can have a profound impact on the results of the simulation and can help highlight or disguise problems within a design. Not only were the actual time values for the response time arbitrarily set by the CG, the form of the distribution was defined to be a uniform random distribution. This approach ignored the data generated in the building industry which had gathered a collection of response times for various types of structures under various conditions, and had also demonstrated that the response time distribution was of a log normal form (Purser, 1998).

The first part of this chapter demonstrates potentially significant difference in egress performance when using an arbitrary 'unrealistic' uniform random distribution (as is assumed in the IMO regulations (IMO, 2002)) as apposed to a log normal distribution used in the building industry. This work was presented in the paper published by Deere et al (2006).

The second part of the chapter demonstrates, using data obtained from ship trials, that the form of the response time distribution is in fact log normal and proposes a set of response time distributions for use in the IMO guidelines. This work was presented in the paper by Galea et al (2007a) and was co-authored by the author of this thesis.

4.2 The Response Time

In recognition of the development of sophisticated evacuation simulation techniques (Sharp, et al 2003, 2004) the IMO - through a Correspondence Group (CG) of the Fire Prevention Sub-Committee FP46 - developed and adopted a set of Interim Guidelines that set out the standards on how evacuation simulation should be undertaken for certification applications (IMO, 2002). These guidelines define two benchmark scenarios (along with two variants) that must be simulated as part of the certification process. These are defined as the "night" and "day" scenarios. While subjectively defined, they establish a baseline performance for the vessel and crew allowing comparison with both the set target time and alternative designs. The scenarios only address the mustering or assembly phase of the evacuation and involve conditions of dead calm (i.e. zero list, heel and roll) and do not explicitly take into consideration the impact of fire. To allow for these omissions a safety factor is added to the predicted assembly time.

In particular, the resulting analysis should allow identification of areas of congestion that develop during an evacuation and demonstrate that escape arrangements are sufficiently flexible to account for the loss of particular parts of the evacuation routes. The difference between the "night" and "day" scenarios consists of the starting locations of passengers and the simulated passenger response time distribution exhibited by the passengers. During an emergency, passengers will not necessarily respond immediately to the call to assemble. The time between the instruction being issued and the passenger moving off to the assembly station – which can take several minutes - is known as the response time. Even when an individual decides to react to the call to evacuate, their situation often prohibits or delays immediate reaction. Individuals may decide to perform a number of tasks prior to actually evacuating, such as collecting belongings, reuniting with family members, completing a financial transaction, finishing a meal etc. Thus, not everyone will react at the same time, some will react sooner and some later than others. As each passenger will have a unique response time it is necessary to define a response time distribution to represent this inherent variation.

If the response time distribution is set to zero or near zero, then all the passengers will react (almost) immediately and so unrealistic levels of congestion may develop. If the response time distribution is too wide then there will be a considerable gap between the starting times of passengers and so potential choke points in the geometry will not be detected. Furthermore, as the process is inherently non-linear, it is not possible to simply set a zero response time distribution and then apply a scaling factor to produce an estimation of the total evacuation time. Thus, understanding and quantifying the response time is a key component of the entire evacuation process.

This chapter will present response time data collected from assembly trials conducted at sea on a real passenger vessel using actual passengers (EU FP5, 2002). These data collections will then be compared against the existing IMO specified response time distributions. Then finally an appropriate response time distribution will be recommended for the use of simulating and assessing human factors.

The response time is a key component of the entire evacuation process and so if evacuation at sea is to be reliably simulated (Sharp, 2003a) using models such as maritimeEXODUS (Galea, et al 2000, 2004), it is essential that the passenger response time is fully understood and quantified (IMO, 2002). The concept of occupant response time is not unique to maritime evacuation applications but is a standard feature of all evacuation situations (Deere, et al 2006). In building applications, occupant response time can in fact be longer than the actual evacuation travel time. As a result considerable effort has been expended in the building industry in attempts to quantify and understand occupant response time for particular situations (Deere, et al 2006).

Unfortunately, little or no data relating to passenger response time in maritime environments exists (Sharp, 2003b). Nevertheless, the passenger response time distribution in MSC 1033 (IMO, 2002) – the IMO document which sets the guidelines for ship based computer evacuation analysis - has been set to a distribution of 210 – 390 seconds with a mean of 300 seconds for "day" case scenarios and 420 – 780 seconds with a mean of 600 seconds for "night" case scenarios. The shape of these distributions is described by a uniform random probability function.

The response time distributions adopted in MSC 1033 (IMO, 2002) involve two key assumptions. The first is that the response time distribution takes the form of a uniform random distribution. Evidence from studies in the building industry suggests that this is not the case with response time distributions, typically following a positively skewed distribution, with large numbers of people displaying relatively short response times and fewer people displaying progressively longer response times. In appearance, these response time distributions resemble log-normal distributions (Deere, et al 2006). The second key assumption concerns the actual range of response times. This range is not based on real measurements but consists of values derived by committee.

4.3 Demonstration of impact of response time distributions on passenger ship assembly times.

4.3.1 Introduction

To demonstrate the impact that passenger response time has on assembly time, assembly time simulations are performed on a hypothetical passenger vessel using a range of response time distributions. The IMO 'day case' scenario is used as the basis for comparison. Comparative scenarios are then run using different response time distributions consisting of:

1) Scenario 1 – IMO response time distribution.
2) Scenario 2 – As scenario 1 but with a modified retail response time distribution
3) Scenario 3 – As scenario1 but with original retail response time distribution
4) Scenario 4 – As scenario 1 but with modified library response time distribution

4.3.2 The Response Time Distributions

The primary purpose of this investigation is to examine the impact that the response time distribution has on the overall evacuation performance. Thus, several scenarios are considered which are identical with the exception of the response time distribution imposed on the passenger population. The base scenario investigated in this chapter is the IMO 'day' scenario. In the IMO day scenario, all passengers are initially distributed throughout the service areas of the vessel; i.e. around the bars, dining areas etc and passengers are not located in their cabins.

In the day scenarios the population is divided amongst the three vertical fire zones as shown in Table 4.3-1. The sections of the vessel with no passengers are typically cabin sections (and hence not occupied in the day scenario) or parts of the vessel that passengers cannot occupy (i.e. crew only). At the start of the simulation, once the passengers assigned response time has expired they move off to the assembly deck (Deck 8) via the shortest route.

Table 4.3-1 – Distribution of passengers for Day Scenarios

Deck	**Fire Zone 1**	**Fire Zone 2**	**Fire Zone 3**	**Total**
6	-	75	175	250
7	-	50	200	250
8	120	24	130	274
9	91	210	-	301
10	-	225	-	225
Total	211	584	505	1300

Several different response time distributions were investigated. The first was the standard IMO specified response time distribution. This consists of a uniform random distribution of response times with a lower limit of 210 sec and an upper limit of 390 seconds. This response time distribution is referred to as Response Time Distribution 1 or RTD1.

To demonstrate the consequence of using more realistic non-uniform distributions several other response time curves derived from the building industry were also implemented. The first curve is derived from data obtained from an actual fire situation in a retail store containing a food hall and clothing section (Purser, 1998). The data was derived from a population of approximately 90 people using video footage recorded using the store's CCTV system (see Figure 4.3-1). Once the fire was detected, the fire alarms were sounded and store staff responded very rapidly and ushered shoppers to the exits. The people in the store were involved in a variety of activities including dining, examining shop merchandise, in the process of purchasing goods, various social interactions, etc.

While these activities are fairly typical of the types of activities that may take place on passenger vessels, it must be remembered that the data is derived from a land based application where the evacuation procedures employed by staff and the expectations (and hence reactions) of the target population may be very different to that of sea based applications. Hence while the actual response times may very well be different for sea based applications, it is possible (and indeed very likely) that the shape of the distribution will be similar for land and sea based applications. The response time distribution derived from this data source has a log-normal appearance (see Figure 4.3-1), typical of land based derived response time distributions. Response times varied from 4 seconds to 110 seconds. As can be seen most people respond within a minute of the alarm. This response time distribution is referred to as RTD2.

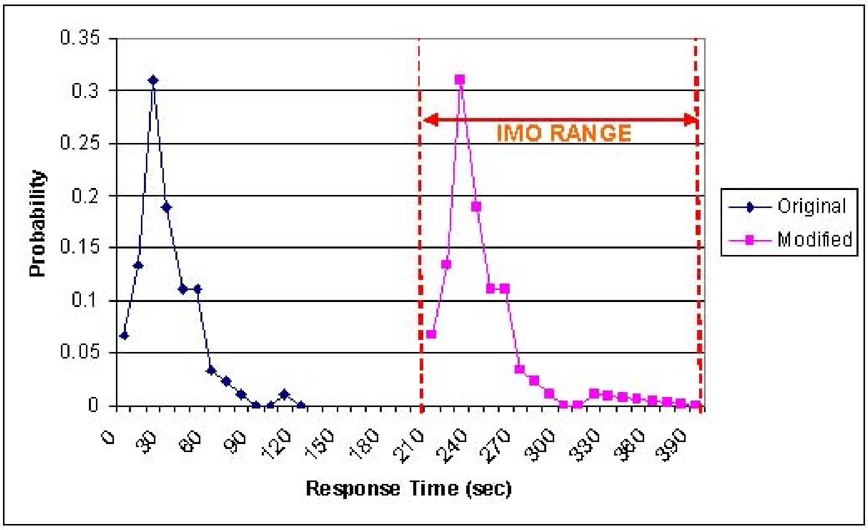


Figure 4.3-1 – Response time distribution derived from land based retail application (Purser, 1998) transformed to fit the IMO response time range.

The range of response times in RTD2 is very different to that found in the IMO day case distribution. To gauge the impact of the shape of the distribution on the evacuation performance the land base response time distribution was modified to fit the response time range specified in the IMO day case. This involved translating the land curve by 210 seconds. Effectively, 210 seconds was added to all of the times recorded in the land curve and an extra point was then appended to the curve in order to make the curve fit exactly the same range as the IMO response distribution. This point extended the curve from 320 seconds to 390 seconds. This transformation is illustrated in Figure 4.3-1 and the response time distribution is referred to as RTD3.

As can be seen from Figure 4.3-1, the modified land based curve (RTD3) is positively skewed. This means that the majority of people move during the first 50% of the range of response values according to RTD3, whereas an even number of people move at the same time throughout the IMO curve (RTD1).

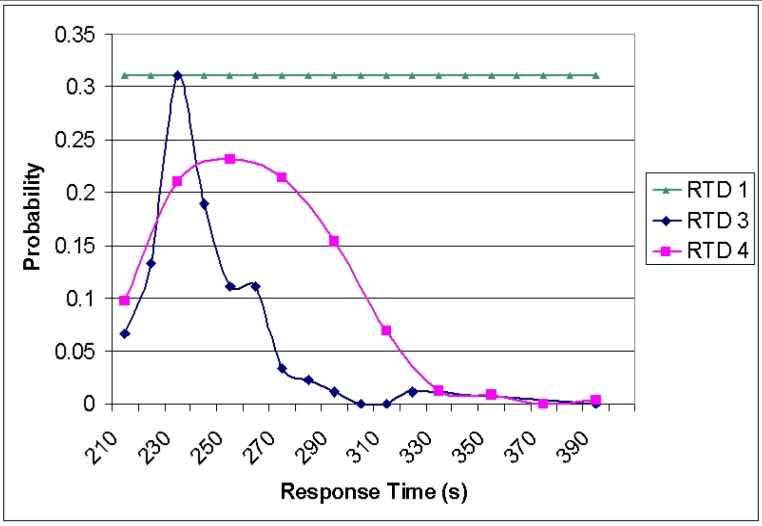


Figure 4.3-2 -The three response time distributions, IMO (RTD1), modified retail (RTD3) and modified library (RTD4)

An additional response time distribution derived from land based data was also examined. This was derived from an evacuation drill undertaken in a multi-storey university library consisting of a large number of rooms of various sizes and function (Gywnne, et al 2003). The rooms were used for a variety of applications including private study, group work, computer based laboratories, discussion rooms, etc. The evacuation involving 247 people was initiated by an alarm. For the building's size and complexity there were only a relatively small number of staff and so most of the occupant responses were initiated not by staff but by the individuals themselves and their interactions with other building users. As in the previous case, individual response times were derived from analysis of CCTV footage. The response times derived from this evacuation ranged from 8 seconds to 200 seconds. As with the previous case, the response time distribution was transformed to fit the IMO response time range. This involved translating the curve by 210 seconds without changing the shape of the distribution. Effectively, 210 seconds was added to all of the times recorded in the land curve. The final curve is displayed in Figure 4.3-2 and the response time distribution is referred to as RTD4.

The three basic response time distributions are depicted in Figure 4.3-2 for comparison purposes. It can be seen from Figure 4.3-2 that RTD4 is less positively skewed than RTD3. After 250 seconds, using the RTD4 distribution we find 53% of the population have responded, using the RTD3 curve 92% of the population have responded and using the IMO distribution (RTD1) only 38% of the population have responded.

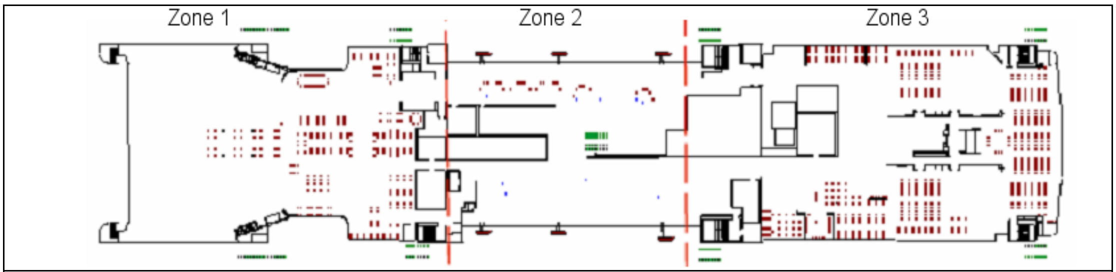
Using the above information, the scenarios examined in this chapter can now be defined as follows:

- Scenario 1: Base Case, IMO Day Case as described in Section 4.3.2 of this chapter, population distribution as described in Table 4.3-1 and IMO specified response time distribution i.e. RTD1.
- Scenario 2: As Scenario 1 but with RTD3 i.e. modified retail response time distribution.
- Scenario 3: As Scenario 1 but with RTD2 i.e. original retail response time distribution.
- Scenario 4: As Scenario 1 but with RTD4 i.e. modified library response time distribution.

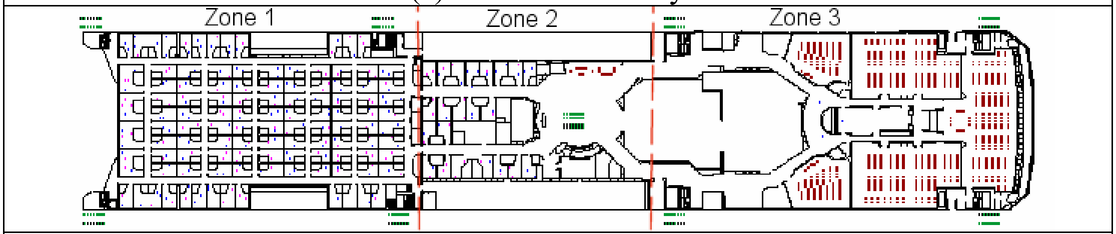
4.3.3 The vessel layout

A large hypothetical passenger ship consisting of 10 decks divided into three vertical fire zones has been defined within maritimeEXODUS using CAD drawings. Only the top five decks (Decks 6 -10) are occupied by passengers and therefore only these decks were modelled within maritimeEXODUS.

The lowest passenger deck is Deck 6 and Deck 10 is the highest. The assembly areas are located on Deck 8 and there are two for each fire zone. The assembly deck also contains six LSA's (Life Saving Appliance such as life boats), each having a capacity of 400 passengers. Each deck of the first fire zone is serviced by four staircases located within the far corner of the fire zone connecting each deck. The second fire zone possesses a single staircase centrally located within the fire zone. Fire zone 3 has a similar layout to fire zone 1. All the stairs are similar in construction and are narrow, capable of allowing only a single lane of passengers to use the stairs. The only exception is the dual lane staircase in fire zone 2. Passenger cabins are located on both decks 6 and 7 in fire zones 1 and 2 and both decks 9 and 10 in fire zone 3. A large theatre is located on deck 7 in fire zone 3, dining areas and bars are located throughout deck 8 and within fire zone 2 on deck 9. Examples of these decks are displayed in Figure 4.3-3. The vessel has a capacity of 1734 passengers and a maximum berthing capacity of 950 passengers.



(a) Deck 8 Assembly deck



(b) Deck 7 showing accommodation and seating areas

Figure 4.3-3 - Two decks of the hypothetical ship layout used in maritimeEXODUS analysis showing location of fire zones

4.3.4 The passengers

The population used in these simulations consists of 1300 passengers representing 75% of the maximum capacity of the vessel as specified by the IMO guidelines (IMO, 2002). The population characteristics are defined as specified in the IMO guidelines (IMO, 2002) and so will not be repeated here.

4.3.5 The results and discussion

As set out in the MSC 1033, each scenario was simulated 50 times in order to generate a distribution of results. After every five simulations the passengers starting locations were swapped. This was undertaken in such a way so as to ensure that the same locations were occupied on each simulation, but that different individual passengers occupied the position as specified by the IMO guidelines.

A summary of the overall results are presented in **Figure 4.3-4** and **Table 4.3-2**. The values shown represent attribute averages produced by each simulation and the range of those attributes over the 50 repeat simulations (shown in []). As can be seen, the average congestion experienced by an occupant is significantly greater for all the cases examined when compared against the IMO day case (Scenario 1). This observation and its ramifications will be examined in more detail in this section.

Table 4.3-2 – Average results (over the 50 repeat simulations) for each scenario

	Average response time (sec)	**Average cumulative congestion experienced (sec)**	**Average distance travelled (m)**	**Average individual assembly time (sec)**	**Assembly time (sec)**
Scenario 1 (IMO Day/RTD1)	298.2	12.1 [9.8 – 14.6]	51.5 [51.2 – 52.1]	382.4 [377.7 – 392.5]	670.3 [633.2 – 703.2]
Scenario 2 (RTD3)	244.6	32.1 [30.3 – 35.0]	53.2 [52.9 – 53.5]	351.4 [349.4 – 354.6]	630.5 [592.7 – 659.0]
Scenario 3 (RTD2)	33.4	35.7 [34.0 – 38.6]	52.1 [51.8 – 52.3]	141.0 [139.4 – 143.4]	428.3 [402.6 – 455.0]
Scenario 4 (RTD4)	268.7	23.5 [21.3 - 25.7]	52.3 [51.9 - 52.6]	365.0 [362.5 - 367.6]	659.0 [640.5 – 689.1]

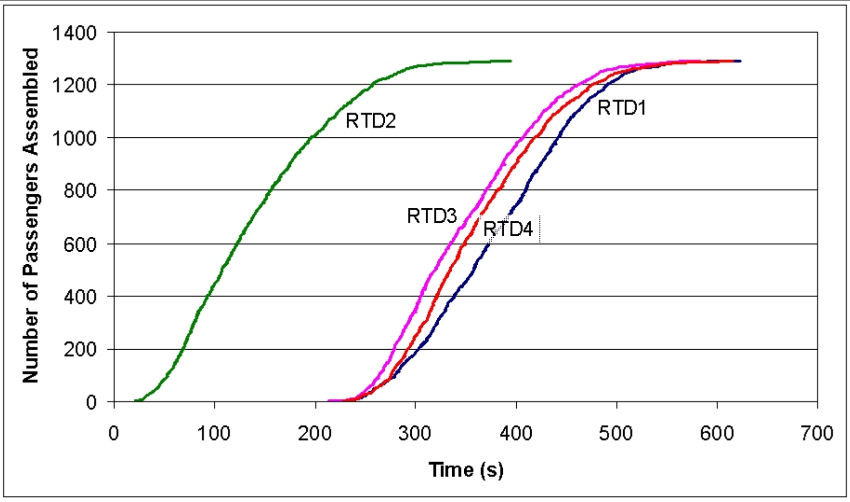
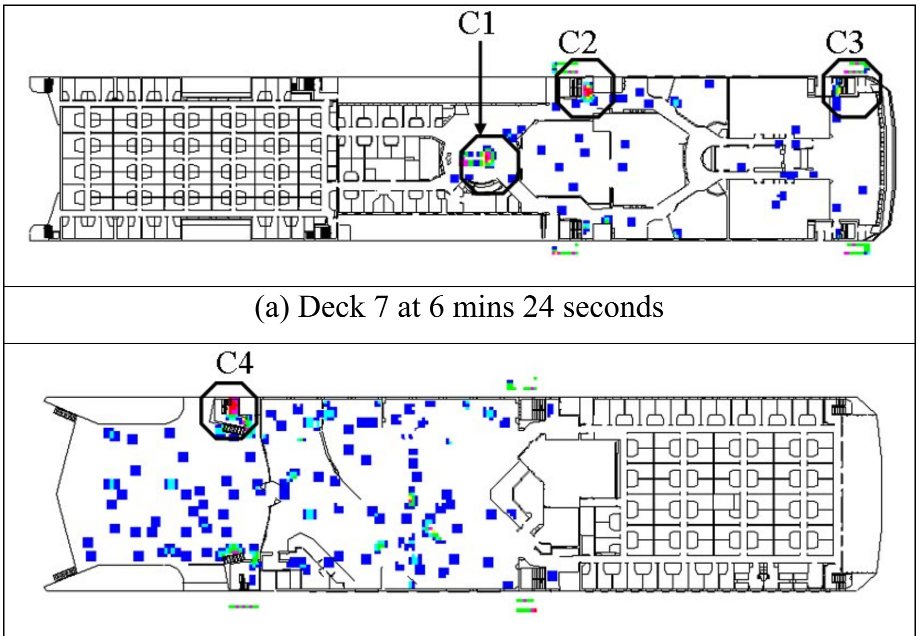


Figure 4.3-4 - Arrival at assembly station curves for the four scenarios

4.3.6 Results for scenario 1

The results presented in Table 4.3-2 for Scenario 1 (using RTD1) suggest that on average, the response time (298 seconds) accounts for approximately 78% of a person's personal assembly time (382 seconds) while the time spent in congestion (12 seconds) accounts for approximately 3% of the assembly time. Thus on average, only 19% of a person's assembly time is spent in free walking (i.e. travelling freely to their destination).

A more detailed analysis of how the scenario unfolds can be conducted by noting the results for a particular simulation. This is done by selecting a simulation from the 50 repeat cases that produces an assembly time near the mean. From a detailed analysis of the individual cumulative wait times (i.e. the total time spent in congestion for each individual) it is noted that most people spent less than 20 seconds in congestion; however, there are still many people who were stationary for longer than a minute with one person stationary for 3 minutes 20 seconds. This suggests that most passengers experienced little congestion and only a few are delayed in congestion for any significant amount of time. It is also noted that with the other three key measures (i.e. Response, Distance travelled and individual assembly times), the mean values lie close to the median values, suggesting that the values for the response times, distance travelled and the individual evacuation times are all relatively evenly distributed.



(a) Deck 7 at 6 mins 24 seconds

(b) Deck 9 at 5 mins 37 seconds

Figure 4.3-5 - Main areas of congestion in Scenario 1

It is noted that most of the time spent in congestion results from the congested areas around the stairs. Displayed in Figure 4.3-5 are the four main congestion areas depicted at specific times during the simulation. They do not demonstrate the extent of the congestion or how this fluctuated during the simulation, merely the locations of congestion. The highlighted areas indicate locations where the density had exceeded 4 persons / m^2 for a significant period of time. The areas of congestion were identified visually using the 'population density' contour feature of maritimeEXODUS which demonstrates the population over time. Areas with a population density of 4 persons/$metre^2$ or higher are depicted as red.

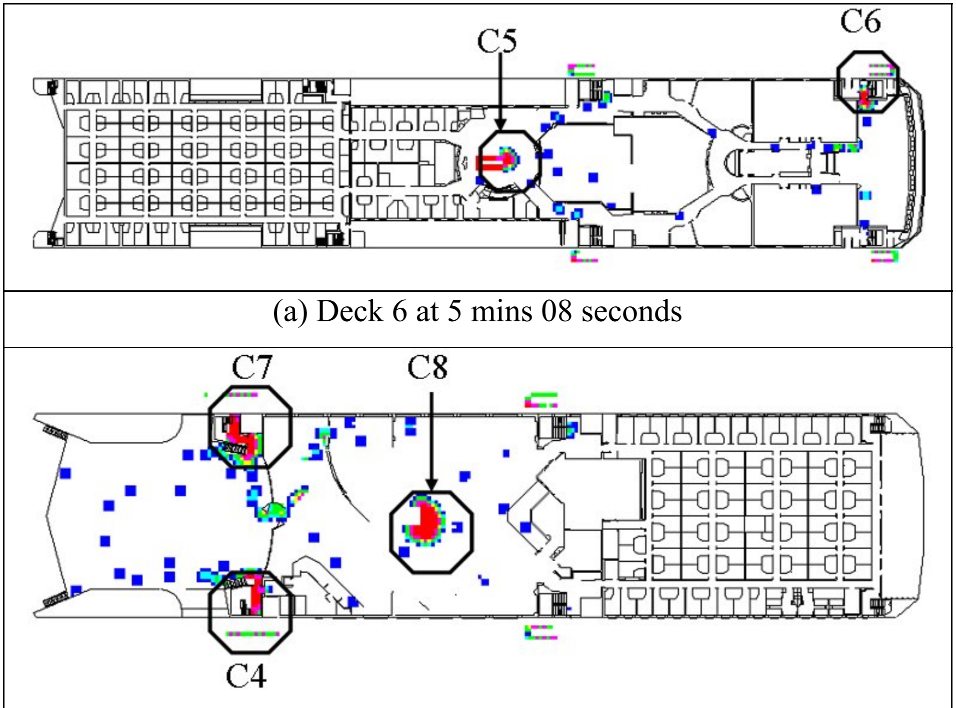
Analysis of the four main congestion areas (C1 – C4 in Figure 4.3-5) reveals that there are no areas of congestion considered significant (i.e. areas with 4 persons/m^2 for more than 10% of the total simulation time). The congestion experienced in these areas can be categorised as follows: C1 8.1% of the total assembly time; C2 5.9% of the total assembly time; C3 7.9% of the total assembly time and C4 6.2% of the total assembly time. Thus, as there are no regions producing congestion of 4 persons/m^2 or greater for more than 10% of the total simulation time, the vessel is deemed to have satisfied the congestion criteria as specified in MSC 1033 (IMO, 2002).

4.3.7 Results for scenario 2

The main results for Scenario 2 (using RTD3) are presented in Table 4.3-2. These results suggest that on average, the response time (245 seconds) accounts for 70% of a person's personal assembly time (351 seconds) while the time spent in congestion (32 seconds) accounts for 9% of the average assembly time. Thus, on average, only 21% of a person's assembly time is spent in free walking. Comparing Scenario 1 with Scenario 2 we note that while there is an 18% reduction in the average response time there is a 165% increase in the average amount of congestion experienced by an individual.

Recall that the difference between Scenario 1 and Scenario 2 is the shape of the response time distribution (see Figure 4.3-2). In RTD3 (Scenario 2) 70% of the people have begun to move after 230 seconds whereas using RTD1 (Scenario 1) only 33% of the people have begun to move. Thus in Scenario 2, the majority of the people have begun to move during the first 50% of the response time range.

As in the analysis of Scenario 1, a case that produces an assembly time near the mean time was selected from the 50 repeat cases and examined in detail. From a detailed analysis of the individual cumulative wait times it is noted that the average congestion time (32.1 sec) is quite low when compared to the maximum congestion time (182 sec) which suggests that the distribution of congestion times is skewed towards the lower end. However, unlike in Scenario 1, a considerable number of people experienced more than 20 seconds of total congestion and there are many more that experienced cumulative congestion in excess of a minute. The maximum cumulative congestion experienced by an individual in Scenario 2 was 3 minutes 2 seconds, slightly less than that experienced in Scenario 1. So while the maximum level of congestion appears to be slightly less in Scenario 2 compared to Scenario 1, there are more people experiencing longer periods of congestion in Scenario 2.



(a) Deck 6 at 5 mins 08 seconds

(b) Deck 9 at 4 mins 43 seconds

Figure 4.3-6 - Main areas of congestion in Scenario 2

Further analysis of this case reveals that there are eight main areas of congestion C1 – C8 (see Figure 4.3-6). Areas C1 to C4 are in the same location as those noted in Scenario 1 (see

Figure 4.3-5) but are more severe i.e. last for longer duration. The congestion levels experienced in all eight locations are considered serious as all produce congestion levels exceeding the 10% total assembly time criteria specified in MSC 1033 (IMO, 2002). The congestion experienced in these areas can be categorised as follows: C1 28.2% of the total assembly time; C2 16.9% of the total assembly time; C3 11.7% of the total assembly time; C4 14.7% of the total assembly time; C5 27.8% of the total assembly time; C6 24.7% of the total assembly time; C7 19.2% of the total assembly time; and C8 22.7%.

As shown, the congestion in this case is significantly worse than that experienced in Scenario 1 with one region (C1) being almost three times over the specified limit. In Scenario 1, the ***most*** significant area of congestion (C1) represented only 8.1% of the total assembly time whereas in Scenario 2 the ***lowest*** level of congestion (C3) represented 11.7% of the assembly time. Furthermore, in Scenario 2, half of the congestion areas (C1, C5, C6 and C8) produced congestion levels over 100% higher that the maximum permitted.

Thus in this case, while the total assembly time is considered acceptable, the vessel fails the MSC 1033 criteria due to local levels of congestion experienced in eight different locations. It should be noted that this difference in performance is caused merely with a change in the nature of the response time distribution, not in the range of response times.

4.3.8 Results for scenario 3

Scenario 3 (RTD2) made use of the retail store response time distribution in its unaltered form (see Figure 4.3-1). Essentially, this meant that the data was not translated by adding an additional 210 seconds to the distribution derived from the actual experiment. In effect, this meant that the passengers in Scenario 3 react 210 seconds faster than in Scenario 2. This is reflected in the overall time to assemble. We note that the average time to assemble in Scenario 3 is 202 seconds quicker than that for Scenario 2 (see Figure 4.3-4 and Table 4.3-2). This is further reinforced by the arrivals graph (see Figure 4.3-4) for this scenario which is simply translated to the left of the corresponding curve for Scenario 2 by approximately 210 seconds. This suggests that the evacuation dynamics are almost identical, albeit occurring at an earlier time. Indeed, as one would expect we find the same eight congestion areas as found in Scenario 2 with each area producing similar congestion conditions. However, as the total assembly time is now shorter than that found in Scenario 1 (by 210 seconds), the period of time that the congestion lasts, represented as a fraction of the total assembly time, is considerably higher. For example, congestion area C1 goes from 28.2% of the total assembly time in Scenario 2 to 40.4% of the assembly time in Scenario 3. Thus, according to the IMO specified congestion measure, the identified areas of concern in Scenario 3 pose a greater problem than those in Scenario 2.

4.3.9 Results for scenario 4

The main results for Scenario 4 (using RTD4) are presented in Table 4.3-2. These results suggest that on average, the response time (269 seconds) accounts for 73% of a person's personal assembly time (365 seconds) while the time spent in congestion (24 seconds) accounts for 7% of the average assembly time. Thus, on average, only 20% of a person's assembly time is spent in free walking. Comparing Scenario 4 with Scenario 2 and Scenario 1 we find that the three scenarios produce an almost identical free walking component.

As in the analysis of Scenario 1, we will examine in detail a case from the 50 repeat cases that produces an assembly time near the mean time. From a detailed analysis of the individual cumulative wait times it is noted, as in Scenario 2, that the average congestion time (23.8 sec) is quite low when compared to the maximum congestion time (198 sec) which suggests that the distribution of congestion times is skewed towards the lower end. The distribution of individual congestion times is similar to that found in Scenario 2, with a considerable number of people experiencing more than 20 seconds of total congestion and many individuals experiencing a total cumulative congestion in excess of a minute. The maximum cumulative congestion experienced by an individual in Scenario 4 was 3 minutes 18 seconds, slightly less than that experienced in Scenario 1 and slightly more than that experienced in Scenario 2. While the maximum level of congestion in Scenario 4 is comparable to that found in Scenario 1, there are more people experiencing longer periods of congestion in Scenario 4.

As with Scenario 2, there are eight main areas of congestion C1 – C8, and they located in the same regions as found in Scenario 2 (see Figure 4.3-6). The congestion levels experienced in seven of the eight locations are considered serious as they produce congestion levels exceeding the 10% total assembly time criteria specified in MSC 1033 (IMO, 2002). The congestion experienced in these areas can be categorised as follows: C1 12% of the total assembly time; C2 14.1% of the total assembly time; C3 26.2% of the total assembly time; C4 13% of the total assembly time; C5 5.9% of the total assembly time; C6 12.9% of the total assembly time; C7 20.5% of the total assembly time; and C8 17.5%.

As can be seen, the congestion in this case is significantly worse than that experienced in Scenario 1 with one region (C3) being almost three times over the specified limit. The congestion regions are also similar to that found in Scenario 2 using RTD3. Thus in this case, as with Scenario 2, while the total assembly time is considered acceptable, the vessel fails the MSC 1033 criteria due to local levels of congestion experienced in seven different locations. It should again be noted that this difference in performance is caused merely with a change in the nature of the response time distribution, not in the range of response times.

4.3.10 General Discussion

Using the artificial IMO response time distribution the hypothetical ship design is deemed to pass the IMO day scenario. However, using the more realistic response time distributions RTD3 and RTD4, the same vessel fails the IMO day scenario due to a number of regions of unacceptable local congestion. This brings into question the suitability of the IMO response time distribution (RTD1).

In land based applications, the occupant response time distribution for day time scenarios (i.e. not involving occupants who may be asleep) typically displays a skewed or log-normal distribution (see Figure 4.3-2). In such scenarios, after the evacuation alarm is sounded, there is a delay, which can last from seconds to minutes before the population begins to react. After the first few people begin to react there is typically a rapid escalation in the number of people moving purposefully towards evacuating the building. After the number of people responding to the alarm peaks, there is a steady decline in the number of people reacting. The decline in the number of people reacting can be rapid, as in RTD3 or slower as in RTD4. The precise form of the response time distribution will be dependent on the nature of the environment (e.g. retail, restaurant, gaming, office, public transport hub, etc), the nature of the activities that the population are involved in (e.g. social interaction, leisure activity, work related activity, purchasing goods/services, etc), the nature of the alarm (e.g. voice alarm, siren, etc), the presence, function and efficiency of marshalling staff and the nature of the population (e.g. trained/untrained, age and mobility, alone or in groups, etc). However, what is clear is that the response time distribution does not follow a random uniform distribution which suggests the number reacting at any one time is no different from the number at any other time.

The shape of the response time distribution will have a profound impact on the detailed nature of the unfolding evacuation dynamics as it will dictate the number of passengers who are moving through the system at any one time. As shown in Table 4.3-3, the response time distribution adopted by IMO assumes that as many passengers will have reacted within the first 20% of the total response time as react within the last 20% of the response time. This in effect produces an ideal distribution of people within the system and does not tend to tax the system at any one time. However, using more realistic distributions we find that considerably more people react within the first 20% of the response time distribution than react in the last 20% of the distribution (see Table 4.3-3). These distributions tend to produce a more challenging (and realistic) evacuation dynamic as the vessel layout must cope with an initial large surge of people.

Table 4.3-3 - Percentage of passengers reacting to call to muster after the first passenger has reacted for the three response time distributions

Time from first passenger reaction (seconds)	RTD 1 (IMO default (IMO, 2002))	RTD 3 (retail store (Purser, 1998))	RTD 4 (library (Gwynne, et al 2003))
36 (20%)	20%	60.5%	37.7%
72 (40%)	40%	96.0%	76.8%
90 (50%)	50%	98.8%	83.0%
108 (60%)	60%	98.8%	93.4%
144 (80%)	80%	99.4%	98.9%

Using these three differently shaped response time distributions, but transformed to cover the same response time range, the total assembly time and the overall evacuation dynamics are almost identical, as can be seen from the arrival curves displayed in Figure 4.3-4. Indeed, just based on the overall time to assemble the passengers, there would appear to be no significant difference between the three response time distributions, and all three produced assembly times which are within the limits specified by MSC 1033. However, when the detailed nature of the evacuation dynamics is investigated we find that the more realistic response time distributions produce very different results. While the IMO distribution does not produce any regions where the congestion approaches critical levels (as defined by MSC 1033), the other two response time distributions produce serious levels of congestion, one producing seven regions of critical congestion (RTD4) and the other producing eight (RTD3). Even though the response time distributions RTD3 and RTD4 follow the typical form of realistic distributions, they are in fact quite different (see Table 4.3-3 and Figure 4.3-4), yet they identify virtually identical problem areas within the vessel. This is quite a strong result, as it suggests that the exact shape of the distribution may not be critical.

It may be argued that a similar effect could be achieved by assuming a zero response time. In such a case all the people would be allowed to react at a single point in time. This would however be unrealistic as people are known not to react together en mass. Furthermore, it would produce much more significant levels of congestion. This could incorrectly highlight areas that would not necessarily be a problem and conceal other areas that are genuine problem areas.

In the above analysis, the realistic response time distributions were translated to fit the absolute and range of response times specified in the IMO distribution (RTD1). This was done in order to isolate the impact that the shape of the distribution may have on evacuation performance. It is interesting to note that in Scenario 3, which uses the original response time distribution associated with retail applications (RTD2), very similar results are produced to those found in Scenarios 2 and 4. The vessel still fails the IMO 1033 congestion criteria, even though it easily passes the overall assembly time criteria. Again, this reinforces the importance of the broad shape of the response time distribution to evacuation performance.

4.4 Suggestion for Realistic Response Time Distribution

4.4.1 Introduction

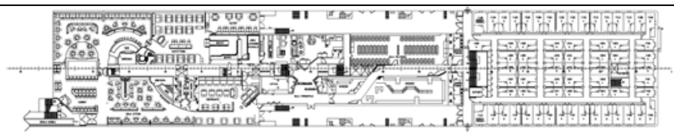
As part of the EU project Fire-Exit (EU FP5, 2002) two full-scale trials using an operational passenger vessel and actual passengers were conducted at sea. The primary purpose of these trials was to collect data relating to the response time of passengers involved in assembly trials. The passenger response times were extracted from the trials and used to create four separate response time distributions. These realistic marine based response time distributions were then compared against the land based response time distributions. It must be noted that these trials were not conducted as part of this PhD thesis; merely the data extracted from the trials have been used here.

4.4.2 The Trials

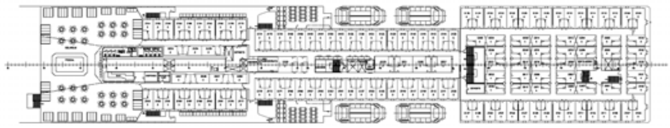
The ship owner/operator GRIMALDI made one of its RO-RO (Roll on – Roll off) ferries available for use in these trials. Two trials were conducted over two days on route between Rome and Barcelona from 18/04/05 to 22/04/05. Both crew and passengers were aware that they were participating in experimental assembly trials. Both trials were conducted in the morning (after breakfast on each day, just after 10am in the morning) with passengers distributed throughout the vessel according to their normal ship board activities i.e. the passengers were not artificially placed in specific locations. On both days, passengers were instructed to assemble and don lifejackets.

4.4.3 The vessel

The vessel used during the trials consisted of 11 decks of which three could be utilised by passengers. The total passenger capacity of the vessel is 1400, with 208 passengers in aircraft style seating, 626 accommodated in cabins and 566 deck passengers. The vessel has a crew complement of 100. The vessel has 200 cabins of single, double, triple or quadruple berth. On board the vessel are two restaurants, two bars and a casino area. The ship also has a reception area, shop and outdoor pool. The passenger cabins, aircraft style seating, restaurants, bars, casino and reception areas are all located on decks 7 and 8 (see Figure 4.4-1). The vessel can also carry 120 cars and 111 trailers.



Deck 7



Deck 8

Figure 4.4-1 - Deck 7 and 8 of the vessel

4.4.4 Assembly procedures

The trials utilised the vessel's normal assembly procedures. The assembling process involved passengers moving from populated areas around the vessel (including their cabins and public service areas) to their designated assembly stations. The vessel has five assembly areas on decks 7 and 8 identified as A, B, C, D and E (see Figure 4.4-2). The assembly process was in two parts, first the passengers assembled in their designated assembly areas and once this was completed, the passengers at assembly stations A, B and C would be instructed to join the passengers at assembly stations D and E prior to abandoning the vessel. The data gathering exercise was focused on Deck 7, due to the number of assembly stations cabins, public spaces and seating areas located on this deck.

On reaching the final assembly stations the exercise was considered complete, except for subsequent data collection activities (i.e. the distribution of questionnaires). From previous experience, the whole assembly process should take approximately 30 to 60 minutes, although the exact time would depend upon the efficiency of the performance of the passengers and crew.

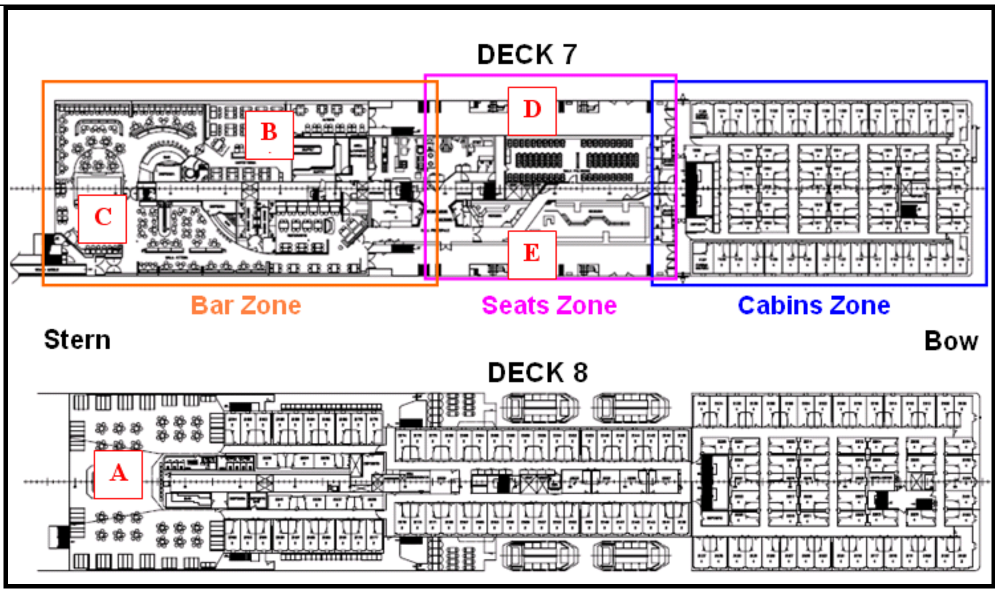


Figure 4.4-2 - Location of Assembly areas

4.4.5 Areas from which response time data was collected

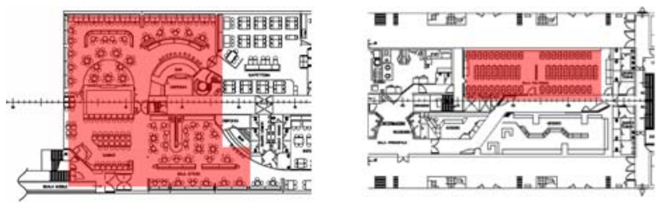
In order to investigate how the nature of the environment and the activity that the passengers were involved in influenced the passenger response, data was collected from four distinct areas of the vessel.

These four areas were:

- Selected cabin blocks,
- Corridors within selected cabin block areas,
- Public spaces (Bar area) and
- Aircraft style seating area.

The cabin data was taken from blocks of cabins across decks 7 and 8 (see Figure 4.4-1). These areas were selected as they were the most likely to be occupied. Cameras were placed in the corridors outside of the cabins in order to record when the passengers emerged from their cabins.

Response times were also collected from a public service area (see Figure 4.4-3(a)) and the aircraft style seating area (see Figure 4.4-3(b)) on deck 7. These were selected because they presented entirely different, but typical locations in which passengers may be found, in day time, prior to a call to assemble. The public service area from which data was collected included a bar, a snack bar, amusements and a seating area. Again this provided a variety of different situations in which passengers may be expected to congregate, all of which may influence their time to respond to the call to assemble. The aircraft style seating area is a seating area used by people without cabin accommodation. There are luggage racks in this room and overnight, passengers will be sleeping in this area. In Trial 2 no data was collected from the aircraft seating area due to the small number of people located in this area.



(a) Deck 7 bar, restaurant and casino area

(b) Deck 7 aircraft style seating area

Figure 4.4-3 - Areas on Deck 7 from which data was collected

4.4.6 The collected data

As the nature of the trials on both days were similar and the data was collected from identical regions in both trials, the response time data derived from these trials have been combined. It should be noted that the distributions for both days are similar in their nature and similar to that of the combined data presented here. This was done in order to obtain statistical significance when fitting a curve to the data.

4.4.6.1 Response time distributions – public spaces

The bar area consisted of passengers socialising in a public space. It should however be noted that the bar, food service and the casino were closed prior to the Main Evacuation Alarm Signal (MEAS). The response time distribution in the bar area should be compared with the

IMO uniform normal day response time distribution (IMO, 2002) which extends from 210 seconds to 390 seconds.

The combined response time data for the public spaces collected from the two trials contained 67 data points, 42 from Trial 1 and 25 from Trial 2. The frequency distribution for these response times is presented in Figure 4.4-4. The range of response times observed across the two trials extends from 3 seconds to 285 seconds with an average response time of 48 seconds. This is a considerably shorter response time than that found for passengers located in their cabins at the start of the drill (see section 4.3). This may have been due to the fact that the passengers in the public spaces were more exposed to other people around them and the crew. In addition, the passengers in their cabins are genuinely likely to incur a longer preparation time (see section 4.4) than passengers in public spaces.

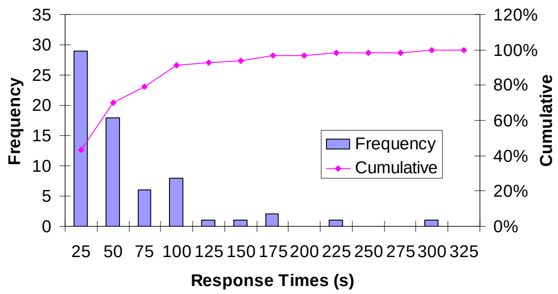


Figure 4.4-4 - Histogram of the frequency distribution of the response times from the bar area across the two trials.

As can be seen in Figure 4.4-4, the response time data is positively skewed with a significant number of the data-points falling within the lower quartile. The combined data appears to display a log-normal type shape, typical of response time distributions collected from evacuations in the built environment. In addition, the response time distribution observed in these trials for public spaces has a considerably lower minimum and a lower maximum than that specified by IMO (2002) for the day case.

4.4.6.2 Response time distributions – aircraft seating area

Data from 58 passengers located in the aircraft seating area was collected from Trial 1 (see Figure 4.4-5). Unfortunately no data from this location was available in Trial 2. On average, these passengers responded after 106 seconds. The range of response times extends from 37 seconds to 230 seconds. The Aircraft Seating Area is a complex space as it represents an area where passengers sleep and store their possessions – as if in cabins - and it also represents a public area with day activities. It is thus potentially a mixture of the MSC 1033 day and night areas. Passengers in this area did not take as long as passengers in the cabin area to respond (7 – 563 seconds with a mean of 98 seconds, see section 4.3), but had response times which are comparable to those of passengers in the public area (3 – 285 seconds with a mean of 48 seconds, see section 4.1). However, in the seated area, unlike in the public spaces, we find fewer passengers with very short response times (i.e. response times near zero). Nevertheless, the overall response time distribution resembles a log-normal distribution, as found in the built environment (Deere, et al 2006), albeit translated slightly to the right.

As in the case of the bar response times, the response time distribution observed in these trials for the Aircraft Seating area has a considerably lower minimum and a lower maximum than that specified by IMO (2002) for the day case.

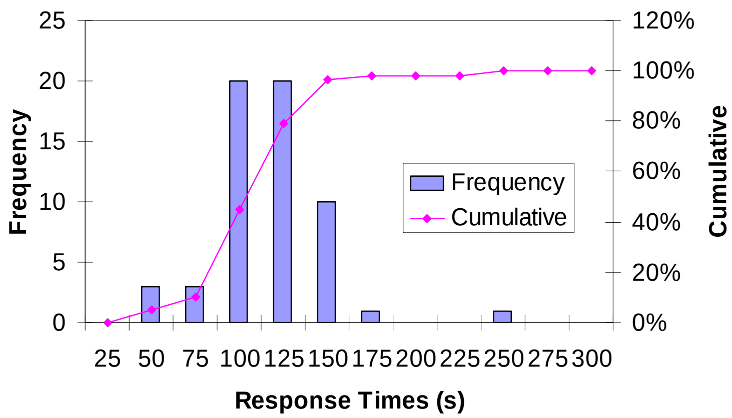


Figure 4.4-5 - Frequency distribution of the response times of the passengers located in the aircraft style seating area during Trial 1.

4.4.6.3 Response time distributions - cabins

The combined data produces a data set involving 127 data points, 22 from Trial 1 and 105 from Trial 2. The frequency distribution for these response times is presented in Figure 4.4-6.

As can be clearly seen from this figure, the data is strongly positively skewed. The range of response times derived from the two trials for the cabin area extends from 7 seconds to 563 seconds with an average response time of 98 seconds. As suggested previously, it must be recalled that the passengers in these trials had a considerable amount of pre-warning and due to the timing of the trials, it is unlikely that many of the passengers were asleep at the time.

The range of observed response times for the cabin area can be compared with the IMO night response time, which refers to *sleeping* passengers in cabins and extends from 420 seconds to 780 seconds and the IMO day response time, which refers to awake passengers in public areas and which extends from 210 seconds to 390 seconds (IMO, 2002). Clearly, the measured range of response time is significantly different from both the IMO night and day scenarios. The upper limit of the observed data falls between the day and night upper limit, being some 28% shorter than the upper limit of the night case. Furthermore, unlike either the night or day case, the lower limit is quite close to zero seconds, significantly different from both IMO cases. In addition, while the upper limit of the observed response time distribution is greater than that of the IMO day scenario, the frequency of occurrence of these long response times is very small. This is significantly different to the situation with the IMO distribution. As the IMO distribution assumes a uniform random distribution, the longest response times are just as likely to occur as the shortest response times. Once again, in reviewing these results it should be recalled that the passengers had a considerable amount of pre-warning in these trials. Furthermore, as the trial took place during the late morning, it is likely that most of the passengers were awake (see Section 4.4.2).

In addition to the range of response times, the nature of the functional form describing the trial distribution should be compared with the uniform random distribution specified in MSC 1033. Clearly, the curve derived from this trial is non-uniform and skewed to the lower quartile times. This trend is similar to that found in response time distributions observed in day evacuations in the built environment (Deere, et al 2006) having a characteristic log-normal shape.

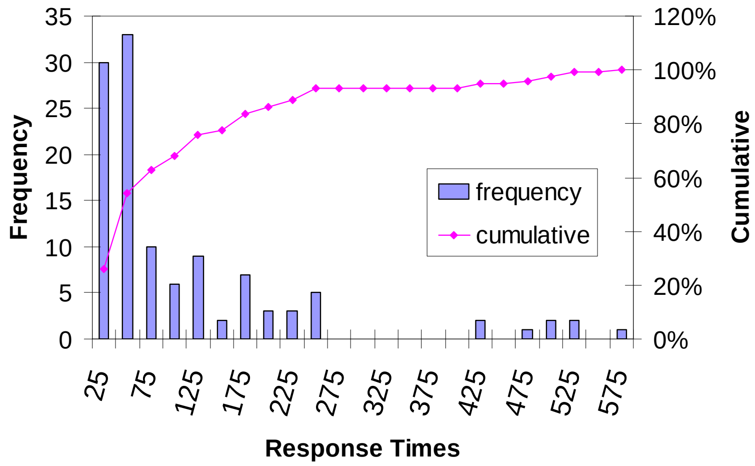


Figure 4.4-6 - Histogram of the frequency distribution of the Cabin response times across the two trials

4.4.6.4 Response time distributions - Cabin preparation times

A total of 16 passengers, 12 from Trial 1 and 4 from Trial 2, were observed to return to their cabins in order to collect lifejackets, reunite with members of their family, collect belongings etc. For these passengers it is possible to determine a preparation time. This relates to the time between the passenger arriving at their cabin and subsequently leaving for the assembly station. It provides an indication of the time required by passengers to prepare for an evacuation after returning to their cabins. Of all of the data collected in these trials, this probably is least affected by the degree of pre-warning as it is measured from the time the passenger enters the cabin to the time they leave.

The frequency distribution for these preparation times is presented in Figure 4.4-7. The range of preparation times observed across the two trials extends from 14 seconds to 224 seconds. Due to the small number of available data points it is not possible to determine with much reliability the nature of the distribution however, Figure 4.4-7 suggests that the preparation time may approximate an almost normal distribution. This would appear to be a reasonable approximation as some passengers are expected to take a long time and some passengers are expected to take a short time, depending on the number of and time spent locating the items being retrieved from their cabins, or indeed any other activity being carried out by the passenger.

On average passengers spent 94 seconds preparing to evacuate once they had arrived at their cabin, a similar amount of time to the average (98 seconds) achieved by those already in their cabins (see Section 4.4.6.3). If the measured Preparation Time is taken as an indication of the general time required by passengers in cabins to prepare to evacuate, it suggests that on average passengers who were originally located in their cabins (see Section 4.4.6.3) took on average only 4 seconds to respond to the Main Evacuation Alarm Signal (MEAS). If the passengers in the cabins were asleep at the time of the MEAS, it is likely that considerably more time would have been required to react to the alarm (for example to awake). This reinforces the earlier comments concerning the likelihood that the majority of passengers already in their cabin were likely to be awake and waiting for the assembly call and that therefore, the times derived in Section 4.4.6.3 should be considered as representative of a "day" rather than a "night" scenario.

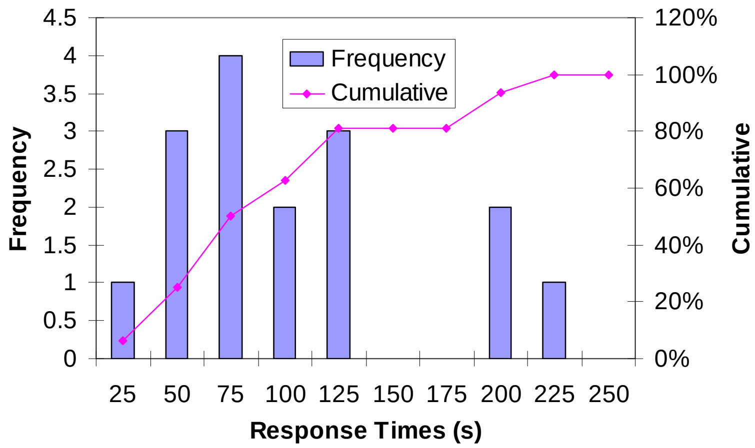


Figure 4.4-7 - Frequency distribution of the preparation times collected across both trials

4.4.7 Generalised response time curves

The response time data presented in Section 4.4.6 for the bar, aircraft seating area and cabins was reformulated as continuous probability density distributions. This was based upon the original data taken over 10 second intervals. These new curves are presented in Figure 4.4-8 to Figure 4.4-10. The total area under the probability density curve is equal to 1.0.

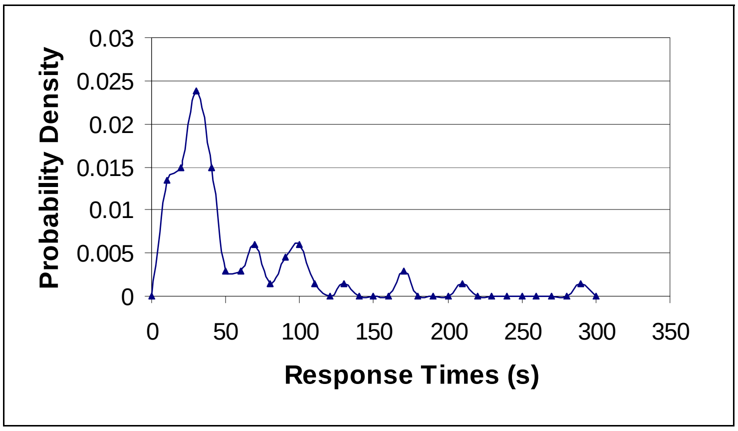


Figure 4.4-8 - Response time probability density distribution for the Bar area.

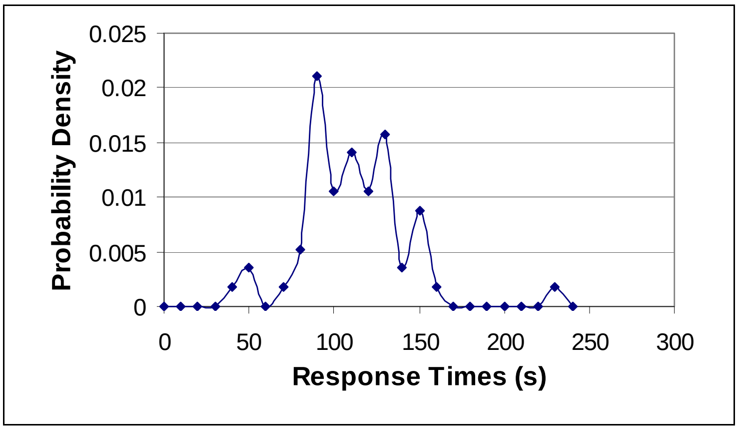


Figure 4.4-9 - Response time probability density distribution for the Aircraft Seating area.

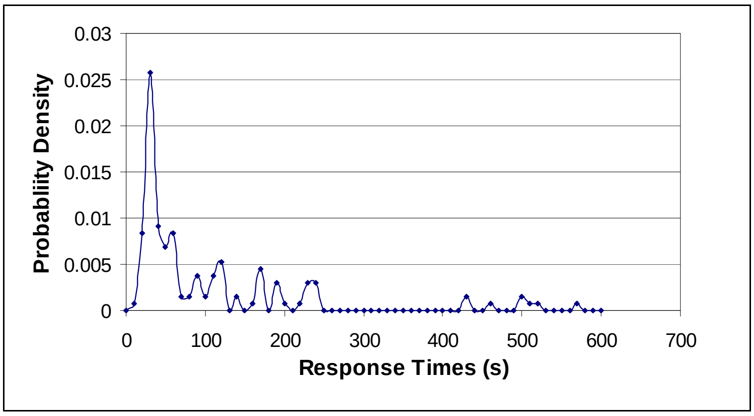


Figure 4.4-10 - Response time probability density distribution for the Cabin area.

Here we attempt to model these probability density distributions using a generalised log-normal curve of the type shown in Equation (4.4.1),

$$y = \frac{1}{\sqrt{2\pi}\sigma x}\exp\left[-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right]$$ **Equation 4.4.1**

where; x is the response time (seconds) as measured in the experiment, y is the probability density function at response time x and σ and μ represent the standard deviation and mean respectively of the normally distributed Ln(x).

In order to test how closely the original data set could be represented by a log-normal curve, a chi-squared test was performed. The chi-squared test can only be carried out on discrete data and so to undertake the test the actual probability distributions were used rather than the probability density distributions shown above. As part of the chi-squared test, two competing hypotheses were examined, namely:

H_0:The response data follows the log-normal distribution.
H_1:The response data does not follow the log-normal distribution.

For the Bar response time data (σ = 0.94 and μ = 3.44) we find the following log-normal probability density curve is generated using Equation (4.4.1),

$$y = \frac{1}{\sqrt{2\pi}0.94x}\exp\left[-\frac{(\ln(x)-3.44)^2}{2\times 0.94^2}\right]$$ **Equation 4.4.2**

For the Bar response time data, the chi-square 'goodness of fit' test, applied to the probability distribution suggested that the data was accepted as coming from the log-normal distribution at the 5% significance level. That means that there would be a 5% chance of rejecting H_0. A comparison between the Bar response time probability density distribution and the log-normal curve described by Equation (4.4.2) is presented in Figure 4.4-11.

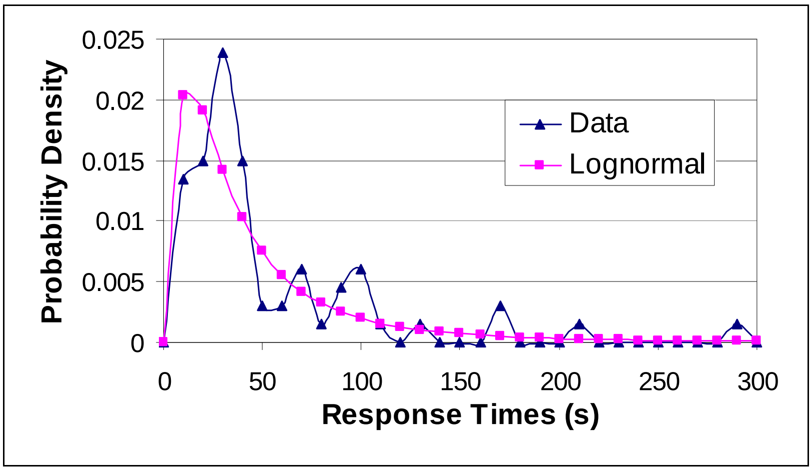


Figure 4.4-11 - Comparison of Bar response time probability density data and fitted log-normal curve

For the Aircraft Seating area response time data ($\sigma = 0.31$ and $\mu = 4.62$) we find the following log-normal probability density curve is generated using Equation (4.4.1),

$$y = \frac{1}{\sqrt{2\pi}0.31x}\exp\left[-\frac{(\ln(x) - 4.62)^2}{2\times 0.31^2}\right] \qquad \textbf{Equation 4.4.3}$$

For the Aircraft Seating area response time data, the chi-square 'goodness of fit' test applied to the probability distribution suggested that the data was accepted as coming from the log-normal distribution at the 5% significance level. That means that there would be a 5% chance of rejecting H_0. A comparison between the Aircraft Seating response time probability density distribution and the curve described by Equation (4.4.3) is presented in Figure 4.4-12.

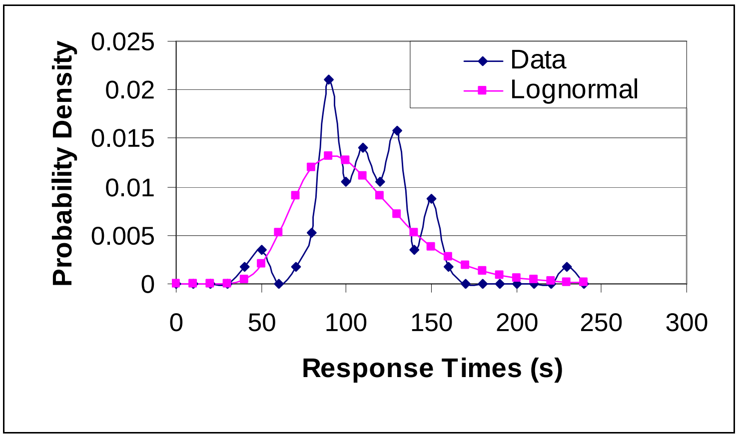


Figure 4.4-12 - Comparison of Aircraft Seating response time probability density data and fitted log-normal curve

Unlike the other two data sets, it was not possible to produce a log-normal curve which fitted the Cabin response time probability distribution which satisfied the chi-square test. A comparison between the probability density data and the fitted log-normal curve is presented in Figure 4.4-13. There are several areas that significantly contribute to producing the poor chi-square test statistic. These are:

a) The relatively large number of people responding within the first 30 seconds.

b) Larger than expected numbers of people responding in the periods, 160-170, 220-240 and 400-520 seconds.

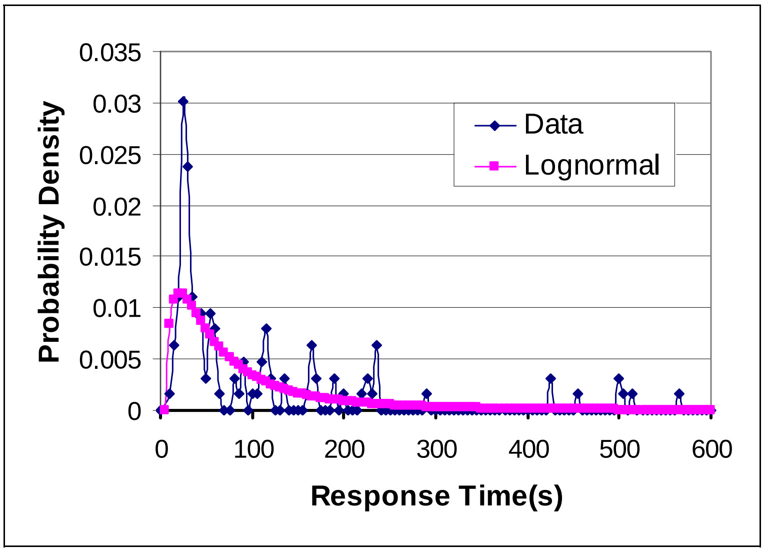


Figure 4.4-13 - Comparison of Cabin response time probability density data and fitted log-normal curve

It is known that for those passengers who returned to their cabins, the preparation time varied from 14 to 224 seconds. This provides an indication of the likely time required by passengers within cabins to prepare for the assembly process. Furthermore, only one passenger required a preparation time of less than 25 seconds. Therefore it is suggested that the relatively large number of passengers with a response time of less than 30 seconds may be accounted for by the level of pre-warning, with a number of passengers simply awaiting the sounding of the assembly alarm before heading off. This contribution to the chi-square statistic may thus simply be an artefact of the participant awareness of the drill.

The unusual number of passengers with response times between 160-170 and 220-240 seconds may also be a result of the passenger awareness of the drill. In both trials there were incidences of groups of people leaving their cabins and standing around in the corridor talking and socialising before they made their way to the assembly stations. As passengers were deemed not to have responded until they made a decisive move towards the assembly stations, these types of activities would have prolonged the response time. It is difficult to say if this type of behaviour would be expected in a genuine emergency situation however, here again the fact that the passengers were aware that this was a drill may have influenced the behaviour of the passengers thereby producing these unexpected groupings of results.

The final cluster of response times which are considered unusual occurred around 400-520 seconds. Two passengers from trial 1 and six passengers from trial 2 contributed to these long response times. From the questionnaire data carried out during the trials, it was found in trial 1, 26 passengers stated that they were asleep at the start of the trial and 1 stated that they were in the shower while in trial 2, 18 stated that they were asleep and four stated that they were in the shower. It is possible that not all of the participants who stated that they were asleep were in cabins however, it is likely that all of the passengers who stated that they were in showers were in cabins. Thus it is likely that all of the passengers who contributed to the long response times were either in the shower or asleep at the start of the drill.

Taking these factors into consideration, it is suggested that the log-normal curve presented in Figure 4.4-14 is a reasonable representation of the response time distribution for passengers located in their cabins during the day.

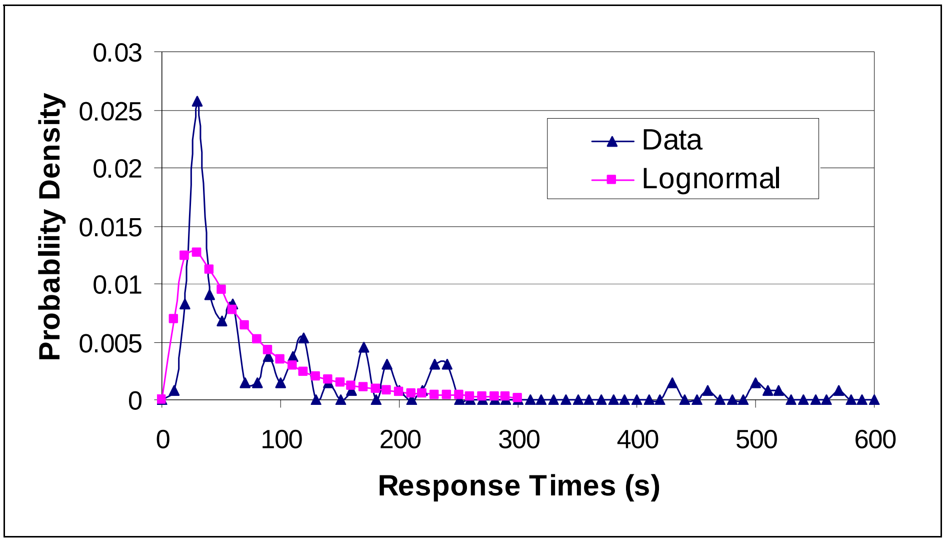


Figure 4.4-14 - Truncated log-normal distribution fitted to smoothed cabin response time probability density data

The chi-squared test for the truncated Cabin response time probability distribution data produced a $X^2 = 18.9$ against a critical value of 14.07 at the 0.05 significance level with 10 degrees of freedom. While the hypothesis H_0 is not accepted, the curve produces a reasonable fit given the anomalies in the data set mentioned above. (Note that the hypothesis that the smoothed Cabin response data follows the log-normal distribution is accepted at the 0.025 significance level.)

The log-normal curve that represents this data ($\sigma = 0.84$ and $\mu = 3.95$) is given by;

$$y = \frac{1}{\sqrt{2\pi}\,0.84\,x}\exp\left[-\frac{(\ln(x)-3.95)^2}{2\times 0.84^2}\right]$$ **Equation 4.4.4**

with $x < 300$ seconds.

4.4.8 Suggested response time curves for day and night applications

Based on the data produced from the two FIREEXIT trials, a recommendation for response time distributions to be used in formal evacuation analysis is suggested. It is acknowledged that data from only two trials is not sufficient to make a reliable recommendation. However, as the current formal evacuation analysis (IMO, 2002) makes use of arbitrary response time data, the response time distributions suggested here have the advantage of being based on real data derived from a maritime environment.

4.4.8.1 Suggested day response time distribution

In the recommended IMO day case analysis (IMO, 2002), passengers are assumed to be located only in the public spaces of the vessel, with no passengers located in cabins. Thus the response time distributions derived from the FIREEXIT trials for the Bar and Aircraft Seating areas are representative of the intent of the MSC 1033 analysis (IMO, 2002). While both sets of curves (Equations (4.4.2) and (4.4.3)) appear quite different to each other, they both can be represented by log-normal curves. Furthermore, it was suggested by Deere (et al 2006) that the exact shape of the log-normal was unlikely to impact the general conclusions of the evacuation analysis. Thus both sets of curves are considered suitable contenders for the day case response time distribution.

Clearly the main differences between the response time distributions derived from the FIREEXIT data i.e. Figure 4.4-11 and Figure 4.4-12 and that recommended in MSC 1033 is the shape of the distributions and the range of response times. As already stated, the shape of the distributions derived from the FIREEXIT data is log-normal compared to the uniform random distribution of the MSC 1033 distribution (IMO, 2002). Furthermore, the shape of the FIREEXIT distributions conforms to the general shape of the response time distributions observed in the building industry (see for example the Retail Store and Library response time data in Section 4.3). Indeed, the response time data collected in the Bar area is similar in nature to that collected in land based retail premises (Deere, et al 2006) while the Aircraft Seating area data (excluding the initial period in which no one responds) is similar in nature to that collected from a land based library (Deere, et al 2006) (see Table 4.4-1).

Table 4.4-1 - Comparison of response time data derived from the FIREEXIT trials and land based data presented in Deere, et al (2006)

	% of people who have responded after					
	50 seconds	**100 seconds**	**150 seconds**	**200 seconds**	**250 seconds**	**300 seconds**
Bar	73.0	90.8	96.3	98.5	99.5	100
Retail	81.1	98.8	100	100	100	100
Aircraft Cabin Seating area	2.5	54.9	91.5	99.0	100	100
Aircraft Cabin Seating area*	42.2	87.6	98.4	100	100	100
Library	53.8	94.1	99.5	100	100	100

*Initial portion of the distribution with zero probability excluded.

The range of response times derived from the FIREEXIT trials differs considerably from that specified in the MSC 1033 requirements (IMO, 2002). According to MSC 1033, the response time distribution extends from 210 – 390 seconds. For the fitted log-normal function describing the Bar response times, the distribution runs from 0 – 300 seconds, while for the Aircraft Seating area, the response times run from 0 – 240 seconds. Clearly the range of response times is quite different and this will have an impact on overall assembly times.

In order to gauge the impact of these response time distributions on an evacuation analysis, they were applied to the hypothetical ship layout described in Section 4.3.3 of this chapter. The vessel and its population distribution are identical to that described in Section 4.2 of this chapter.

Two sets of simulations were performed for the day case. In these simulations the Response Time Distribution (RTD) was specified using Equation (4.4.2) (RTD 5) and Equation (4.4.3) (RTD 6). The results from these simulations are compared with the results presented in Section 4.2 of this chapter generated using the default IMO response time distribution (RTD 1) and the unmodified retail premises response time distribution (RTD 2) from the built environment.

Table 4.4-2 - Average results (over the 50 repeat simulations) for each Scenario

Response Time Distribution	Average response time (sec)	Average cumulative wait time (sec)	Average individual assembly time (sec)	Assembly time (sec)
RTD 1 IMO distribution	298.2 [298.1 – 298.4]	12.1 [9.8 – 14.6]	382.4 [377.7 –392.5]	670.3 [633.2 – 703.2]
RTD 2 Retail premises distribution	33.4 [33.4 – 33.5]	35.7 [34.0 – 38.6]	141.0 [139.4 – 143.4]	428.3 [402.6 – 455.0]
RTD 5 Bar distribution	46.7 [46.6 - 46.9]	29.1 [26.0 - 32.6]	145.9 [142 - 149.1]	488.0 [418.8 - 555.6
RTD 6 Aircraft seating area distribution	105.8 [105.7 - 105.9]	28.5 [26.3 - 30.8]	203.9 [201.7 - 206.5]	484.7 [457.6 - 511.0]

A summary of the overall results are presented in Table 4.4-2 and Figure 4.4-15. The values shown in Table 4.4-2 represent attribute averages produced by each simulation and the range of those averages over the 50 repeat simulations (shown in "[]"). The Cumulative Wait time is a parameter determined by maritimeEXODUS for each person during the assembly process. It represents the total amount of time wasted by a person in congestion during the assembly process. The Cumulative Wait time for each person in a particular simulation can be averaged to produce the Average Cumulative Wait time. This then is a measure of the average amount of time wasted in congestion for a particular simulation. When the simulation is repeated a number of times, the average of the Average Cumulative Wait times can be determined. The Assembly Time is simply the time required for all the passengers and crew to gather at the assembly stations. The Individual Assembly Time is the time required for each individual person to reach the assembly station. Thus, the Average Individual Assembly time is the average time required for a person to reach the assembly station within a particular simulation. When the simulation is repeated a number of times it is possible to determine the average Individual Assembly time.

As can be seen, the average congestion experienced by an occupant is significantly greater for all the cases examined when compared against the IMO day case (RTD 1). This observation is consistent with the observations from the earlier work utilising the land based response time distributions. This is due to the relatively large number of passengers with short response times produced by the log-normal distributions. Furthermore, we note that the Total Assembly Time for the three response time distributions derived from real data are similar with the time produced by RTD 5 being the greatest. This is due to RTD 5 producing the longest response times (see Table 4.4-2). Here we have a few passengers with a response time greater than 200 seconds (see Table 4.4-2) prolonging the total assembly time as noted in Figure 4.4-15.

A more detailed analysis of how a scenario unfolds can be conducted by noting the results for a particular simulation. This is achieved by selecting a simulation from the 50 repeat cases that produces an assembly time near the mean. Depicted in Figure 4.4-15 is a graph of the total assembly time for a representative simulation for each response time distribution.

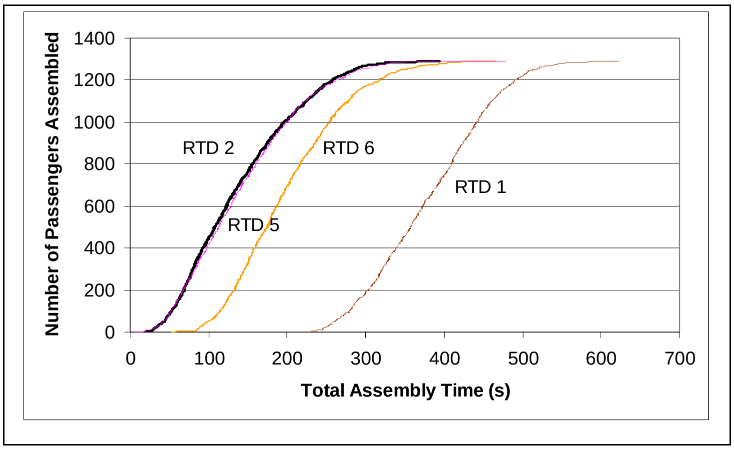


Figure 4.4-15 - Arrival at assembly station curves for the four response time distributions

It is noted from Figure 4.4-15 that RTD 2 and RTD 5 produce virtually identical assembly time curves. This is due to the similar nature of the RTDs in these two cases, in particular the time that the first people start to move and the relative numbers of people commencing to move at different times. The RTD 1 and 6 curves are also similar in shape to the other curves but effectively translated to the right. This is due to the relatively long delay that is incurred by the first people who start to move.

Table 4.4-3 – Congestion areas produced in a representative simulation for each Response Time Distribution

Congestion Region	RTD 1 (IMO)		RTD 2 (retail premises)	
	Duration (s)	% of assembly time	Duration (s)	% of assembly time
C1	55	8.1	123	28.2
C2	40	5.9	137	31.4
C3	54	7.9	104	23.9
C4	42	6.2	175	40.1
C5	-	-	138	31.7
C6	-	-	115	26.4
C7	-	-	181	41.5
C8	-	-	145	33.3

Congestion Region	RTD 5 (Bar)		RTD 6 (Aircraft seating area)	
	Duration (s)	% of assembly time	Duration (s)	% of assembly time
C1	157.7	31.1	90.5	18.1
C2	62.0	12.2	87.7	17.5
C3	63.8	12.6	159.7	31.9
C4	79.3	15.6	72.8	14.6
C5	51.7	10.2	58.5	11.7
C6	57.3	11.3	54.0	10.8
C7	143.5	28.3	154.7	30.9
C8	128.5	25.3	122.3	24.4

Analysis of the simulation results from a particular simulation (close to the mean) produced using RTD 1 suggests that four main congestion areas occur where the density had exceeded 4 persons / m^2 for a significant period of time. However, analysis of the four main congestion areas (C1 – C4) revealed that none of the congestion areas are considered significant i.e. population densities of 4 persons/m^2 for more than 10% of the total simulation time (see Table 4.4-3).

Using the IMO response time distribution, the vessel is therefore considered to pass the MSC 1033 criteria in terms of total time required for the assembly process and the level of congestion observed. This type of analysis was repeated for RTD 2. This revealed that there were eight main areas of congestion C1 – C8. Areas C1 to C4 are in the same location as those noted using RTD 1 except are more severe i.e. last for longer duration. The congestion levels experienced in all eight locations are considered serious as all produce congestion levels exceeding the 4 persons / m^2 for 10% total assembly time criteria specified in MSC 1033 (IMO, 2002) (see Table 4.4-3). Thus, the vessel is deemed to fail the IMO day case scenario due to the levels of congestion experienced.

It is noted that for the two new log-normal response time distributions (RTD 5 and 6), the same eight congestion regions are identified as were found using the retail premises response time distribution. For each of these two response time distributions, all eight identified regions produce congestion exceeding 10% of the total assembly time and thus the vessel is deemed to fail the IMO congestion requirement. Thus, using any one of the three log-normal response time distributions would lead to the same conclusions concerning the suitability of the vessel.

Comparing the three log-normal distributions, it is clear that RTD 2 produces the greater levels of congestion (see Table 4.4-3). This is due to the larger proportion of short response times and the shorter range of response times (see Table 4.4-1 and Figure 4.4-16) found in this distribution compared to the other two response time distributions. Of the three response time distribution curves, RTD 2 would therefore produce the most challenging congestion test conditions. However, RTD 2 is not generated from a maritime scenario and so it can be argued that it is not truly representative of the maritime environment.

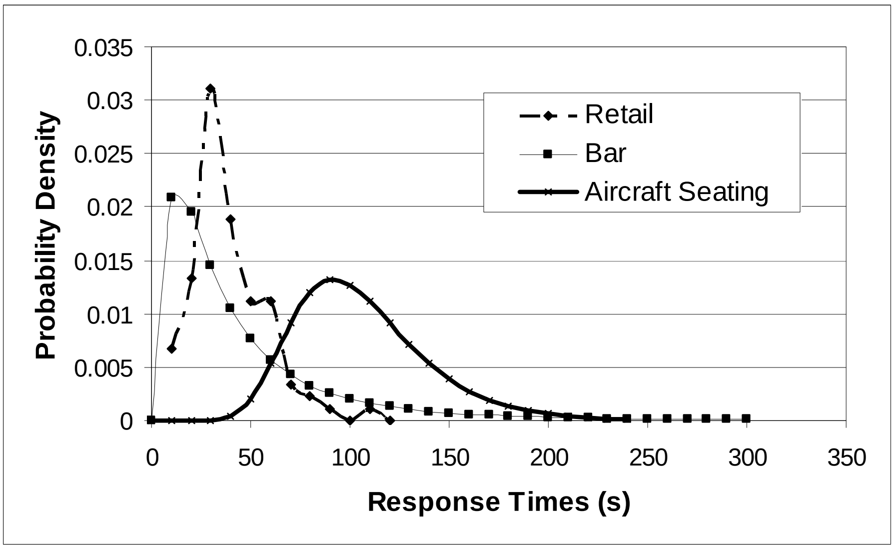


Figure 4.4-16 - Comparison of probability density distributions for RTD2 (retail premises), RTD5 (bar) and RTD6 (aircraft seating area)

RTD 5 and RTD 6 identify identical congestion problem areas and broadly similar levels of congestion. However, RTD 5 produces longer assembly times due to its larger range of response times. Furthermore, RTD 5 is based on data from two separate trials while RTD 6 is based on data from a single trial. In addition, RTD 5 is based on a larger set of data than RTD 6. Therefore there is a greater degree of confidence in the validity of RTD 5 compared with RTD 6.

Of all the simulations, the ones involving the Bar response time distribution (RTD 5) produces the longest total assembly times. As noted above, this is due to RTD 5 generating the largest range of response times. It therefore produces the most challenging total assembly time test conditions.

Of the four response time distributions, it is thus suggested that RTD 5 (described by Equation (4.4.2)) is the best candidate for use in Day Case evacuation scenarios. However, as the probability density distribution is truncated at 300 seconds, the area under the curve will no longer equal 1.0. In order to keep the area equal to 1.0 we must multiply the probability density equation by a factor which scales the area back to 1.0. The factor may be found by integrating probability density distribution given by Equation 4.4.2 from 0 to 300 seconds.

This produces the following functional form,

$$y = \frac{1.00808}{\sqrt{2\pi}\,0.94x} \exp\left[-\frac{\left(\ln(x) - 3.44\right)^2}{2 \times 0.94^2} \right] \qquad \textbf{Equation 4.4.5}$$

with x < 300 seconds.

It is recommended that the probability density distribution given by Equation (4.4.5) be adopted as a replacement to the existing Day case uniform random distribution found in MSC 1033.

4.4.8.2 Suggested night response time distribution

In the recommended IMO night case analysis (IMO, 2002), passengers are assumed to be located only in their cabins and are assumed to be asleep at the start of the evacuation. None of the response time distributions derived from the FIREEXIT trials strictly meet this requirement. Of all the data collected during the FIREEXIT trials, the Cabin Response Time data comes closest to meeting the MSC Night scenario requirements.

While the Cabin response time data is not representative of sleeping passengers in their cabins, data from these trials can be used to postulate a response time distribution that may be representative of sleeping passengers in their cabins. It was noted that six passengers that were located in their cabins and were believed to be sleeping or in the shower, could have produced response times in the range 400 – 520 seconds. Furthermore, the distribution shown in Figure 4.4-14 and described by Equation (4.4.4) could be used to describe the response time of awake passengers in their cabins. Thus, it is suggested that a reasonable distribution to use in the night scenario (to represent sleeping passengers in their cabins) would be to adopt the distribution shown in Figure 4.4-14 and described in Equation (4.4.4) with the curve translated to the right by 400 seconds.

Thus, the response time probability density distribution for sleeping passengers in their cabins would be represented by the log-normal distribution described by Equation (4.4.6). The response time data described by this equation extends from 400 seconds to 700 seconds and the equation has a scaling factor of 1.01875 introduced to maintain the total area beneath the curve to 1.0. This compares with the MSC 1033 night time distribution of 420-780 seconds defined using a uniform random distribution.

$$y = \frac{1.01875}{\sqrt{2\pi}\,0.84\,(x-400)} \exp\left[-\frac{\left(\ln(x-400)-3.95\right)^2}{2\times 0.84^2}\right] \qquad \textbf{Equation 4.4.6}$$

with $400 < x < 700$ s.

It is recommended that the probability density distribution given by Equation (4.4.6) be adopted as a replacement to the existing Night case uniform random distribution found in MSC 1033 (IMO, 2002).

4.5 Conclusion

This chapter has demonstrated how the response time distributions specified in the IMO MSC/Circ 1033 (IMO, 2002) is not suitable for simulating passengers in various scenarios. During simulations using the IMO specified response time distributions (RTD) and land based realistic response time distributions, the IMO RTD did not identify areas of severe congestion which meant that the design in question complied with the regulations. However, using the land based log normal shaped RTD, areas of severe congestion did occur, which meant that the design failed to comply with the regulations.

The work in this chapter recommended that the response time distribution to be used in simulating 'day ' scenarios should be based upon the response times of passengers in the bar area during the full scale trials on board a passenger ferry. This distribution followed the shape of a positively skewed log normal curve. A formula for which was fitted to this response time distribution and is as follows:

$$y = \frac{1.00808}{\sqrt{2\pi}\,0.94x}\exp\left[-\frac{\left(\ln(x)-3.44\right)^2}{2\times 0.94^2}\right] \qquad \textbf{Equation 4.5.1}$$

with x < 300 seconds.

As for the 'night' scenarios, there were no specific data extracted from the full scale trials regarding passenger response times at night, but the closest distribution related to the passenger response times of those in their cabins. It was noted how some of these passengers were asleep in their cabins. For this reason, the response time distribution was mapped to the current IMO specified night response distribution range of 400 seconds to 700 seconds. This too was a positively skewed log normal curve. An equation was fitted to this response curve and is as follows:

$$y = \frac{1.01875}{\sqrt{2\pi}\,0.84\,(x-400)} \exp\left[-\frac{\left(\ln(x-400)-3.95\right)^2}{2\times 0.84^2}\right]$$ **Equation 4.5.2**

with 400 < x < 700 s.

The recommended response time distribution for day and night scenarios and the work carried out in this chapter was presented to the IMO's Fire Prevention Sub-Committee FP46, whom accepted the proposal and have adopted the suggested response curves in the regulations superseding the MSC./Circ's 1033 , the MSC.1/Circ. 1238.

The result of resolving the issue of using an unrealistic response time distribution provides a more valid simulation tool which can be used in assessing the human factors performance of a design much more competently. Therefore maritimeEXODUS can be used to assess the human factors performance of a design with more confidence.

The work carried out in this chapter has far more outreaching effects than just in maritimeEXODUS, as the work described here was used to update the international regulations governing the modelling of evacuation scenarios, this work will also make all evacuation modelling software, using the response time distribution suggested here, more accurate.

Chapter 5

Development of the Human Performance Metric

5.1 Introduction

Ship evacuation models such as maritimeEXODUS can be used to determine the performance of people under emergency conditions for both passenger (Gwynne et al, 2003) and naval vessels (Boxall et al, 2005) as well as the normal circulation of personnel for both passenger and naval vessels (Caldeira-Saraiva et al, 2004). These models produce a wide variety of simulation outputs, such as time to assemble, levels of congestion experienced, time required to undertake specific tasks, distance travelled by individuals in achieving goals and number of likely fatalities resulting 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 human factors (HF) performance associated with changes in vessel configuration across a wide range of scenarios and performance requirements.

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

This chapter proposes a methodology to assess changes in HF performance resulting from changes to vessel configuration. Furthermore, the methodology is intended to determine whether or not a net benefit results from imposed changes to the configuration and identify specific areas where performance may be improved. The approach is intended to be both diagnostic and discriminating. 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.

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 ES can take the form of evacuation or NOP scenarios and are intended to assess the design within its intended environment.

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 watertight 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 order for the proposed HPM methodology to be implemented, a number of steps are required. Each step is described in more detail in this chapter and the subsequent chapters. Each section of work will be classified as either implementing the HPM concept as a stand alone system, i.e. not requiring any other software except the human simulation tool maritimeEXODUS, or as an integrated system whereby it can accept and produce files for an external software. This integrated system will allow an external software tool, such as PARAMARINE (Pawling, 2007), to provide all the necessary information required for a human simulation tool such as maritimeEXODUS to set up and run simulations to test a geometry and produce the required data for the human performance matrix to be populated.

The work presented in this chapter has been published in the papers by Deere (2008a, 2008b, 2008c)

5.2 The Components of The Human Performance Metric

5.2.1 Evaluation Scenarios

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 1238 (IMO, 2007) and include the IMO night and day scenarios or their naval equivalent (NATO, 2006). 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 a set period of time.

To gauge vessel performance across a range of criteria, the ES consist of evacuation and NOP scenarios as shown in Table 5.2-1. NOP scenarios represent situations where the ship's 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 organization of personnel, equipment, machinery and watertight (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 watertight 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.

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 (NATO, 2006), much like the IMO MSC Circular 1238 (IMO, 2007). 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 ship's 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 remain open. Finally, in WT integrity condition Z, all WTD are shut.

The draft 'Naval Ship Code' (NATO, 2006) 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 as crew are able to utilise most areas of the vessel, although they would generally be within a particular region for example within a certain watertight zone. Only half the complement would be on watch, the other half could be in their cabins, mess room or somewhere 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.

Table 5.2-1 –List of Evaluation Scenarios

Evaluation Scenario identifier	Scenario
	Naval Evacuation Scenarios
ES_1	Normal Day Cruising A
ES_2	Normal Day Cruising B
ES_3	Action stations
- - -	- - -
	NOP scenarios
ES_4	State 1 Preps
ES_5	Blanket search
ES_6	Family Day A
ES_7	Family Day B
- - -	- - -
- - -	- - -
Etc	etc

Presented in Table 5.2-1 are a selection of possible ES that may be used as part of the HPM to assess the performance of naval surface combatants.

5.2.2 Functional Groups

As members of the ship's complement may be involved in undertaking different tasks during a particular ES, the ship's 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 overwhelm that of other FGs or be overwhelmed 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 on a naval vessel.

In addition to the FGs defined by a specific ship’s compliment, a special FG, identified as Entire 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. For example this FG would contain such PM as the final time it takes for the scenario to be completed, the total number of WT doors used on board during the scenario and the number of severe congestion regions which develop during the scenario.

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 FGs. The crew can be in different FGs in different ESs, 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 5.2-2 are a selection of possible FGs that can be found on board naval combatants.

Table 5.2-2 – Example List of Functional Groups

Functional Group Identifier	Function Group
FG_1	Entire ships company
FG_2	Damage Control and Fire Fighting
FG_3	Civilians
FG_4	Warfare
FG_5	Flight
- - -	- - -
- - -	- - -
Etc	etc

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

Some 31 PMs have been defined which assess many aspects of crew performance for a frigate. These PMs were defined in conjunction with our project collaborators in the Royal Navy and were 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 in metres, while non-dimensional parameters simply return numerical values such as 'number of WT 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. The current list of the PMs identified for the analysis presented in this thesis are presented in Table 5.2-3.

a) CONGESTION CRITERIA

This group contains two PMs extracted from the IMO Circ. 1238 (IMO, 2007) relating to the level of congestion experienced by FG during an ES. They measure the amount of time that an area of congestion exceeds the regulatory limit of 4 persons/metre^2 for longer than 10% of the overall simulation time. These criteria can be used to identify possible bottlenecks and other causes of congestion

b) GENERAL CRITERIA

This group contains five PMs which assess the performance of the FGs in completing general activities associated with the ES. They relate to the length of time it takes on average for each member of the FG to traverse the vessel and complete their tasks. The PM are useful in determining how long it took the FG to complete their part of the scenario as well as determining the level of congestion experienced.

c) PROCEDURAL CRITERIA

This group contains two PMs which assess the performance of the FGs in completing specific tasks associated with the ES. This can help in identifying whether more people are required to speed up the completion of tasks.

d) POPULATION CRITERIA

This group 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. These PMs are useful for assessing whether or not more or less crew members are required in the group to carry out the specified tasks.

e) GEOMETRIC CRITERIA

This group 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; M_1: the number of WTD used in the ES and M3: the number of times the FG moved between decks.

Table 5.2-3 - List of Performance Measures

Specific Performance Measure	Description
	CONGESTION CRITERIA
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'
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	Average level of individual exposure to narcotic gases (FIN)
E_2	Average level of exposure to elevated temperatures or radiative fluxes (FIH)
E_3	The number of fatalities
E_4	The % of the geometry affected by the spread of smoke
E_5	The average time that individuals spent in (significant levels) of smoke
- - -	- - -
	GENERAL CRITERIA
G_1	Average time required for each member of FG to complete all their tasks
G_2	Average time spent in transition
G_3	Time to reach final state
G_4	Average time spent in congestion
G_5	Average distances travelled by each member of FG
G_6	Time for group to reach dispersal stations
- - -	- - -

	PROCEDURAL CRITERIA:
P_1	The total number of operations completed by function group
P_2	The average number of operations required per active member of staff
P_3	The average time to complete each functional group task
- - -	- - -
	POPULATION CRITERIA:
U_1	The overall population size
U_2	Percentage of inactive population (compared to group 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 ladders used during the scenario.
M_4	The number of 60 degree stairs used during the scenario.
M_5	The number of doors used during the scenario.
M_6	Longest time that a WTD was open during scenario.
M_7	Longest time that a Hatch was open during scenario.
M_8	The number of times the population moved between decks
M_9	Longest time that a Smoke Curtain was open
M_{10}	Average number of components used by the FG during the ES
M_{11}	Most number of times a WT door was operated by the FG during the ES
M_{12}	Most number of times a hatch was operated by the FG during the scenario
M_{13}	Average number of WT doors used per member of FG
M_{14}	Average number of Hatches used per member of FG
M_{15}	Average number of doors used per member of FG
M16	Time to close all WT doors (i.e. time to achieve WT integrity Z)
M17	Time to report back that vessel has upheld WT integrity
M18	Dispersal Time
- - -	- - -

5.3 Defining the Human Performance Metric Structure

The HPM is used to compare the human performance capabilities of competing vessel designs X_1, X_2, X_3, … X_n. These alternative designs may simply be different iterations of a particular vessel design or competing design options. To assess the performance of the vessels, a set of evaluation scenarios ES_1, ES_2, …. ES_n are selected (see Table 5.2-1) which are relevant to the intended operation of the vessel.

The design alternatives are then populated with the required number of personnel and the crew assigned to their functional groups FG_1, FG_2….FG_n (see Table 5.2-2). 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 5.2-3).

Within a design alternative, each ES may have a different set of FGs and each FG may have a different set of PMs, but the structure of the HPM (formed of ES, FG and PMs) must be identical between competing vessel designs in order to make a direct and meaningful comparison.

The relationship between the various components of the HPM is illustrated in Figure 5.3-1. It must be noted that every design alternative must have the same structure in order for a direct comparison to be made between designs and for the HPM to be used as a diagnostic tool.

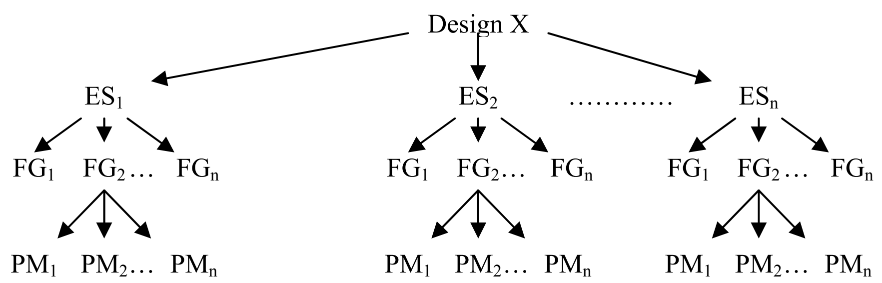


Figure 5.3-1 - Tree diagram setting out the relationship between the various components of the HPM.

5.3.1 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,

$a_{i,j}(PM_k)$ = Performance score derived from the simulation software for evaluation scenario ES_i, functional group FG_j and performance measure PM_k.

Each page in the HPM is made up of a collection of these raw scores as shown in Table 5.3-1.

Table 5.3-1: 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	$a_{n,n}(PM_1)$	$a_{n.n}(PM_2)$	- - -	$a_{n,n}(PM_n)$	- - -
:	:	:	- - -	:	- - -

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') during the evacuation ESs, are normalised using the largest performance score from the competing design variants as shown in Equation (5.3.1).

$$\bar{a}_{i,j}(PM_k). = a_{i,j}(PM_k) / max_{i,j}(PM_k) \qquad \textbf{Equation 5.3.1}$$

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 and greater than or equal to 0.0. 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 (ES), the Performance Measure (PM) G_3 (time to reach final state) is normalised using the regulatory defined maximum (IMO, 2007). Thus a value of 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. Alternatively, appropriate weights could be determined through canvassing expert opinion using the Delphi method (Harmathy, 1982).

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 Equation (5.3.2).

$$\acute{\alpha}_{i,j} = (A_{i,j,1} \times \bar{a}_{i,j}(PM_1)) + (A_{i,j,2} \times \bar{a}_{i,j}(PM_2)) + \text{- - -} + (A_{i,j,n} \times \bar{a}_{i,j}(PM_n)) + \text{- - -} \qquad \textbf{Equation 5.3.2}$$

The HPM with functional group score are presented in Table 5.3-2.

Table 5.3-2 - 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)	- - -	- - -		$\acute{\alpha}_{nn}$
:	:	:	:	:	- - -	- - -	:	:	- - -	- - -		:

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 Equation (5.3.3).

$$SS_i = (B_{i,1} \times \acute{\alpha}_{i,1}) + (B_{i,2} \times \acute{\alpha}_{i,2}) + - - - + (B_{i,n} \times \acute{\alpha}_{i,n}) + - - - \qquad \textbf{Equation 5.3.3}$$

Crew members can be a member of more than one function group. For example, all crew are members of FG_1 (the entire population) and some of these may also be a member of the damage control and fire fighting group (FG_2). To avoid crew performance being counted more than once, the weights assigned to the various FGs must sum to 1.0. Thus, in ES involving only FG_1 i.e. the entire ship's 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. As such, 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.:

$$B_{i,1} = 0.5$$
$$\sum B_{i,j} = 0.5 \text{ where } j > 1$$

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 SS_i will have a weight associated with it C_i, where subscript i refers to evaluation scenario ES_i. Hence the overall Vessel Performance VP_x for design X is given by Equation (5.3.4).

$$\mathbf{VPx = (C1 \times SS1) + (C2 \times SS2) + - - - + (Cn \times SSn) + - - -} \qquad \textbf{Equation 5.3.4}$$

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 Equation (5.3.5).

$$SFG_1 = (\acute{\alpha}_{1,1} \times B_{11} \times C_1) + (\acute{\alpha}_{2,1} \times B_{21} \times C_2) + - - - + (\acute{\alpha}_{n,1} \times B_{n1} \times C_n) + - - -$$

Equation 5.3.5

The HPM with scenario and design score along with the all the associated individual scores and weights are presented in Table 5.3-3.

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. Since the performance measures are designed such that the lower their score the better the performance when compared to the other designs, therefore the design alternative with the lowest overall vessel performance is considered the best design. 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.

Table 5.3-3 - General HPM for Design X showing individual weights.

Design X												
Evaluation Scenario	Functional Groups											
	FG_1		FG_2		- - -		FG_n		- -		Scenario Score	Scenario Weight
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								$VP_{DESIGN(X)}$	

5.4 Sensitivity analysis of the HPM Concept

In order to assess the confidence of the result from analysis of the HPM, it would be required to know how sensitive the HPM is to a small / large change in any of its components, especially with respect to the weights. The values of the performance measures are obtained from simulation software which are controlled by a set of rules and constraints however, the weights are obtained from the opinion of a human and therefore are bias. For example a designer could have very different ideas as to what is important to the human factors of a design, to a crew member using the final built vessel. Even though the concept proposed in this chapter is reproducible, the HPM could be recreated with different weights. It would be useful to develop a method which will show how sensitive the HPM is to a change in the weights. Indeed it would also valuable to know how much of an effect changing a normalised PM value would have on the scenario and also the overall vessel performance.

5.4.1 The sensitivity of a Scenario

Firstly let us analyse the potential impact of changing a normalised PM value or its weight on the scenario.

The scenario score (SS) is made up from the weighted (W) sum of all the performance measures (PM), thus:

$$\mathbf{SS_1 = W_1PM_1 + W_2PM_2 + W_3PM_3 + W_4PM_4 + - - - + W_nPM_n} \qquad \textbf{Equation 5.4.1}$$

To devise a method to determine the sensitivity of the metrics it would be worth comparing the scenario score against the same scenario but with slightly different values. Thus it would be possible to ascertain;

a) how much to change a value in order to reach a desired performance from the design
b) how much of an error could creep into the metric

With this in mind, it is necessary to introduce a new term to the formula which accounts for the change in values that make up the scenario score.

$$\mathbf{SS_2} = \left(\frac{100 - X}{100}\right)\mathbf{W_1PM_1 + W_2PM_2 + W_3PM_3 + W_4PM_4 + - - - + W_nPM_n} \qquad \textbf{Equation 5.4.2}$$

From Equation (5.4.2), it can be seen that the first term, W_1PM_1, is multiplied by X%; where X is the percentage change in the weighted performance measure score or its weight, for example X = 10 equates to a 10% reduction in the weighted performance measure score W_1PM_1. Equally X = -10 equates to a 10% increase in the weighted performance score. Therefore by changing the value of X, effectively either the weight or the normalised PM score can be decreased by the value of X. With the value of X being 0, there would be no difference between SS_1 and SS_2. At the opposite extreme the value of X = 100 would have the effect of removing that PM from the formula.

The next task is to see how much a change in the values can affect the scenario score. This can be done by working out the percentage difference between the original scenario score (SS_1) and the altered scenario score (SS_2).

$$\frac{SS_2 - SS_1}{SS_1}$$

Using Equation (5.4.1) and Equation (5.4.2), we can create a formula which will work out how much of an affect changing a single normalised PM value and / or its weight can have on the scenario score and by rearranging that equation it would also be possible to calculate how much to change a normalised PM value in order to obtain a desired result from the design.
The formula to see the effect of changing a PM's normalised value and / or its weight has on the scenario score is:

$$\frac{SS_2 - SS_1}{SS_1} = \frac{-\frac{X}{100} \times W \times PM}{SS_1} \times 100$$ **Equation 5.4.3**

Equation (5.4.3) will calculate the effect that X will have on the scenario score in the form of a percentage difference. The x100 value has been added to Equation (5.4.3) just for the purpose of creating a percentage and was not there when the equation was formulated from Equation (5.4.1) and Equation (5.4.2). This equation can then be rearranged to make X the subject (see Equation (5.4.4) below). This would allow the assessor to calculate how much a single normalised PM value would need to be changed by in order to achieve a desired performance from the scenario.

$$X = 1 + \frac{(SS_2 - SS_1)}{W \times PM}$$ **Equation 5.4.4**

5.4.2 The sensitivity of a HPM

The same means of devising equations can be used to create a system to see the effects of changing a normalised PM value or its weight on the overall vessel performance score.

If the following equations were used to calculate the original vessel performance score and the desired vessel performance score, then it would be possible to calculate the percentage difference between the two.

V_1 = original Vessel Performance score = $W_1SS_1 + W_2SS_2 + W_3SS_3 + - - - + W_nSS_n$
V_2 = desired Vessel Performance score = $W_1SS_1 + W_2SS_2 + W_3SS_3 + - - - + W_nSS_n$

Where SS_1 in V_2 should be rewritten to take into account the change in the normalised PM value or its weight:

$$\mathbf{SS_1} = \left(\frac{100 - X}{100}\right)\mathbf{W_1PM_1 + W_2PM_2 + W_3PM_3 + - - - + W_nPM_n} \qquad \textbf{Equation 5.4.5}$$

If the percentage difference between VP_1 and VP_2 was calculated, it would be possible to see how much of an affect X has on the vessel performance score. Thus we want to calculate:

$$\frac{V_2 - V_1}{V_1}$$

Taking this into account the percentage difference between the two vessel performances can be written as:

$$\frac{V_2 - V_1}{V_1} = \frac{-W_{ss}\left(\frac{X}{100} \times W \times PM\right)}{V_1} \times 100 \qquad \textbf{Equation 5.4.6}$$

Where X is the percentage difference made to the normalised PM value (PM) or its weight (W), W_{SS} is the weight of the scenario and V_1 is the original vessel performance score. The result of this equation will provide the percentage difference ($V_2 – V_1 / V_1$) that the change in the normalised PM value and / or weight has on the overall vessel performance score.

This equation, Equation (5.4.6), can be rewritten in order to work out how much to change a single normalised PM value or its weight in order to obtain a desired performance from the scenario. This is achieved by rearranging Equation (5.4.6) to make X the subject.

$$X = 1 + \frac{(V_2 - V_1)}{Wss \times W \times PM}$$ **Equation 5.4.7**

Where V_2 is the desired vessel performance score and the resulting X value is the fraction with which to multiply the normalised PM value or its weight by in order to achieve the desired vessel performance.

It must be remembered that these equations only take into account the change of one PM, in practise when attempting to achieve the desired performance from a scenario, either by modifying the procedures employed or the geometry of the vessel, a number of the PMs will be affected. As such the value produced from the equations should be used as a guideline. If the actual change in the performance is higher than the predicted value then the changes made has had a better than expected effect on the performance of the design. This would be due to the implemented change having a positive effect on the majority of the PMs. However, on the other hand if the actual change in the performance is lower than the predicted value then the changes implemented, although improving the performance of the isolated PM, has a detrimental effect on the majority of PMs in the scenario.

So far it has been assessed how much of an affect a single PM can have on the scenario and overall vessel performance, however there is one more permutation to examine which is, what affect does a change in the scenario score or its weight have on the vessel performance score.

In essence, this is the same as calculating the effect of changing a PM value on the scenario score except in this case we are examining one stage up in the HPM structure.
In this instance, to compute the vessel performance score, the sum of all the weighted scenario scores would be calculated. As such:

$$VP_1 = W_1SS_1 + W_2\,SS_2 + W_3\,SS_3 + - - - + W_n\,SS_n$$ Equation 5.4.8

Then if there was a change in one of the scenario scores or its weight, we would have the equation:

$$\mathbf{VP_2} = \left(\frac{100 - X}{100}\right)\mathbf{W_1SS_1 + W_2\,SS_2 + W_3\,SS_3 + - - - + W_n\,SS_n} \qquad \textbf{Equation 5.4.9}$$

Using Equation (5.4.8) and Equation (5.4.9), the percentage difference between the two vessel performance scores would be calculated as follows.

$$\frac{VP_2 - VP_1}{VP_1} = \frac{-\frac{X}{100} \times W \times SS}{VP_1} \times 100 \qquad \textbf{Equation 5.4.10}$$

Where W is the weight applied to the selected scenario (SS) and X represents the percentage change applied to the scenario. Equation (5.4.10) will allow the assessor to calculate how much of an affect, as a percentage, a change in the selected scenario score or its weight will have on the overall vessel performance.

As before, Equation (5.4.10) can be rearranged to make X the subject. This would then permit the calculation of the fraction with which the scenario would need to improve by in order to reach a desired vessel performance (VP_2). Doing this produces the following equation:

$$X = 1 + \frac{(VP_2 - VP_1)}{W \times SS} \qquad \textbf{Equation 5.4.11}$$

Each of the six equations devised (Equations (5.4.3), (5.4.4), (5.4.6), (5.4.7), (5.4.10) and (5.4.11)), can be used to calculate the effect on the HPM of changing either the normalised PM value (or scenario score in the case of Equation (5.4.10) and Equation (5.4.11)) or its weight. Therefore, each equation could be used to assess how much of an effect a change in the structure or procedures employed could have on the HPM, for instance, how much of an impact would it have on the HPM if one location of severe congestion was eliminated or if it was possible to reduce the overall simulation time by 60 seconds. Alternatively these equations could be used to see how much of an impact on the HPM there would be if the weights were changed. For instance, the designer of the vessel believes that the level of congestion is very important and as such gives the appropriate weight a value of 8, but the prospective captain of the vessel believes the level of congestion to be far less important than the time it takes to complete a scenario and as such gives a weight of 4 to the respective congestion PM. The equations developed in this section could be used to see if there would be any great difference in the results by using each set of weights.

It must be noted that the normalised PM value is utilised in the creation of these equations since it is these values which are used to calculate the scenario scores and vessel performance scores. If the raw data values were used then these values would have to be normalised.

5.4.3 Factors affecting sensitivity of the HPM

From testing these sensitivity equations, it became apparent that there are three factors which affect the sensitivity of the HPM. These are the number of performance measures and scenarios, the relative difference between the raw data values and the size of the weights.

It was found that the greater the number of each component that exists, the smaller the effect of changing any one of them will be on the HPM. This comes about since the more PMs there are the higher the value for SS_1 in Equation (5.4.3) and Equation (5.4.4). Therefore the larger the denominator will be in Equation (5.4.3) and the larger the numerator in Equation (5.4.4). In Equation (5.4.4), this has the effect of increasing the value of X which is required to change the value of the normalised PM value or its weight by in order to achieve a desired level of performance from the design. Having more scenarios or having more PM in each scenario will have the effect of increasing the value for VP_1 in Equation (5.4.10) and Equation (5.4.1)). As with changing the value of SS_1, this has the effect of increasing the denominator in Equation (5.4.6) and increasing the numerator in Equation (5.4.7).

Regarding the relative difference between PM raw data, if it is possible to half a PM's raw data value, this could have the effect of making the design more efficient than other designs in that PM or could just make the design more competitive against other designs. This can have a large difference on the impact that it has on the HPM.

The third factor affecting the sensitivity of the HPM is the size of the weights. The weights are there to incorporate the importance of the component, whether that is the performance measure in Equation (5.4.3) and Equation (5.4.4) or the scenario as in Equation (5.4.6) and Equation (5.4.7). As such if a PM or scenario has a high weight then it is considered an important PM / scenario and if it has a low weight then it is considered to have little importance to the HPM. The problem here is that a large change in the normalised PM value with a small weight can be swamped by relatively low changes in the normalised values with a relatively high weight. This could potentially lead to oversight of problems which reside within the design. Thus a significantly large change in the performance of a PM or scenario can be missed due to it having a small weight while a relatively small change in a PM can be highlighted by a large weight. This factor helps to demonstrate how important it is to assign weights appropriately to the scenarios and performance measures.

In addition to these six developed equations, an alternative method to assess the sensitivity of the HPM in terms of the weights is to set all of them to 1. This has the effect of removing the importance of the component, whether that be the performance measures, functional groups or the scenarios. In this instance, it can be concluded what affect the scenario weights have on the HPM (with the scenario weights set to 1 and all other weights as they are), what affect the PM weights have on the HPM (with PM weights set to 1 and all other weights as they are) and finally what affect having no weights has on the HPM (with all PM, FG and ES weights set to 1).

5.5 Use of Gold Standard

The Human Performance Metric approach to assessing the human factors performance of a structure does not merely need to compare two (or more) designs and select the most efficient design, the approach can also be used for regulatory purposes. This can be achieved by defining the structure of the HPM to match the requirements of the regulations, i.e. have the scenario(s) as defined by the regulations and the performance measures which are defined as pass / fail criteria for the ES. If a design has any normalised PM with the value of 1 then the design would be deemed to have failed to meet the regulatory standard. In this sense, there only needs to be one design in the analysis.

Classification societies, regulatory bodies, fleet owners and new ship customers can all use the HPM concept in order to define the standards with which a new design should meet in terms of its human factors performance. An existing vessel design can be elected as being the standard for HF performance, and then any new design must at the very least match the performance of this benchmark design. In this fashion, fleet owners can also impose specific performance related criteria such as 'the new design must be able to evacuate at least 15% more efficiently than this existing vessel'

5.6 Summary

This chapter has put forward a novel approach to assessing the human factors' performance of a design.

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 modified.

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 vessel owner 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.

Chapter 6

Defining a HPM for a Naval Vessel

6.1 Introduction

This chapter will aim to define a human performance metric for a naval vessel. Since different vessels in a navy have very different roles to perform, such as the difference between an aircraft carrier and a submarine, the evaluative scenarios (ES) utilized to assess the designs would be quite different. Therefore it would be rather difficult, if not impossible, to compose a generic HPM that could be used for all types of naval vessel. For this reason, the work carried out in this chapter and during the rest of the thesis is based upon a specific ship type.

Discussions with our UK MoD project partners, working on the 'EGO' project (see Chapter 1 – Introduction), suggested that a surface combatant vessel would be an appropriate vessel type to concentrate on due to the varied roles that they have to perform. In particular the MoD suggested the Type 22 Batch III frigate since information relating to this design could be readily available for the project. In addition, our point of contact in the UK MoD had personal experience on board a Type 22 Batch III frigate and as such would be in a better position to aid in the definition and implementation of the evaluative scenarios for use in the HPM.

Originally built for anti-submarine warfare, the Type 22 Batch III frigates evolved into general purpose frigates with substantial anti surface and anti aircraft weaponry in addition to the anti-submarine capabilities. There were four vessels of this class built, those being the Campbeltown, Chatham, Cornwall and Cumberland. To date all four vessels are still in active service. Each vessel is approximately 148 metres long and 14 metres wide and can carry a complement of around 250 crew members (Royal Navy, 2011).

This chapter will now present the outcome of discussions with the UK MoD regarding which scenarios should be simulated, what these scenarios entail and what functional groups would be required for each ES. In addition, this chapter presents the performance measures which were recommended to the UK MoD as appropriate for assessing the selected ES.

6.2 Evaluative Scenarios

As defined in Chapter 5, Evaluation Scenarios (ES) are intended to define the scope of the challenges the vessel will be subjected to during its lifetime. In order to gauge vessel performance across a range of criteria, the ES are made up of both evacuation and normal operations (NOP) scenarios.

For the demonstration of the Human Performance Metric for the UK navy's Type 22 Batch III frigate, three evacuation ES and three Normal Operational (NOP) ES were defined. The evacuation ES defined consisted of evacuation from 'normal day cruising' state and evacuation from 'action stations'. The NOP ES defined for the HPM demonstration consisted of 'State 1 Preps', 'Blanket Search' and 'Family Day'. These were suggested and defined by the UK MoD project partners working on the EGO project.

The evacuation ES were suggested as appropriate to fully satisfy the Naval Ship Code (NATO, 2006). In addition to these ES, the UK MoD project partners were very interested in modelling the normal operational scenarios. They selected scenarios which could be considered most important and frequently performed on this class of vessel.

Presented in Table 6.2-1 is the selection of ES that would be used as part of the HPM assessing the performance of Type 22 Batch III naval surface combatant. This is not by any means a definitive list of ES to assess the Type 22 Batch III but was considered sufficient to demonstrate the HPM concept. These Evaluative Scenarios will now be discussed in greater detail.

Table 6.2-1 –List of Evaluation Scenarios

Evaluation Scenario identifier	Scenario
	Naval Evacuation Scenarios
ES_1	Normal Day Cruising A
ES_2	Normal Day Cruising B
ES_3	Action stations
- - -	- - -
	NOP scenarios
ES_4	State 1 Preps
ES_5	Blanket Search
ES_6	Family Day A
ES_7	Family Day B
- - -	- - -

6.2.1 ES_1 – Normal Day Cruising A and ES_2 – Normal Day Cruising B

The normal day cruising scenario involves the ship's complement initially located at their state 3 (cruise) locations. The vessel is considered to be in a safe haven whereby no attack is expected without prior warning and as such the vessel is in state 3 with watertight (WT) integrity condition X. This means that the majority WT doors can be open.

The scenario would then begin with the identification of an incident, such as a fire. The ship's company move from their state 3 locations to their emergency stations in preparation to deal with the incident. The fire repair party would dress in full fearnought fire fighting clothing and attend to the incident. If the incident then becomes uncontrollable and the vessel is considered uninhabitable then the commanding officer will give the command to evacuate, at which point the entire ship's company will move to the muster stations where they will be given vital life saving equipment, such as life jackets, life suits etc. The crew would then disembark the vessel by any means possible, whether that is by life raft or jumping over the side.

After consultation with the UK MoD project partner (SSG), the industrial partners on the 'EGO' project, it was suggested that there would be a great interest in simulating the crew's movement to the emergency stations and then simulating the crew's movement from the emergency stations. Therefore on this basis, the normal day cruising scenario was split into two separate scenarios, namely Normal Day Cruising A and Normal Day Cruising B.

Normal Day Cruising A would simulate the crew's movement to the emergency stations and Normal Day Cruising B would simulate the crew's movement to the muster stations. Essentially Normal Day Cruising B scenario would start the simulations with the crew in the same locations where they finished during the Normal Day Cruising A scenario. However, the ship would be considered to be in state 1 at the start of the Normal Day Cruising B scenario. In this state, the ship would be at watertight integrity condition Z whereby every WT door on the vessel is considered to be shut.

In summary there are two scenarios to be simulated here:

Normal Day Cruising A;

This scenario simulates the ship's complement moving to their emergency stations from their state 3 locations.

Normal Day Cruising B;

This scenario simulates the ship's complement moving from their emergency stations to the muster stations.

6.2.2 ES_3 – Action Stations Evacuation

A final scenario required to satisfy the Naval Ship Code (NATO, 2006) consists of an evacuation whereby the crew start from their action stations, i.e. their state 1 location.

The Action Station Evacuation scenario involves the ship's complement initially located at their state 1 (action) locations when an incident is identified and the need to evacuate arises. During this scenario the vessel would be considered to be in a war zone whereby an attack is imminent and as such the vessel would be in state 1 with a watertight integrity condition Z. This means that all the WT doors must be closed in order to contain any damage which the ship may sustain.

After the identification of the incident the alarm would be sounded and the call to abandon ship is given. This is then the starting point for simulating the scenario. The complement would then move from their state 1 location directly to the muster stations where they would receive vital life saving equipment prior to disembarking the vessel.

This differs from ES_1 and ES_2 since the ship would be at its highest state of preparedness and readiness for an incident of such nature and as such the NBCD (Nuclear, Biological, Chemical, Defence) teams would already be in position to tackle the incident. This reduces the need to get people into position. Additionally, during ES_1 the vessel would be in state 3 with a watertight integrity condition of X, meaning that most WT doors would be open, conversely during this scenario, the vessel would be in state 1 with a watertight integrity of Z, meaning that all WT doors would be closed. This means that the crew would have to encounter closed WT doors in this scenario which would slow their progress in moving around the ship.

6.2.3 ES_4 - State 1 Preps

The aim of this normal operational scenario is to prepare the vessel for a battle situation. All watertight (WT) doors are closed to bring the vessel to WT integrity condition Z and the ship's complement and machinery is organised such that the vessel is at it's highest state of preparedness and readiness to deal with any emergency that might occur.

This scenario can commence with the ship in state 2 or in state 3. The scenario, as the title suggests, involves the vessel changing to state 1.

With the vessel initially in state 3, the crew would be at their state 3 (cruise) locations and the ship would have a watertight integrity condition X. In this situation a complete State 1 Preps would be required. This would require such tasks as securing all loose items, switching off all unnecessary lighting, patrols being set up, fire lockers and fire fighting equipment being checked, smoke curtains checked and stowed away, portable pumps checked and isolating the sanitary system. All WT doors are required to be closed. The exact list of tasks required to be perform would depend on the nature of the vessel's operations.

With the vessel initially in state 2, the crew would be at their state 2 (defence) locations and the ship would have a watertight integrity condition of Y, whereby in general the WT doors below the waterline would be shut and the rest can be open. In this situation the majority of the tasks required for the vessel to be considered to be in state 1 would have been carried out. Therefore the process of changing state becomes much simpler. The entire complement are still required to move to their state 1 locations, the patrols will need to be set up and the NBCD teams will need to be assembled and prepared for any emergency. At the same time members of the NBCD team would need to go around and close all WT doors in order to up hold a watertight integrity condition of Z.

For the purposes of the work carried out in this PhD thesis, the naval vessel in question will initially be in state 3 and will require the crew to move to their state 1 (action) locations and close all the WT doors. The ships compliment will also need to secure all loose items, fire lockers and fire fighting equipment being checked and portable pumps checked.

As a general rule of thumb, it was suggested that this scenario would take no longer than 45 minutes to complete, however this was not a strict requirement and certainly not a pass/fail criteria.

6.2.4 ES_5 - Blanket Search

In this scenario, the vessel is considered to be in state 1, i.e. the ship is at waterintegrity condition Z with all WT doors closed, and the complement are at their state 1 (action stations) location. The scenario involves the commanding officer suspecting that the vessel has taken onboard damage. The commanding officer will then give the command to blanket search, for which the complement search every possible space looking for damage and then report back their findings to HQ.

To simulate this scenario the following storyboard will be used:
The crew will start at their state 1 positions with all the WT doors closed. Eight crew members will be selected from the damage control and fire fighting group and sent to the forward and aft FRPPs (Fire Repair Party Post). These eight crew members will be split into pairs and assigned a WT zone to search (there are four WT zones on board the selected vessel analysed in this thesis) and assigned a dispersal station within their specified WT zone. These dispersal stations are positioned as far away from the FRPP station and each other as possible. The crew will be sent to the dispersal stations in their pairs. Once all 8 crew members are at their dispersal stations, the command to search the vessel is given. At this point the entire complement search the compartments they are in and report in their findings to HQ. In the meantime, the eight crew members search all the unmanned compartments which have not been searched. The pairs of crew members at the dispersal stations follow the same routes as each other as they work their way around the WT zone that they are in, whereby the first crew member searches the first compartment while the second crew member searches the next compartment. Each pair will search all the unoccupied compartments of the WT zone they are in and then move on to search the next WT zone en route back to their FFRP. The crew members will limit the number of times they have to pass through WT zones since opening a WT door could let water or fire into their current WT zone.

Once all the compartments have been searched, these 8 crew members return to their state 1 position (i.e. their FRPP) where they will report their findings. The FRPP may then send the crew members back out to search more compartments if the FRPP has not received reports from other WT zones.

In reality, the crew members would report to HQ using a variety of different communicational methods such as hand held radios, internal intercom or by word of mouth. For the purpose of modelling the scenario, it is considered that the crew will search all the compartments and then report their findings in person to their FRPP. The FRPP will then transmit those findings to HQ using an internal telephone system.

6.2.5 ES_6 - Family Day A and ES_7 - Family Day B

The Family Day scenario follows the same storyboard and procedures as the Normal Day Cruising Evacuation scenario. The difference here is that there are a number of civilians on board.

For the purposes of the example application in this thesis there will be 60 civilians on board. These civilians will generally be in groups of 5 or 6 and would be escorted around the vessel by an off watch crew member. The groups of civilians are allowed to travel any where on the vessel which is above the waterline, which for the Type 22 Batch III frigate used in the example application is the No 2 Deck.

As with the Normal Day Cruising scenario, this ES is also split into two separate scenarios; Family Day A and Family Day B.

During Family Day A, the ship is considered to be in state 3 (Cruise) whereby the ship is considered to be in a safe area and would not expect any attack without prior warning. In this situation most of the WT doors are considered to be open and only a few crew members need be at their action stations, the rest can be any where on board the vessel.

At the start of this scenario, an incident such as a fire or flood is detected. The civilians are immediately ushered to the muster stations while the crew move to their emergency stations in preparation to tackle the incident. This scenario ends once all the civilians are at the muster stations and the crew are at their emergency stations

In reality there would now be an NBCD effort to resolve the incident and the ship would be brought up to state 1 (all WT doors would be closed).

The second scenario, Family Day B, starts where the first scenario ends: all the civilians are at their muster stations and the crew are at their emergency stations. For this scenario the ship is now considered to be in state 1 whereby all the WT doors are assumed to be closed. At the start of this scenario, the incident is considered to have become uncontrollable and the executive decision is given to evacuate, at which point the entire ship's complement move to the muster stations to join the civilians. Once all the crew have arrived at the muster stations, the simulation ends. However in reality, once at the muster stations the crew and civilians would disembark the vessel as quickly as possible by any means. In many cases the vessel would be moored up along side during this scenario therefore the population would disembark via platforms on to dry land. But due to the great number of possibilities as to how to disembark, the simulation was simplified to modelling the population to the muster stations.

6.3 Functional Groups

As members of the ship's complement may be involved in undertaking different tasks during a particular ES, the ship's 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.

As discussed in chapter 5, there should always be a functional group which assesses the entire population. This is labelled FG_1 'Entire Ships Company'. This FG is used to provide an overall measure of the performance of the ship's personnel when taken as a whole.

In addition to FG_1, It was suggested that both the 'State 1 Preps' and the 'Blanket Search' ES would contain a functional group labelled 'damage control and fire fighting' (FG_2). 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..

In relation to the ‘Family Day’ scenarios (ES_6 and ES_7), it was considered important to have a functional group which would assess the human factors performance of the civilians. Therefore the FG called ‘civilians’ (FG_3) was created. On naval vessels, these are a group of untrained people who are not familiar with the layout of the vessel or the procedures employed for the scenario being simulated. As such, civilians would normally travel around the vessel in groups which would be escorted by members of crew. In general, civilians would not be allowed down into the lower compartments such as the engine rooms and nor would they normally be allowed near ammunition, both for health and safety purposes.

In practise there may be many FG on board the vessel whose performance must be evaluated. Presented in Table 6.3-1 is the selection of FG which were considered sufficient to assess the ES defined in this chapter.

Table 6.3-1 –List of Functional Groups for Type 22 Batch III frigate

Functional Group Identifier	Function Group
FG_1	Entire ships company
FG_2	Damage Control and Fire Fighting
FG_3	Civilians

6.4 Performance Measures

As described in Chapter 5, Performance Measures (PM) uniquely assess a particular aspect of the scenario, whether that is 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.

For the work carried out as part of this PhD thesis 31 PMs have been defined which are designed to assess many aspects of crew performance for a Type 22 Batch III frigate. These PMs were defined in conjunction with our project collaborators in the UK Royal Navy and are considered to represent relevant performance indicators for the type of vessel under consideration. 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. These categories were described in more detail in Chapter 5. The list of the performance measures utilised during the analysis in this work is presented in Table 6.4-1. It must be noted that these were considered sufficient for the demonstration of the HPM concept for a UK Royal Naval Type 22 Batch III frigate. There are many more performance measures which could be used and every class of ship may have a different set of PMs.

Table 6.4-1 - List of Performance Measures

Specific Performance Measure	**Description**
	CONGESTION CRITERIA
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'
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	Average level of individual exposure to narcotic gases (FIN)
E_2	Average level of exposure to elevated temperatures or radiative fluxes (FIH)
E_3	The number of fatalities
E_4	The % of the geometry affected by the spread of smoke
E_5	The average time that individuals spent in (significant levels) of smoke
- - -	- - -
	GENERAL CRITERIA
G_1	Average time required for each member of FG to complete all their tasks
G_2	Average time spent in transition
G_3	Time to reach final state
G_4	Average time spent in congestion
G_5	Average distances travelled by each member of FG
G_6	Time for group to reach dispersal stations
- - -	- - -

	PROCEDURAL CRITERIA:
P_1	The total number of operations completed by function group
P_2	The average number of operations required per active member of staff
P_3	The average time to complete each functional group task
- - -	- - -
	POPULATION CRITERIA:
U_1	The overall population size
U_2	Percentage of inactive population (compared to group 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 ladders used during the scenario.
M_4	The number of 60 degree stairs used during the scenario.
M_5	The number of doors used during the scenario.
M_6	Longest time that a WTD was open during scenario.
M_7	Longest time that a Hatch was open during scenario.
M_8	The number of times the population moved between decks
M_9	Longest time that a Smoke Curtain was open
M_{10}	Average number of components used by the FG during the ES
M_{11}	Most times a WT door was operated by the FG during the scenario
M_{12}	Most times a hatch was operated by the FG during the scenario
M_{13}	Average number of WT doors used per member of FG
M_{14}	Average number of Hatches used per member of FG
M_{15}	Average number of doors used per member of FG
M16	Time to close all WT doors (i.e. time to achieve WT integrity Z)
M17	Time to report back that vessel has upheld WT integrity
M18	Dispersal Time

Each of the above performance measures will now be briefly described.

6.4.1 IMO DERIVED CRITERIA:

C1 – The number of locations in which the population density exceeds $4p/m^2$ for more than 10% of the overall scenario time

As part of IMO Circ. 1238, this is a pass/fail criterion. This measure identifies the number of severe congestion regions, which are defined as areas where the population density exceeds $4p/m^2$ for more than 10% of the total simulation time. In an evacuation scenario, if this measure is exceeded at any single location, the vessel is deemed to fail to meet the evacuation standard. This is also a very useful criterion in normal operational scenarios in identifying possible bottlenecks and would follow the same ethos as in the evacuation scenarios, whereby only a value of zero for the measure would be acceptable. This is a very useful criterion in diagnostic analysis. In identifying severe congestion, the designer should look into why the congestion developed and ascertain ways to eradicate them. Congestion regions can be avoided by providing alternative routes or modifying the procedures to disperse the population.

C2 – The maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time

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. A very low value for this measure will show that although there were areas of severe congestion, they were only just severe and the areas should be eliminated relatively easily. If on the other hand the value for this measure was high then a serious concern about the levels of congestion should be raised. There would be probably a lot of work involved in reducing the great level of congestion. Although it must be considered that this criterion is measured against the simulation time, if the final simulation time is low, then any congestion could be considered severe.

6.4.2 ENVIRONMENTAL CRITERIA:

E1 – Average level of individual exposure to narcotic gases (FIN)

This performance measure assesses the average amount of narcotic gases that each individual experienced during the simulation. With a value of 0, the agents are not exposed to any harmful gases, however as this value approaches a high value of 1, the agents are experiencing dangerously high levels of harmful gases such as carbon monoxide (CO) and hydrogen cyanide (HCN). Agents become incapacitated when this value reaches 1. This is a non-dimensional measure, having no units of measure.

E2 - Average level of exposure to elevated temperatures or radiative fluxes (FIH)

This performance measure assesses the amount of heat the average individual experienced during the simulation. With a value of 0, the population has not experienced any abnormal heat and this is what a designer should strive to achieve. If this value reaches 1, the agents are considered to have been incapacitated. This is a non-dimensional measure as it has no units of measure.

E3 – Number of fatalities

This is a measure of the total amount of fatalities incurred by a FG in completing the ES. This is probably the most important PM as no fatalities can be tolerated in any scenario on any vessel. If there are any fatalities then action should be taken to rectify this, either by modifying the vessel design or by altering the procedures used. This PM is a non-dimensional parameter which simply returns the number of fatalities incurred by the FG.

E4 – The % of the geometry affected by the spread of smoke

The higher this value, the greater proportion of the vessel that is uninhabitable. Since the smoke carries the narcotic and irritant gases, the higher the spread of smoke then the more the population will be exposed to the harmful gasses. In addition to this, the smoke restricts a person's vision making navigation through the vessel difficult. In light of these, it is strongly suggested that procedures are put into place in order to limit the value for this performance measure. Procedures could consist of inserting more smoke curtains, sprinkler systems, ventilation systems. All of which will help in controlling the spread of smoke through the vessel.

E5 – Average time that individuals of a FG spent in (significant levels) of smoke

The more time individuals spend in smoke the higher the levels of intake of narcotic gasses will be. This can lead to serious health issues and even death. This performance measure is measured in seconds and thus is a dimensional criterion.

6.4.3 GENERAL CRITERIA:

G1 – Average time required for each member of functional group to complete all their operations;

This performance measure assesses the average length of time it takes for each member of a functional group to complete their assigned tasks. This includes their response time, time required to traverse through vessel and the congestion experienced, as well as the time required to actually complete the tasks. If this value is close to that of PM G2 (see next measure), then it can be concluded that most of the crew completed all of their assigned tasks at the same time. However if there is a great difference between the value for this measure and the value for PM G2, then it can be concluded that a small number of people were responsible for the simulation time. In this situation, the designer could look at redistributing the tasks; this may result in reducing the overall simulation time (as measured by PM G2).

G2 – Average time spent in transition; i.e. moving from one location to another.

This is a PM which refers to the average amount of time individuals within a FG spend travelling to their target locations. Ideally, this PM should be kept as low as possible. High values could suggest that target locations associated with various tasks are too far apart or there is too much congestion on route or environmental factors such as smoke or damage may have affected the progress of the FG team members. This PM is a dimensional parameter measured in seconds.

G3 – Time to reach final state

This is an important measure which indicates the time required to complete the ES. As such it best indicates the overall performance of the vessel in each scenario. The lower the value for this measure, the more efficient the vessel layout and procedures employed. This PM is affected by all the other PMs and so on its own does not provide much diagnostic information. The PM is a dimensional parameter measured in seconds.

G4– Average time spent in congestion

This is a PM which refers to the average amount of time individuals within a FG spend travelling to their target locations. Ideally, this PM should be kept as low as possible. High values could suggest that target locations associated with various tasks are too far apart or there is too much congestion on route or environmental factors such as smoke or damage may have affected the progress of the FG team members. This PM is a dimensional parameter measured in seconds.

G5 – Average distances travelled by each member of functional group

This is a dimensional parameter which measures the average distance travelled by members of the FG. It is measured in metres. This can be an important measure in understanding why a functional group performed well / badly in the scenario. The further a crew member is required to travel, the more time required to complete the scenario. If the 'average distance travelled' is deemed to be detrimentally large, it may be necessary to rearrange the location of compartments in order to shorten common routes. Alternatively, it may be necessary to insert additional doors / ladders or passageways resulting in more direct routes between commonly used spaces. Another solution to lower the average distance travelled, could be to distribute the tasks over the functional group, thus requiring each member of the functional group to travel less in order to complete their tasks.

6.4.4 PROCEDURAL CRITERIA:

P1 – The total number of operations required to be completed by the functional group

This PM returns an integer value representing the total number of tasks which was required to be completed by the functional group. The more tasks required to be carried out by the functional group, in general, the longer it would take to complete the scenario. This is not strictly correct, since this measure does not take into account the type of task to be completed and the distance required to be travelled between tasks. The challenge for the designer is to strike a balance between the number of tasks required to be performed by the functional group and the number of crew members required to complete the tasks. The ideal situation would be to have as few crew members as possible. However this could be difficult since certain tasks may require a number of crew members to carry them out for example to fire a gun may require as many as five people. Also having few people performing the tasks may take an intolerably long length of time to complete the scenario.

P2 – The average time to complete each functional group task

This is a measure of the average time required to perform each task carried out by the FG in order to complete the ES. It is determined by adding the time to complete each task completed by the FG and dividing by the number of crew in the FG. The larger the value for this measure, the longer it takes for each member of the functional group to complete their tasks. If it is determined that crew members are taking too long to complete their tasks then additional crew members could be employed.

6.4.5 POPULATION CRITERIA:

U1 –Overall population size

This is a measure of the total number of people within the FG This PM is a non-dimensional parameter which simply returns the number of people within the FG. The higher this value, the more people required to man the ship the higher the costs are to maintain the vessel. If it is required to limit the number of crew members, then the number of tasks to be completed for each scenario need to be reduced. This can be done by introducing more automation, moving common tasks closer together thus allowing the crew members to perform the same number of tasks quicker or training crew members in more areas so that they can perform more tasks.

U2 – Percentage of inactive population

This measure is expressed as a percentage of the number of inactive crew members to the total number of people in the FG. The higher this value then the more people who could be better employed elsewhere in a bid to speed up the time required to complete each scenario. Alternatively, the higher the value for this measure then the more people who could be made redundant.

6.4.6 GEOMETRIC CRITERIA:

M1 – Number of WTDs used during the scenario.

This is a measure of the total number of Watertight Doors (WTD) operated by the FG in completing the ES. Depending on the state of the WT integrity, crew passing through a WTD will have to open all the clips, swing the door open, walk through the door, close the door behind and close all the clips. This can cause a lengthy time delay which will slow the individual's progress. Minimising the number of WTDs in the vessel, while still maintaining WT integrity will potentially reduce the time required to complete the ES. Additionally, changing the routes taken by the agents could also reduce the number of WTDs used, although this could increase the distance they have to travel which could also increase the time taken to complete their tasks. This PM is a non-dimensional parameter which simply returns the number of WTDs used.

M2 - Number of Hatches used during the scenario.

This PM assesses the total number of times hatches are operated by the FG in completing the ES. A crew passing through a hatch will have to open all the clips, swing the hatch open, climb through the hatch, close it behind them and close all the clips. This can cause a lengthy time delay which will slow the individual's progress. Minimising the number of hatches in the vessel, whilst still maintaining WT integrity will potentially reduce the time required to complete the ES. This PM is a non-dimensional parameter which simply returns the frequency of the use of hatches.

M3 - Number of ladders used during the scenario.

This performance measure assesses the number of times the population traverse vertically via ladders. Using ladders will slow an agents' progress in completing their tasks, since climbing a ladder takes longer than travelling the same distance horizontally. Therefore the aim should be to keep this number to a minimum. This performance measure assesses the frequency of ascents / descents and as such has no units of measure and is considered a non-dimensional PM.

M4 - Number of 60 degree stairs used during the scenario.

Similar to M3, this performance measure assesses the number of times the population traverse the vessel vertically using 60 degree stairs. Although an agent can climb up 60 degree stairs quicker than they can up ladders, 60 degree stairs will still slow an agent down in their quest to complete their tasks. This measure counts the number of times every member climbs up or down a 60 degree stair. Since this PM measures the frequency of an occurrence then there are no units involved and as such the PM is considered a non-dimensional PM.

M5 – Number of doors used during the scenario

This is the total number of doors used during the scenario, which includes WT doors, normal non-WT doors, sliding doors, double doors and hangar doors. If a door is used once then it is included in this number, if the door is used 20 times during the scenario then it is still only counted once in this number.

M6 – Longest time that a WTD was open during scenario

In scenarios whereby watertight integrity is highly important, for example State 1 Preps where all WT doors are to be closed, this measure is of great interest. This measure returns the most number of seconds that a WT door was open for. If this value is very high (when compared to the overall simulation time), it may suggest that the WT door responsible for this time may be extremely busy (i.e. in a dominant position). Alternatively it may mean that the WT door is in a remote location which takes a crew member a long time to reach in order to close the door. It would be very difficult to reduce this value since watertight zones / bulkheads are set at an early stage of the design and usually have very little room for adjustment. The only changes which can be made are to the precise location of WT doors along the bulkheads. Procedures could possibly be changed in order to keep WT doors closed for longer, however this should not make too much impact on completing the scenario. Although it is important to keep the WT doors closed, it is more important to get the scenario completed in as little time as possible.

M7 – Longest time that a Hatch was open during scenario.

This measure returns the most number of seconds that a hatch was open for during a scenario. For scenarios, such as the State 1 Prep ES, where the watertight integrity is of upmost importance, this measure is of great interest. These scenarios need these hatches to be open for as little time as possible to ensure that if the hull is breached, as much of the damage can be contained as possible. This is a dimensional performance measure returning a value in seconds.

M8 – Number of times the population moved between decks

This is a measure of the total number of times members of the FG were required to traverse between decks by using ladders or stairs in order to complete their tasks associated with the ES. Travelling the vertical distance between decks, i.e. climbing ladders or stairs is slower than walking the same distance horizontally. For this reason deck traversals should be avoided if possible. Furthermore, stairs and ladders are prone to heavy congestion as typically only one or two people can use these components at any one time. Whilst some travel between decks is unavoidable, if the value for this measure is considered too high it may be necessary to rearrange compartments so that common routes are contained on a single deck, alternatively modifications could be made to procedures in order to make individual routes more efficient. This PM is a non-dimensional parameter which simply returns the number of times agents move between decks.

M9 - Longest time that a Smoke Curtain was open during the scenario

In scenarios where an attack is imminent, for example State 1 Preps, this measure is of great interest. This measure returns the most number of seconds that a smoke curtain was open for. The smoke curtains are very important in controlling the spread of smoke in the event of a fire. This would mean that more of the vessel can be habitable for longer, providing more time for the crew to tackle the cause of the smoke. If this value is very high (when compared to the overall simulation time), it may suggest that the smoke curtain, responsible for this time, may be in a dominant position where it is frequently used..

M10 – Average number of components used by the FG during the ES

This measure returns the average number of structural components such as WT doors, non WT doors, ladders etc that each member of the functional group would expect to encounter en route to completing their tasks. The value of this criterion does not take into account the types of components encountered but every component will slow the individuals' progress.

M11 – Most times a WT door was operated by the FG during the scenario

This measure returns the most number of times that a WT door was opened and closed (as a pair). Every time that a door has to be operated, a time delay is applied which slows down the progress of the crew member operating it, therefore the lower this number, the less the population is delayed in carrying out their tasks. In addition, the more times that a WT door is opened, the longer the watertight integrity condition is not met.

M12 – Most times a hatch was operated by the FG during the scenario

This PM assesses greatest number of times that a hatch was opened and closed by the member of a functional group. With every hatch operation is an assigned time delay which will extend the time required for an agent to complete their tasks. Additionally, the more times that a hatch is opened, the longer the watertight integrity condition is not met.

M13 – Average number of WT doors used by the FG during the ES

This measure assesses the number of WT doors that each member of the FG uses en route to completing their assigned tasks. Operating WT doors can be a time consuming act and therefore the designer should try to limit the value for this criterion. Even walking through an opened WT door can slow a persons' progress. To reduce this value, the designer could look at reducing the number of times a person has to traverse between WT zones.

M14 – Average number of doors used by the FG during the ES

This measure assesses the number of doors (including non-WT doors, double doors, sliding doors and hangar doors) that each member of the FG uses en route to completing their assigned tasks. Operating doors can slow a person's progress in completing their tasks, although not as much as a WT door does.

M15 – Average number of hatches used by the FG during the ES

This measure assesses the number of hatches that each member of the FG uses en route to completing their assigned tasks. Operating hatches can slow a person's progress in completing their tasks. The user of the HPM concept should aim to keep this value to a minimum in order to reduce the time taken for an agent to complete their assigned tasks.

6.5 Summary

This chapter has laid out a HPM structure which can be employed to suitably demonstrate the HPM approach to assessing the human factors performance of a Type 22 Batch III frigate. This chapter has discussed the ES, FG and PM required in order to assess the HPM and has identified and defined seven ES required to assess the frigate along with three functional groups. In addition to these, 31 performance measures have been defined to assess the FG within each ES.

The following chapters will discuss the software developments required to model these identified ES, FG and PM as well as analysing the HPM for the Type 22 Batch III frigate.

Chapter 7

Software Developments Required for the Implementation of the HPM Methodology

7.1 Introduction

In this chapter we discuss the model development that was necessary in order to implement the HPM concept. In the first part of this chapter we consider the additional behaviours that were implemented into maritimeEXODUS in order to perform the naval normal operational (NOP) scenarios. The chapter then moves on to explore the requirements for semi-automating the process of producing and assessing the human performance matrix for each design. This has been achieved through the development of a stand-alone software tool known as the Human Performance Metric Analyser (HPM Analyser). The chapter also presents the development of the Scenario Generator, as a stand alone software tool which semi-automates and greatly simplifies the complex task of setting up a scenario.

The Scenario Generator and the HPM Analyser were designed and developed by the author of this thesis. Designing and testing the new behaviours described in this chapter, was also carried out by the author of this thesis, whilst the implementation of the behaviours in maritimeEXODUS were carried out by the maritimeEXODUS development team.

7.2 Developments within maritimeEXODUS

Before being able to assess the human factors performance of a design, it is necessary to ensure that the human factors in question can be modelled, i.e. that a simulation tool exists which has the necessary capabilities to model human factors during evacuation and normal operational scenarios. maritimeEXODUS has been demonstrated to be capable of simulating emergency evacuation scenarios (Galea, 2001), but the software was not designed for simulating general circulation scenarios on-board naval vessels. Therefore, additional itinerary tasks were required to modify the behaviour of the population during a general circulation scenario, to mimic those behaviours which were observed during the real life occurrence of the simulated scenario.

7.2.1 Behaviours

As mentioned in Chapter 3 (model review of maritimeEXODUS), prior to the work carried out as part of this PhD thesis, maritimeEXODUS had four itinerary tasks that could be assigned to agents. These were ‘Delay’, ‘wait’, ‘muster’ and ‘evacuate’ tasks which are explained below.

Delay

This is the most frequently used task. This command represents a time delay in the range of ‘minimum delay’ to ‘maximum delay’, whereby the agent will spend a random period of time stationary.

Wait

This task sends an agent to a specified location where they will remain for a specific time duration before moving on to the next task in their itinerary.

Evacuate

This instructs the agent to move directly to their nearest exit (LSA – Life Saving Appliance). No parameters are required for this task since the agent will automatically take the shortest path to the nearest LSA. maritimeEXODUS has been designed so that agents within certain zones (pre defined by the user) can be sent to a specific LSA.

Muster

With this instruction, an agent will move to a designated muster station. This will be selected depending on the agents' initial starting zone.

These commands are sufficient to satisfactorily simulate an emergency evacuation scenario; however, for maritimeEXODUS to simulate non-evacuation scenarios, such as those highlighted in Chapter 6, which would be of greater value on a naval vessel, maritimeEXODUS must be developed to incorporate the ability to model additional behaviours. The remainder of this section will discuss the new behaviours required to satisfactorily simulate each of the NOP evaluative scenarios discussed in Chapter 6; i.e. State 1 Preps, Blanket Search and Family Day scenarios.

Seven new behaviours were identified and implemented in maritimeEXODUS and three existing behaviours were further developed. The new behaviours were: 'Terminate', 'Give', 'Receive', 'Close door', 'Search Compartment', 'Blanket Search' and 'Repeat'. In addition to these, the 'delay' task was extended to 'delay zone' and the existing 'wait' command and group behaviours were developed.

7.2.1.1 Terminate Command

A fundamental difference between an evacuation scenario and a non-emergency scenario is the finishing location of the population. Traditionally, when simulating an evacuation scenario the entire population leaves the geometry and enters the LSA's or muster stations at which point the simulation is complete. However with non-emergency scenarios the majority of the population would expect to remain inside the geometry. Therefore, the first step in adapting maritimeEXODUS to simulate non-emergency scenarios is to develop the capability to enable agents to stop in the correct locations within the geometry and play no further part in the simulation.

In response to this requirement a new behaviour was developed called, '**Terminate'**. This behaviour involves 'terminating' an agent's involvement in the simulation. Put simply, this action, when reached, instructs the individual to stop. Their personal simulation clock will stop as well as all their other attributes (e.g. cumulative wait time), but maritimeEXODUS leaves the agent in place on the node within the geometry. Then once all individuals have either evacuated or terminated, the simulation will end. This in essence allows maritimeEXODUS to simulate circulation scenarios as well as evacuation simulations.

After testing this new behaviour in various scenarios, it became apparent that there were issues with instructing agents to 'terminate' on the last node they visited. The problem occurred with the possibility that individuals could 'terminate' on a node which was next to an internal exit, thus blocking the doorway and creating congestion with other agents who were trying to use the door. Since the individual instructed to 'terminate' would not move and the 'crowd of people' wishing to pass through the door would never dissipate, the simulation would continue indefinitely. It was therefore decided that the behaviour should be enhanced such that individuals would wander around or 'mill' about the last node and stay within the boundary of the presently occupied compartment (if defined). As such when the individual terminates, they will cease to take part in the simulation, but will then randomly move about within the current compartment zone (if defined). The enhanced behaviour was labelled '**TerminateMill'**.

7.2.1.2 Wait Command

As an alternative to the mill behaviour in the 'terminateMill' command, the 'Wait' command was developed. The 'wait' command, which was already implemented in buildingEXODUS, was adapted for maritimeEXODUS such that, when added to a agent's itinerary after the 'terminate' command, the agent moves to the specified location, as indicated in the 'wait' command, and waits there until either a set time has passed or, all other agents have terminated or evacuated, at which point the simulation ends. The 'wait' command was modified so that maritimeEXODUS would first check the status of all the agents remaining in the geometry and would then terminate the 'wait' command once all other agents have either terminated, evacuated or are carrying out the wait command in the same manner (i.e. ‘terminate’ command followed by ‘wait’), at which point the simulation will end.

This action will also ensure that an agent does not block the paths of others who are still participating in the simulation and trying to get to a particular location, for example, this command prevents the agent from terminating in front of a door. This action requires the following parameters to be specified; where the wait command is to be carried out and a time at which the agent should stop waiting. In general, when using the ‘wait’ command in this context, it is normally sufficient to set a simulation time of 9999 seconds. In some instances, NOP scenarios may take longer than 9999 seconds to complete and therefore the time set in the ‘wait’ command would have to be increased.

The difference between the ‘terminateMill’ command and the ‘terminate’ + ‘wait’ commands implemented is where the agent ceases to have an involvement in the simulation. In the case of the ‘terminateMill’ command, the agent moves to the specified location in the command and then ‘terminate’. Whereas in the ‘terminate’ + ‘wait’ command, the agent ceases their involvement in the simulation and then moves to another location.

The development of the ‘Terminate’ action was a key capability necessary to realistically simulate the normal operational (NOP) scenarios. The first scenario suggested by our UK MoD project partners to simulate was ‘State 1 Preps’. This was seen as the most challenging to model due the vast number of tasks being carried out by the population. The scenario has been defined in the previous chapter (Chapter 6) and is illustrated in a storyboard created for the scenario (Figure 7.2-1).

7.2.1.3 Behaviours required for the State 1 Preps scenario

It was originally decided that at the start of the State 1 Prep scenario, the ship’s complement would be located at their state 3 (cruise) locations. The crew would then move to their state 1 (action) location where they would report to their designated action station. Located at each action station would be a commanding officer who would give new orders to the crew. These orders would need to be completed in order to end the scenario.

The orders would include;

- Move to state 1 location,
- closing all watertight (WT) doors,
- searching every compartment and securing any loose items,
- checking all fire fighting equipment (including hoses, mobile pumps and valves),
- the fire fighters to dress in full 'fearnought' fire fighting gear,
- individuals or groups tasked with patrolling the vessel.

In practise many more orders would be issued but the tasks listed here have been considered sufficient to simulate a basic State 1 Prep scenario.

In order to better visualise the State 1 Preps scenario being simulated, a storyboard was created. This storyboard went through a number of iterations in consultation between the UK MoD and the author of this PhD thesis, before the final version (Figure 7.2-1) was agreed upon. This was considered an efficient method of accurately defining the client's (MoD) required scenarios.

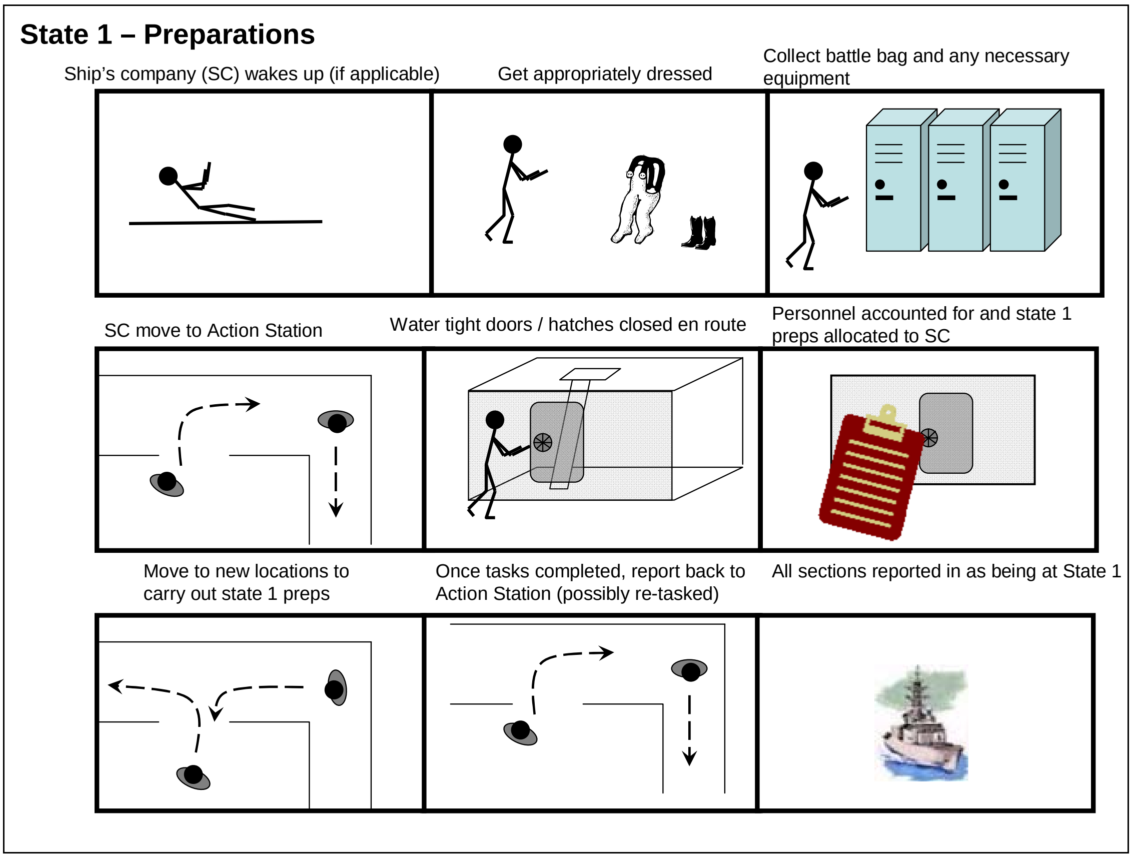


Figure 7.2-1 - Storyboard for State 1 Preps

From Figure 7.2-1, the first picture box (top left), requires setting appropriate response times to the ships company and does not require any additional developments within maritimeEXODUS for its implementation. The second picture box (top centre) and third (top right) requires crew members to experience a delay to represent the time taken to get appropriately dressed and collect equipment. These make use of the aforementioned ‘delay’ command and thus do not require any developments within the maritimeEXODUS model.

The fourth picture box (left, centre row) requires an agent to move into a specified compartment. Previously this would have entailed assigning a delay task to an agent on a specified node, however it was considered more efficient from the user’s point of view to assign a delay to an agent in a specified compartment zone rather than a node.

The central picture box (box 5) requires crew to close WT doors en-route to their destinations. This could not be carried out by a simple delay task or indeed any other of maritimeEXODUS commands. Therefore a new behaviour was required to simulate the closing of WT doors as part of the State 1 Preps scenario.

The sixth picture box (right, centre row) requires crew members to approach an ‘Action Station’ and receive orders from a commanding officer. The assignment of tasks to other agents could not be performed within maritimeEXODUS, and thus further developments were required within the model in order to create this capability.

The final three picture boxes make use of the actions already discussed in this paragraph and as such no further developments are required.

The following sections discuss the development of these required behaviours.

7.2.1.3.1 Give and Receive Command

In regards to the State 1 Preps scenario, development was required which would allow one agent to give new itineraries to another agent. This would represent a commanding officer, at an action station, issuing orders to lower ranking crew members (See Figure 7.2-1).

The novel implementation of this behaviour involved creating a new type of node, '**Redirection**' node (see Figure 7.2-2). This type of node already existed in a simple form in other versions of EXODUS but was not in maritimeEXODUS. A redirection node can contain itineraries which are given to individuals who stand on the node. These itineraries are issued on a first come first serve basis, thus for example the first 10 individuals arriving at the node will be given the first itinerary associated with the node, and the next 10 individuals will be given the second itinerary associated with the node and so on.

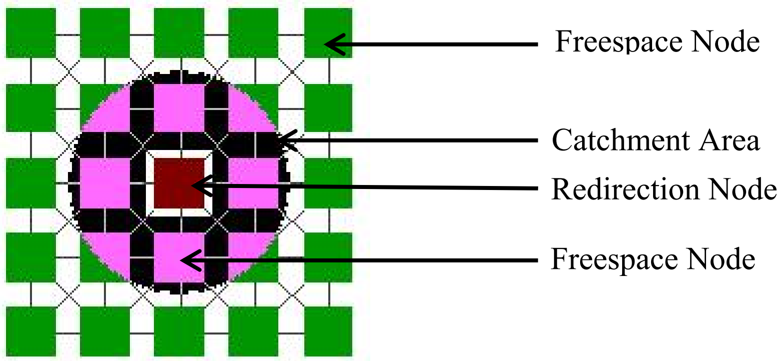


Figure 7.2-2 - Catchment Area Surrounding Redirection Node

This node was implemented into maritimeEXODUS and then developed to fulfil the requirements of the scenario. A catchment area was implemented on the node, the radius of which can be set by the user. By default the redirection node would have a catchment area of 0.5 metre (see Figure 7.2-2); this means that any nodes within half a metre distance from the redirection node would be considered in the catchment area. Any agent who stands on a node in the catchment area can be considered to have arrived at the redirection node and thus are able to receive an itinerary from the node. The redirection node has also been developed such that the redirection node will only issue itineraries once the commanding officer stands on it, this guarantees that crew members can only be given orders by a commanding officer. With these developments, the redirection node is considered to be the action station and when the commanding officer stands on the node the redirection node will issue itineraries to crew members who are standing in the catchment area. Further refinements were then required, since members of different functional groups (FG) would receive different types of orders, for instance a member of the damage control group may be told to close all the WT doors whereas a member of the medical team may be asked to check the first aid locker. Taking this into consideration, the itineraries associated with the redirection node are linked to a specific FG. The redirection node still issues itineraries to agents on a ‘first-come first-served’ basis but only assigns them depending on the agents’ FG.

A potential problem with the redirection node is that the commanding officer will only move off of the node once all the itineraries have been assigned to the crew, however if the simulation has not been set up correctly then it is possible that not all the itineraries will be assigned. Thus, the commanding officer will remain on the redirection node indefinitely and the simulation will not end. To ensure that this does not occur, users wishing to employ redirection nodes to issue itineraries must ensure that the set up phase is carried out correctly.

Once the redirection node was implemented, the next stage was to instruct the agents as to how they should interact with the redirection node (action station). This was achieved by introducing two new behaviours; ‘Give’ and ‘Receive’ commands. An agent with the ‘Give’ command will walk up to, and stand on a redirection node and effectively give instructions to everyone within a catchment area who has a ‘Receive’ command instruction. In practise, it is not the agent who assigns itineraries to others but rather the redirection node. The individual with the ‘Give’ command simply activates the redirection node while they occupy the node. Agents with the ‘Receive’ command will enter the catchment area of the redirection node and wait there until the node is activated (see Figure 7.2-3 and Figure 7.2-4).

Once all itineraries have been assigned to agents, the agent standing on the redirection node is considered to have completed their task and can move off.

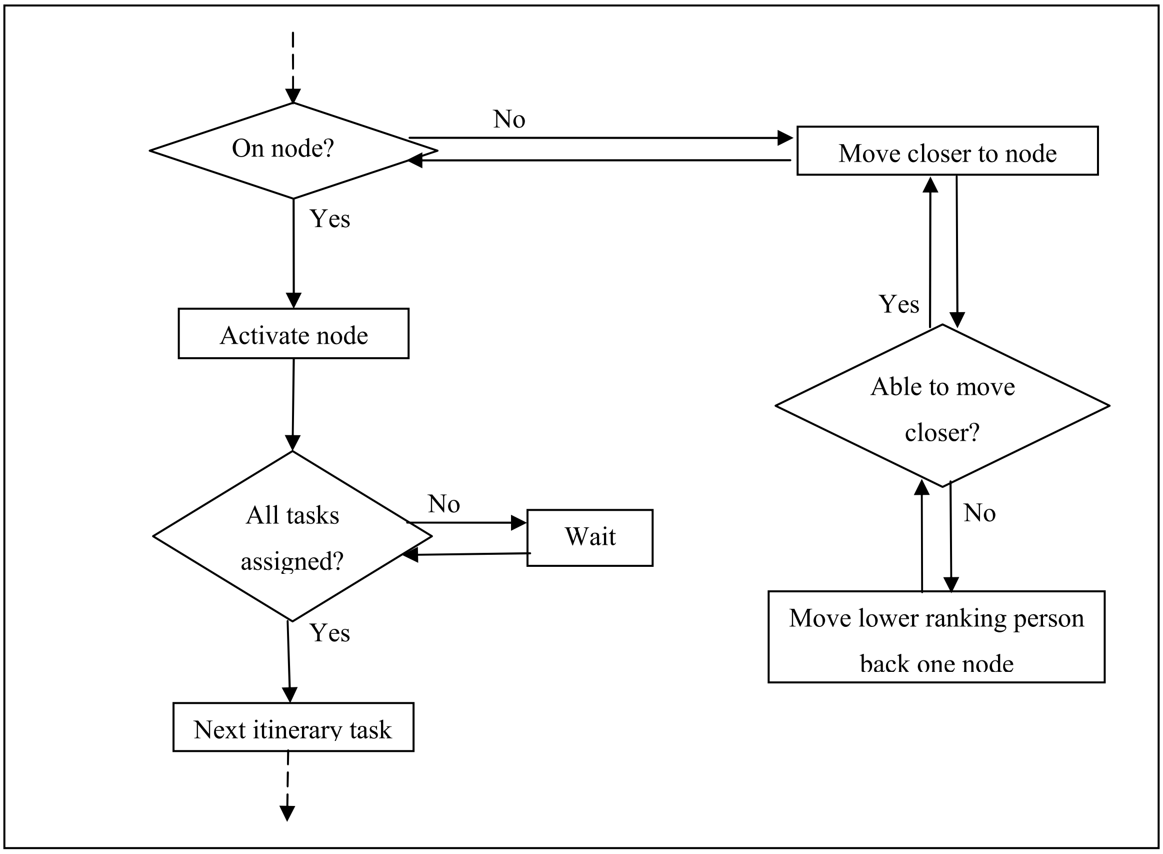


Figure 7.2-3 - Logical diagram for 'Give' command

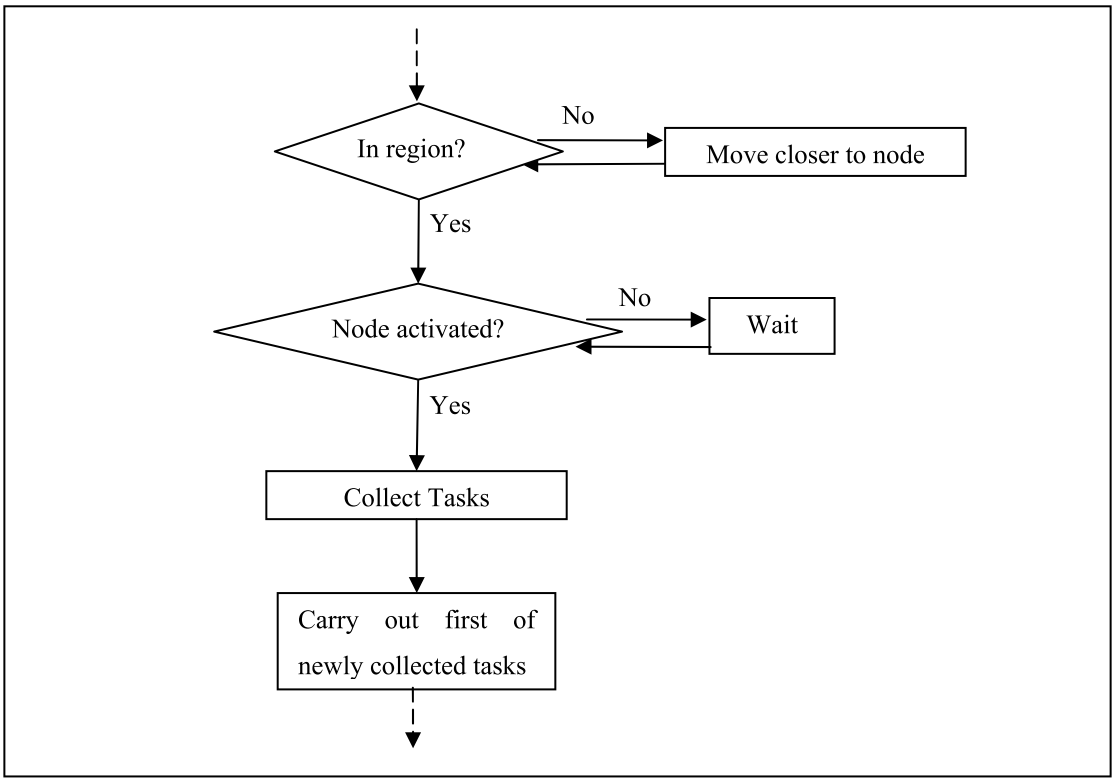


Figure 7.2-4 - Logical diagram for 'Receive' command

A problem could arise with this implementation of assigning itineraries to agents since the simulation can only end once every agent has either evacuated or terminated, but if the redirection node does not assign all of its itineraries to agents then the agent on the node will never leave it. Thus the agent on the redirection node will never terminate nor evacuate and consequently the simulation will not stop. Allowing agents to be members of other functional groups reduces the risk of this problem but does not eliminate it. Assigning agents to multiple functional groups helps, since although each agent will be a member of a specific FG, if they can accept tasks from other FGs then there is less chance of tasks having not been issued by the redirection node. This is not a complete solution, but does reduce the risk.

Another problem that was identified whilst testing the newly implemented redirection node was, if a crowd of crew members surround the redirection node prior to the commanding officer (CO) arriving, then the CO cannot get through the crowd, in order to activate the redirection node, thus no itineraries are assigned to the crew members who are waiting for new orders. The solution implemented allowed maritimeEXODUS to identify the CO as the agent with the 'Give' command and as such the software gave this agent a higher 'drive' (level of motivation) than the agents in the crowd surrounding the redirection node. Consequently if the CO cannot reach the redirection node then they effectively have the power to 'push' other agents out of the way in order to get to the target node. Simulating this in maritimeEXODUS, the agents in front of the CO will step back and away thus creating a space for the CO to step into. If the CO still cannot reach the redirection node then the agents surrounding them will have to step back in order for the CO to take another step further (see Figure 7.2-3). This continues until the CO reaches the target node, at which point they can activate the redirection node and itineraries can be given to the crew members.

The ability of crew to step back and allow the CO through resolves the issue of the CO being blocked in their efforts to approach the action station. The next stage of developing the maritimeEXODUS software was to enable it to model all the required tasks which the commanding officer could issue.

7.2.1.3.2 The 'Close Door' Command

One of the tasks which a Commanding Officer (CO) could issue to lower ranking crew members during the 'State 1 Preps' scenario was the command to close all WT doors.

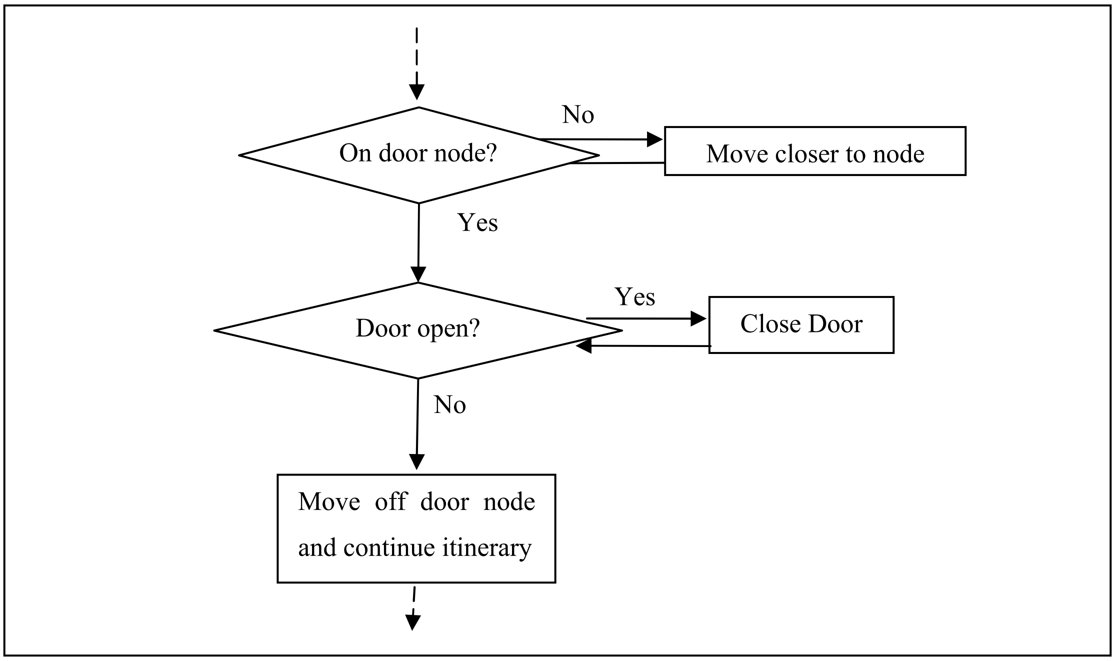


Figure 7.2-5 - Logical diagram for 'Close Door' command

The actual instruction issued by the CO at the action station would be to close all WT doors within a WT zone, however this would involve having to define the WT zones within maritimeEXODUS which would mean the creation of a complex algorithm. Therefore, it was decided to introduce a command to close a single WT door and a list of these commands would be assigned in order to close all the necessary WT doors. The command implemented was labelled 'Close Door'.

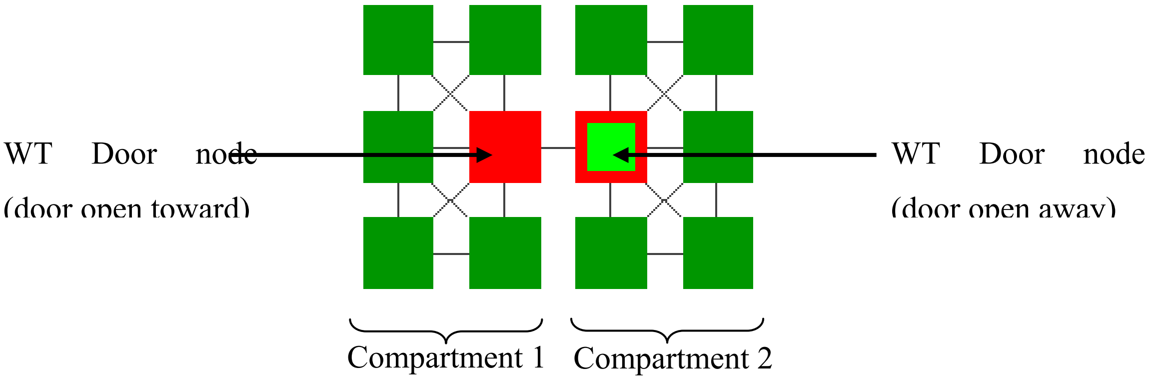


Figure 7.2-6 - WT door representation maritimeEXODUS

With the 'Close Door' command an agent will walk up to the WT door and stand on the first of the two WT door nodes (see Figure 7.2-6) where they will check if the WT door is closed. Even if the WT door is already closed they will still walk up to it and check. If the WT door is open then the agent will close it and there would be an appropriate time delay imposed upon them for this task. If the WT door is already in use, the agent assigned the 'close door' task would approach the WT door and they would assume that the other agent(s) would close the door behind them and so would not carry out any action.

7.2.1.3.3 The 'Delay Zone' command

It was decided that a commanding officer (CO) would send crew members to compartments where they would be required to perform tasks. The crew would not normally be sent to an exact location within a compartment. As such the 'delay' command was extended so that an agent could be sent to a compartment zone rather than a specific node. For this the extended command was given the label '**DelayZoneName**'. This new command still required the minimum and maximum time delay to be specified but, instead of a node id being requested, the name of a compartment zone was required. The agent will act in the same manner as they would do if they were given the command 'delay'. But instead of carrying out the task once they arrive at the specified node, they will perform the task once they arrive at the centre of the specified compartment or as close as they can get to the centre.

7.2.1.3.4 The 'Search Compartment' Command

Another of the tasks which a commanding officer may issue to the crew, is to secure all loose items in a compartment. To model this requirement a new command was developed which would send an agent to a zone (compartment zone) where they would move to the centre and experience a delay. The delay in this case represents the crew member securing all loose items. The newly incorporated command is called '**Search compartment**'. This action has three parameters; 'max delay' and 'min delay' which define a range of times that the delay could take and the third parameter is the compartment / zone which the agent has to search. This command bears a close resemblance to the 'DelayZoneName' command, except that the agent moves further into the compartment than they would do with the delay command. It was initially intended to develop this 'Search Compartment' command further to better represent an agent searching the space and also for the command to be more intelligent. One idea proposed was for an agent to experience a delay whose value was calculated on the size of the compartment they were searching. As such the agent would move to the centre of the compartment and experience a predefined time multiplied by the number of square metres of space within the compartment. An alternative proposal for the implementation of this command was for the agent to walk around the perimeter of the compartment zone. For the purposes of this work, it was considered sufficient for demonstration of the capabilities for the agent to just enter the compartment before experiencing the delay.

7.2.1.3.5 The 'Repeat' Command

Another of the tasks which a commanding officer may issue to the crew is for them to patrol the vessel. Their duty would be to circumnavigate the ship checking for any intruders or other security breaches. The patrols may also flag-up areas of the vessel which need immediate maintenance. For this task the crew members would be told to visit a number of specific locations on-board the vessel. These locations would generally be along the perimeter of the vessel. The route which the crew members are told to follow would have to be taken continuously during the scenario until they are told to stop. A patrol would have to be carried out continuously while the vessel is in state 1.

With this brief, an additional behaviour was developed, '**Repeat'**. This command has been defined such that when specified, the agent will repeat the previous X number of tasks Y number of times, where X and Y are parameters specified in the command. As such the route of the patrol would be defined as a series of delays at a range of locations in an organised fashion and then the repeat command would follow it. Since the patrol route is to be carried out continuously throughout the simulation, the command is given a high number for the specified number of repetitions, for example 9999 repeats. This would keep the agents patrolling the vessel for the duration of the scenario, however the patrol would carry on well after the rest of the scenario has been completed. Therefore if the 'terminate' command is the last task to be performed then the individual will carry out all the tasks in the cycle and when they reach the 'terminate' command maritimeEXODUS will check the status of all the other agents. If the rest of the population have terminated, evacuated or at the same stage of waiting for everyone to terminate then maritimeEXODUS will break the cycle of the continuous patrol and the simulation will end.

The novel capabilities implemented thus far would be sufficient to model the State 1 Preps scenario. The next task was to modify maritimeEXODUS so that it could simulate the Blanket Search scenario.

7.2.1.4 Behaviours required for the Blanket Search scenario

In the 'Blanket Search' scenario, the crew believes the ship may have sustained some damage and it is necessary to investigate the extent of the damage (if any) and report this to HQ. To do this the entire complement search their compartment (which they occupy) and report their findings to HQ. At the same time a few crew members (typically from the damage control and fire fighting group) will search all the unoccupied rooms which have not been searched.

On further analysis, it was found that prior to the blanket search commencing, the crew members searching all the unoccupied compartments would be selected from the FRPP's (Fire Repair Party Post). From there they would be sent in different directions, in pairs, to the furthest points from the FRPP, these locations are labelled their 'dispersal station'. These are not set locations on-board the vessel instead they are decided by the commanding officer when assigning the blanket search commands. 'Dispersal' meant that these designated crew members would be given a list of compartments to search. Once assigned with these search locations they would be sent to their dispersal station and be spread widely across the vessel.

Having arrived, an arbitrary time may elapse prior to the blanket search commencing, which could be any duration from a couple of minutes to a couple of hours. The command would then be given by HQ to blanket search, at which point the entire complement search their compartment and report their findings to HQ; in addition the crew members at their dispersal stations start searching their list of assigned unoccupied compartments.

To model this scenario, firstly the ship's complement will search the compartment which they initially occupy. This is achieved simply by setting an initial delay (response time) representing them carrying out the search and reporting in to HQ. Therefore no modifications to the software are required for this.

The second part of modelling this scenario is much more involved. It entails sending selected crew members to their dispersal stations and then making them search a list of unoccupied compartments. Initially the idea was to simply give each agent a list of 'search compartment' commands (as defined earlier in this chapter) which would be organised such that the agents would search all the required compartments in a logical order. However, this is more involved than it was first thought and rather time consuming. One of the problems was knowing which compartments were unoccupied and therefore required searching.

It was decided to automate this process of assigning compartments to the crew members. This would reduce the amount of time required to set up the scenario and would also allow more accurate comparisons between designs, since the method of designing the crew's route would be the same.

Another detail identified while analysing how this ES would be simulated was that the scenario would normally be carried out while the vessel was at state 1 (action). In this scenario all the WT doors would be closed as there is reason to believe that the vessel may have sustained damage. It would therefore be wise to reduce the number of WT door operations (i.e. opened and closed) and the amount of time the WT doors are open as these components are vital in containing such incidents as fire and flood. As such, the crew would have to be given a route which would search all the unoccupied compartments within a WT zone before moving onto the next WT zone.

Within each WT zone there are also WT compartments, although these internal zones do not use WT doors, they do still form a sealed zone which would to an extent help contain a fire or flood. Therefore in addition to the crew searching all the unoccupied compartments, WT zone by WT zone, they should ideally search WT compartment by WT compartment.

To model this, it was decided that each compartment would be associated with a WT zone and a WT compartment. A new command was then implemented in maritimeEXODUS, called '**Blanket Search**'. This command would be given 5 parameters; the initial location of the crew, the minimum and maximum time delay associated with searching each compartment, the number of people searching the WT zone and the WT zone they are to search. A crew member could be given a number of these commands if they are to search a number of WT zones.

When a simulation is run and a crew member comes to carry out the blanket search command, maritimeEXODUS will check all the compartments within the defined WT zone and see which are unoccupied and add them to a list. maritimeEXODUS will then create a 'search compartment' command for each compartment in the list and give that command the time range as specified in the 'blanket search' command. maritimeEXODUS will then initially organise the search compartment commands depending on the starting location of the agent tasked with searching the WT compartments. Then maritimeEXODUS will take the furthest compartment from the FRPP (as indicated in the 'blanket search' command) as the dispersal station where the crew member is to start the blanket search. The software will then organise the 'search compartment' commands based on the distance between the compartments assigned to the crew member.

In addition to creating and organising the 'search compartment' commands, when the crew member arrives at their dispersal station, they will wait for all agents with the 'blanket search' command to arrive at their dispersal stations. This means that the software can model the crew getting to their dispersal stations. Once everyone with this command arrives at their dispersal station, maritimeEXODUS records the simulation time and then the crew will start the blanket search.

Since the ‘blanket search’ command indicates how many people are to search the WT zone, maritimeEXODUS will split the ‘search compartment’ commands between all the agents searching that WT zone. Commonly this task is carried out by a pair of crew members, therefore maritimeEXODUS will distribute and organise the ‘search compartment’ commands so that each agent searches alternate compartments.

With the implementation of the ‘blanket search’ command, it was then possible to simulate the Blanket Search scenario

7.2.1.5 New Group Behaviours

The final scenario to be implemented within maritimeEXODUS was the ability to simulate the family day scenario. This is very similar to the evacuation scenarios whereby an incident such as a flood or fire occurs and the population has to evacuate the vessel. However, the difference with this scenario is that there are a number of trained naval personnel and untrained civilians on-board the naval vessel. The civilians would commonly be in groups accompanied by a small number of crew members. These groups could initially be located anywhere on-board the vessel. Civilians would not be expected to use ladders and for this reason these groups of civilians would not normally be on the lower decks where the cabins and engine rooms are.

When an incident is detected the crew members accompanying the civilians will usher them to the muster stations,. At the same time, the rest of the ship’s complement will move to their emergency stations, where a NBCD effort is launched to tackle the incident. If the NBCD effort fails and the situation is not contained the vessel is then considered lost. The command will be given to evacuate and the rest of the ship’s company will move to the muster stations where they will receive vital life saving equipment such as life jackets. The population will then disembark the vessel by any means possible. Commonly the vessel will be alongside in a harbour, therefore the population will simply disembark via a gangway on to dry land.

maritimeEXODUS was designed to carry out an evacuation scenario, however group behaviour, whilst a capability of the software, was limited. To further develop this capability, each agent is given an additional attribute labelled ‘Gene’. As a default this value will be set to zero meaning that they are not part of a group. However, if this value is not zero then they are a part of a group which has a common gene value. If an agent has a gene value greater than 0 then they will try to form and move as a group during the simulation.

One feature of the group behaviour relates to the response times. If the members of the group are within the same area then when the first person in the group responds, they will make everyone else in the group respond as well. In this sense, the group can all start moving together. In addition, an attempt has been made to keep the people together in a group as they move to their destinations. If anyone in the group starts to race off ahead of the rest, then they will stop and wait for the rest of the group to catch up. Similarly, if any group members start to lag behind then the rest of the group will stop and wait for the slower members to catch up.

When tested, the new ‘Gene’ capability worked extremely well and allowed satisfactory grouping and movement of agents. However this capability could be further developed for example to enable the group to move at the same speed and to group agents more closely together which may make the group behaviour even more realistic.

Once these group behaviour features had been developed within maritimeEXODUS, they then had to be extended sufficiently for modelling the family day scenario. As mentioned, during this scenario the crew usher civilians to the muster stations. This means that the civilians need to take their cue from their assigned crew members, and as such need to respond when the crew members tell them to and follow the instructions that the crew gives them.

The first task was for maritimeEXODUS to distinguish between crew members and civilians. This utilised an existing attribute associated with each individual labelled ‘type’, where it can be specified whether a person is a member of crew or not. Once this was defined, maritimeEXODUS could instruct the civilians to inherit all of the crew members’ tasks, where the crew member has the same gene as them. The civilians would also take the same response time as the crew member.

7.3 Modifications to maritimeEXODUS Inputs

Setting up a model in maritimeEXODUS can be a time consuming and repetitive process, especially as the scenarios get increasingly complex. It was a desire of the work to automate this process as much as possible so as to reduce the time required to set up a simulation. At present generating a population with their individual itineraries is an extremely long and tedious task carried out via a very complex interface. The user has to also set a number of attributes associated with how the simulation is modelled, for example what outputs are to be produced and whether there are any special behaviours to be implemented in the model such as an instant response time for the population.

In order to simplify the process of setting up a model inside maritimeEXODUS, it was decided to extend the software's capability's to accept a scenario scripting file. This new input file would be text based which could be used to load in to the maritimeEXODUS model the population along with their itineraries. The file type implemented was called 'Scenario Specification File' and was given a file extension of SSF. The SSF file follows the same format as a MTA file (see Chapter 3) in so far as each line has an attribute / command name followed by a semi colon (':') which in turn is followed by the attribute value.

Table 7.3-1 shows a sample of a SSF file used to set up a simple state 1 preps scenario.

Table 7.3-1 - Sample of a SSF file

```
TaskListItem: Damage_Control
TaskListItem: First_Aid
TaskListItem: Flight
TaskListItem: Warfare_(Fighting)
TaskListItem: Civilians

GroupMovement: 1
PersonIconShape: 0

InternalDoor: Internal_WT_doors.No_3_deck.door_h_n3_1 open
```

```
InternalDoor: Internal_WT_doors.No_3_deck.door_h_n3_1 closeBehind

# The population Definitions
population: myPopDefinition
AssignResponseCurve Cabin ALL

Person
Name: LT
AssignedType: 1
ZoneRandLocate: Compartment_Zone_64
TaskCanDo: Damage_Control
ClearItinerary
ACTDelayZoneName Compartment_Zone_69 0 0
ACTTerminateMill
```

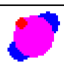
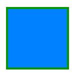
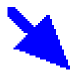
From Table 7.3-1, it can be seen that a single person called ‘LT’ (from the tag ‘Name’) is inserted into the compartment labelled ‘Compartment_Zone_64’ (from the tag ‘ZoneRandLocate’). This agent will be a part of the functional group ‘Damage_Control’ (from the tag ‘TaskCanDo’) and is highlighted as a crew member (from the tag ‘AssignedType’). They have been given the itinerary to move to compartment ‘Compartment_Zone_69’ where they will terminate and mill around randomly until the end of the simulation. It can be seen from Table 7.3-1 that all the itinerary commands start with the word ‘ACT’ to denote that it is an action which an agent has to perform. Table 7.3-1 shows that the command ‘ACTDelayZoneName’ has three parameters; the compartment zone where the action is to be carried out, the minimum and maximum time for which the delay may have. In this case the agent would have to travel to the compartment zone specified but would not experience any time delay once there.

Along with inserting an agent into the model, the SSF also sets the conditions of the WT door. It can be seen from Table 7.3-1 that the WT door ’Internal_WT_doors.No_3_deck.door_h_n3_1’ is initially open at the start of the simulation and as agents pass through it, they must close the door behind them (provided that no one else is about to pass through the door). This command could alternatively have had the values of ‘close’ and ‘leaveOpen’ to signify that the WT door should initially be closed at the start of the simulation and as agents pass through it they should leave the door open.

In addition, the SSF code example in Table 7.3-1 lists what functional groups are present in the model. This can be seen from the list of ‘TaskListItem’ tags. Within maritimeEXODUS, the functional groups merely defines which tasks an agent can perform hence the tag ‘TaskCanDo’ in the person definition. This defines the functional group the individual is a part of and the list of ‘TaskListItem’ defining the possible functional groups.

The SSF code example in Table 7.3-1 also sets some flags which will affect the simulations. ‘GroupMovement’ has been set which means that agents with the same gene will form a group and ‘PersonIconShape’ has been given a value of 0 which means that each agent will appear as a square block (Table 7.3-2(b) in the 2D visualisation of the simulation. Alternatively, this value could have been set such that the population are represented by arrows pointing in the direction which the agents face (Table 7.3-2(c)) or as a human like shape (Table 7.3-2(a)).

Table 7.3-2 - Representations of individuals within maritimeEXODUS

		
(a) Human like representation	(b) Square block representation	(c) Arrow representation

The line ‘# The population Definition’ in Table 7.3-1 represents a comment in the SSF file. Any line starting with ‘#’ is considered a comment and is not processed by maritimeEXODUS. The two lines which follow this define the attributes of the population. Without these lines a default agent will be created. The first of the lines means that any agents created after it will be given attributes based on a population panel which is already defined within maritimeEXODUS (user defined as opposed to hard coded in maritimeEXODUS). In the case of the example in Table 7.3-1, each agent will be created based on the population panel labelled ‘myPopDefinition’. The second of the two lines overrides the response times as defined in the population panel ‘myPopDefinition’ and assigns each agent a response time based on a curve defined in maritimeEXODUS (again defined by the user not hard coded into maritimeEXODUS). Commonly, the response times will be distributed to the population based upon a random uniform distribution but as a result of the paper published by the author of this work relating to the IMO response times (Deere, 2006), the response times can now be assigned based on a lognormal, normal, polynomial (of a maximum of 6 degrees) or a user defined curve.

In addition to the commands used in Table 7.3-1, other commands which can be used in the SSF file are:

Table 7.3-3 - List of SSF file commands used in maritimeEXODUS

SSF Command	Description / Parameters
GenerateOn	Creates an agent on a given node. Requires the node to insert individual on.
GenerateAt	Creates an agent at a given coordinate. maritimeEXODUS will place the agent on the nearest node to the given coordinates. Requires the Window ID, X and Y location to be specified.
ZoneGenerateOn	Creates an agent within a predefined area. Requires the name of zone to insert agent in.
LocateNear	Creates an agent on the given node. If node is already occupied then will place the agent on next nearest node. Requires the name of the node to insert the agent on.
ACTWait	Creates a 'wait' action in the agent's itinerary. Requires the node to wait at, time to wait until and radius of the area to wait in.
ACTDelay	Creates a 'delay' action in agent's itinerary. This is the more commonly used action in maritimeEXODUS. Requires the minimum and maximum time that the delay can take.
ACTBlanketSearch	Requires the initial start location of the crew member, the minimum and maximum time delay for searching each

	compartment, the number of agents searching the WT zone and the WT zone to search.
ACTSearch	This action commands the agent to search a specified zone. Requires the name of the compartment zone to search and the minimum and maximum time given to searching the zone.
ACTTerminate	This command ends the agent‘s involvement in the simulation. This command does not require any parameters.
ACTCloseDoor	This command instructs the agent to close a WT door. It requires the name of the WT door to close and the minimum and maximum time delay associated with closing a WT door.
ACTWaitForMembers	This command instructs the agent to remain where they are until all members of specified gene group are ready to continue with next command. It requires the gene to be specified and the radius of the area in which to search for other group members.

Other SSF commands have been developed but not as part of this work and as such have not been noted.

7.4 Modifications to maritimeEXODUS Outputs

In response to the developments of the Human Performance Metric, maritimeEXODUS was required to produce additional outputs. Some of these additional outputs included;

- The time agents spent travelling, i.e. how much of their individual simulation time was spent travelling as opposed to responding to the scenario, waiting in congestion or carrying out their tasks.
- The number of tasks performed by each agent. Previously maritimeEXODUS would produce a list of tasks carried out by each agent but the HPM is more interested in the overall number of tasks performed.

- The average time taken by agents to perform each task. Again, maritimeEXODUS previously outputted all the information about each task but the HPM is more interested in the average time taken to perform each task.
- The percentage of inactive agents. Previously maritimeEXODUS was predominately an evacuation model whereby everyone in the model would evacuate the structure. Now that it can simulate general circulation simulations there will be agents in the model who may well be present but do not actually do anything. These agents may not be of any real interest but still have to be simulated since they may contribute to the human factors performance of a design, for instance they may be standing idle in a small confined space which other agents have to pass through. In this sense, the idle agents could cause congestion by standing in the path of others.

Although maritimeEXODUS already produces all the results required for the HPM, it did not produce them in an appropriate format. For example, maritimeEXODUS outputs the details about every task each agent performs; however, the HPM requires the total number of tasks performed and the average time taken to complete each task which although they can be calculated from the previous maritimeEXODUS outputs, were not automatically produced. In addition, the HPM splits the population up into functional groups, each of which would output their own data. This could not be extracted by the previous maritimeEXODUS outputs. As a result of this requirement a new text based output file was created which would produce the required data for the HPM in an easy to use file.

This new file format follows a very similar format to an MTA file; in the sense that the name of the attribute, such as simulation time, would be followed by a colon which would also be followed by the value of that attribute. An example of the new file format can be seen in Table 7.4-1.

Table 7.4-1 - Sample extract of a BMX file

sim: 17.5557
Response: 0
Distance: 13.207
TravelTime: 17.5557
ActivePop: 1

From the snippet of the new output file format illustrated in Table 7.4-1, it can be seen that there was one agent who was moving about the vessel. That agent had an instant response to the scenario (i.e. their response time was 0 seconds) and they travelled 13.2 metres in 17.6 seconds.

To identify this file as a separate output file, it has been given the extension '.bmx'. This came about since the HPM concept was originally called the behavioural matrix thus this could be abbreviated to BMX. However during the life of the project it was decided that the concept should be renamed in order to better describe its use thus the Human Performance Metric was devised, however the file extension '.bmx' was kept.

The list of performance measures developed in Chapter 6 were analysed and the required output from maritimeEXODUS was identified. The identified outputs were as follows:

- Final Simulation Time
- Average individual simulation time (for each FG group)
- Average cumulative wait time (for each FG group)
- Average response time (for each FG group)
- Average distance travelled (for each FG group)
- Number of severe congestion regions
- Severity of worst congestion region (as a percentage of the final simulation time)
- Total number of fatalities (for each FG group)
- Average FIN (for each FG group)
- Average FIH (for each FG group)
- Average time spent in smoke (for each FG group)
- Percentage smoke spread throughout the geometry
- Total time spent performing each task (for each FG group)
- Total number of tasks (for each FG group)
- Population size (for each FG group)
- Number of inactive population (for each FG group)
- Total number of WTD used (for each FG group)
- Number of WTD operations (open and closed) (for each FG group)
- Most times a single WTD was operated (open and closed) (for each FG group)

- Longest overall time a WTD was open
- Total number of hatches used (for each FG group)
- Number of hatch operations (open and closed) (for each FG group)
- Most times a single hatch was operated (open and closed) (for each FG group)
- Longest overall time a hatch was open
- Total number of ladders used (for each FG group)
- Total number of standard doors used (for each FG group)
- Average number of standard doors used (for each FG group)
- Number of times population moved vertically through the geometry (for each FG group)

It can be seen that the majority of the outputs required in the list above need to be produced for each functional group, but there are also a few which are not dependent on a functional group. It was decided to incorporate these few independent outputs into the first functional group 'Entire Ships Company'. This was decided since this functional group provides information relating to the ships company as a whole and since most of these independent factors are in fact dependant on the actions of the entire population. The exception here is the percentage of smoke spread through the geometry.

Having identified all the required data, this then needed to be incorporated into the output file. It was decided that to distinguish between the functional groups and the performance measures, different indentation would be used. With this, the functional group name would be on a separate line and have no indentation and then the data required for the performance measures would be indented by a single tab.

To help identify the scenario from which the results were produced, maritimeEXODUS would automatically name the file with the same name as that used for the geometry's EXO file. This would help identify the geometry which produced the results. The BMX output file also contains a line which identifies the Scenario Specification File (SSF) used to set up the simulation. This will allow a user to identify the file used to set up the simulation. Using both the EXO filename and the SSF filename, it then becomes simple to recreate the simulation in the future.

In addition to the BMX file for outputting all the required data for the HPM, it was considered desirable to produce images of useful screenshots from maritimeEXODUS. These images could help explain why certain results were produced by the HPM. Two of the performance measures used by the HPM relate to level of severely congested regions, which are very useful in identifying the performance of a design in terms of its human factors. However to complement this it would be ideal to know where these congested regions are and perhaps just how severe these regions were. For this reason, maritimeEXODUS was modified to produce a JPEG image of its IMO congestion contour map which shows any severely congested region in red. It is not possible to see from the image how long a region was congested for but it is possible to see just how large the congestion became at any one location. In addition to the congestion performance measures, there are PMs which assess the average distance travelled and the average number of components used.

It would also be useful to have an image which could help to understand the numbers produced by the HPM for these PMs. Therefore maritimeEXODUS was modified to produce an image of its footfall contour map. With this image it is possible to see what routes the population took and what routes were the most popular. This information allows the user to understand what doors were most commonly used, what compartments were travelled to the most and which deck connections were most commonly used. With this information the designer maybe able to introduce new access routes between common destinations or even move compartments around. These two suggestions could then reduce the average distance travelled and the number of components used which in turn could reduce the overall time required to complete the scenario.

As well as the two JPEG output images, it was deemed necessary to have a moving image which could show the population navigating about the vessel. In response to this maritimeEXODUS was modified to produce a GIF file for each deck of the vessel which shows the population density at every user specified time slice. maritimeEXODUS allows the user to input a time interval of any value. The default value is set to 60, i.e. maritimeEXODUS will capture the population density contour once every 60 seconds. The software effectively captures a screenshot at each time interval and then amalgamates all the screenshots into a GIF animation.

7.5 The Scenario generator

Prior to the work carried out as part of this PhD thesis, maritimeEXODUS was an evacuation simulation tool whereby all agents in the model were pre-programmed to evacuate. This meant that once the agents were created within a model, no further work was required. However, with the added ability to model normal operations, scenarios and itineraries became more complex. The agents are not necessarily evacuating, if they are not evacuating then they need to be told what to do, which means they need at least one itinerary task to perform. As has been discussed, even simple itineraries can be time consuming to implement within maritimeEXODUS and require the user to navigate through many windows and menus in the user interface. maritimeEXODUS is capable of assigning itineraries to agents, however this is a very time consuming process.

In addition to the time required to implement a population with their itineraries in maritimeEXODUS, some regulative bodies, such as IMO (2007), require several different populations to be used in order to properly test a design. This requires population to be deleted after X number of simulation runs and a new population to be inserted. This extends the amount of time required to perform the regulative specified number of simulations on a design.

In response to this, the SSF (Scenario Specification File) file was developed as a way to import a population into the model with itineraries and all the settings required to run the simulation as specified by the user. In this way, the population could be deleted and a completely new population with different characteristics could be inserted within seconds. This capability would allow 50 simulations to be carried out on a design with the ability to change the entire population on every simulation run. Previously, in EXODUS simulations (Deere et al, 2006), the location of each agent would be swapped with another, however essentially the same population would be used throughout. This would restrict the amount of randomness in the simulation results. With the ability to replace the whole population, comes more randomness in the model, which in turn will build up a better distribution of results from which to analyse further.

This SSF file implementation used for inserting a population into the maritimeEXODUS model is text based and human readable. To improve the process of creating a SSF, a utility tool was required. The brief for this tool was to enable the definition of the population and their itineraries without having to navigate through a complex interface. The user of the tool should be able to define the population with their itineraries in as few a steps as possible and with little effort.

With this task set, a C++ MFC application was created and entitled the '**Scenario Generator'**. This program consisted of 3 windows; the main menu window, the population definition window and the itinerary definition window. This tool requires the geometry to have already been produced within EXODUS and an MTA file created. The Scenario Generator could then import the MTA file and extract all the compartment zones and other possible locations where the population could be initially located at or sent to. These could include redirection nodes which were used as actions stations and weaponry in the State 1 Preps scenario.

When the user first loads the utility tool, they will be presented with the main menu, see Figure 7.5-1. From here they can choose to create a new scenario, exit the program, load a previously saved scenario, KCL file or NMTA file, save a scenario or automatically produce SSF files. In this section of the thesis, only the first two buttons will be examined more closely; 'Create Scenario' and 'Exit program'. The other buttons will be discussed in Chapter 10)

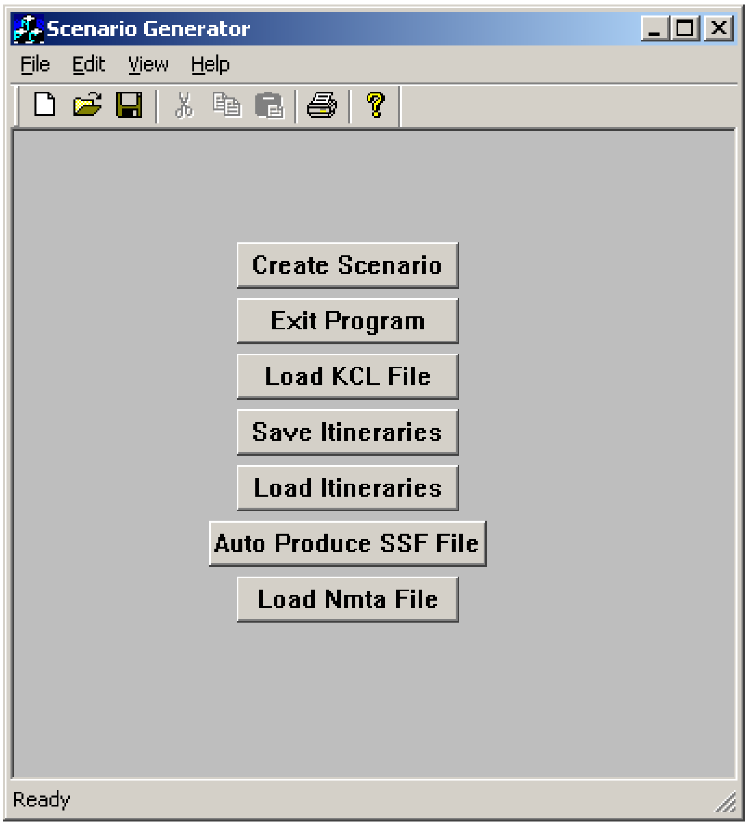


Figure 7.5-1 - Scenario Generator Main Menu

The ‘Exit Program’ button closes down the program.

The purpose of the program is to produce SSF files which can then be used within maritimeEXODUS. This can be done by clicking on the ‘Create Scenario’ button. By doing so the user would be prompted with the ‘Itinerary Set up’ window, see Figure 7.5-2, where the scenario can be created.

From the Itinerary Set up window, Figure 7.5-2, the user can create the scenario which they want to simulate within maritimeEXODUS. The first step the user must take before defining the population and their itineraries is to load in the geometry from a MTA file. This is done via the ‘’Load MTA File’ button in Figure 7.5-2, which will then display a standard file open dialog box where the user can then search through the file directories and select the appropriate MTA file.

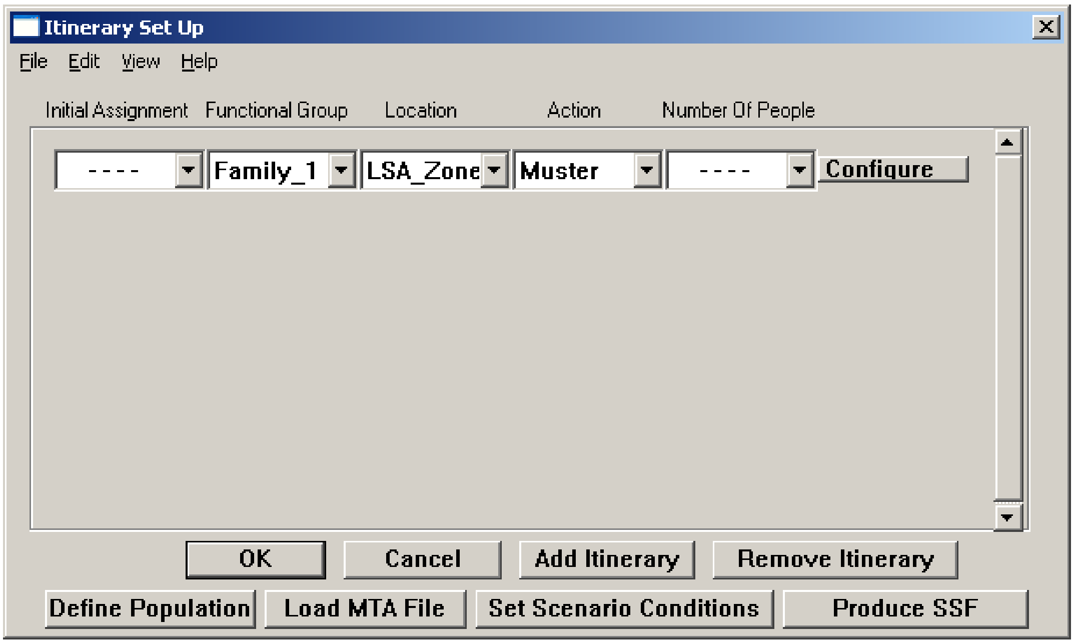


Figure 7.5-2 - Itinerary Set up Window

With the geometry now defined, the user can define the population. By clicking on the ‘Define Population’ button, the user is presented with the Population Definition Window as seen in Figure 7.5-3. From here they can define groups of people to be inserted into the model and where they will be located. This window also allows each member in the group to have the same gene, which, as defined earlier, means that the people will act as a group. With the ‘Same Gene Group’ check box being unselected, each individual will not have a ‘gene’ and therefore will move and behave independently to the rest of the population.

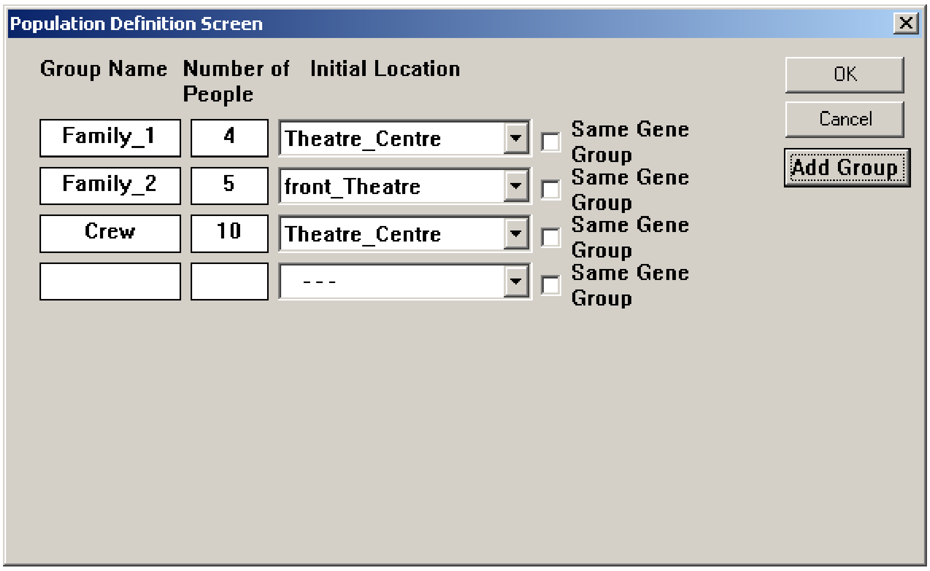


Figure 7.5-3 - Population Definition Window

The user is required to type in the name and the number of people in the group into the appropriate text boxes; they can then select the zone where the group will be initially located from a drop down box.

In Figure 7.5-3 three groups have been defined, Family 1, Family 2 and crew. There are 19 people in total and they are all located in the theatre. It can be seen that the 5 people from Family 2 are initially located at the front of the theatre and the rest are in the centre.

Initially the 'population definition screen' displays three empty groups. Users can add more groups by clicking on the 'Add Group' button as shown in Figure 7.5-3. The disadvantage to this window and utility tool is that an agent cannot be a member of more than one group and the characteristics of the population, i.e. their travels speeds and demographics, cannot be defined. These could be suggested improvements for the future. For the time being though, the user can manually make agents members of more than one function group either by editing the resulting SSF or using maritimeEXODUS' complex user interface after the SSF file has been imported. Both are viable but time consuming. The Scenario Generator still significantly improves the efficiency and ease of generating a population even with this restriction. The extent of this improvement would depend on the complexity of the population, however, even with a small population with simple itineraries (e.g. 30 agents with 3 tasks each), this tool could save an hours work. However, in much more complex populations (for example 250 agents with 20 tasks each), this tool could save a few days worth of manpower.

Once the population has been defined, the user can click ‘OK’ where they will return to the ‘Itinerary Set up’ window, Figure 7.5-2. At which point they can start creating the itineraries. By default there will not be any itineraries displayed on the screen, therefore the user will have to click on the ‘Add Itinerary’ button to create one. With an itinerary created, the user will be presented with 5 drop down boxes which will allow the user to select who will perform the task, what they will have to do and where they will perform the task. They can also state how many people will carry out this task.

The user can select either a single person to assign a task to or they can assign a task to a group of people using the second drop down box. In the case of a single person, the first drop down box contains the ID of the person. The person’s ID is a sequential number derived from the size of the population when they were defined in ‘population definition screen’.

If the user accidentally selects both an individual and a group when producing the SSF file, the scenario generator will ask the user to specify whether to assign the task to an individual or a group. This is done via a pop up screen and reduces the ability to make an error in creating the population.

Once the person(s) is selected, the location where the task will be performed can be selected from the third drop down box. This drop down list contains all the compartment zones and other locations extracted from the MTA file. After this, the user can select the task that the person(s) will perform. The user can select between ‘blanket search’, ‘check’, ‘delay’, ‘muster’, ‘repeat’, ‘search’, ‘terminate’, ‘wait’ and ‘evacuate’ commands. With the task selected, the user must then configure that task, i.e. how long will the individual(s) spend performing the task and what will the task involve. The tasks are configured by clicking on the ‘Configure’ button. This will prompt the user with a window which will ask for the required information to build up the task.

When the ‘Terminate’, ‘Muster’ or ‘Evacuate’ commands are selected and the configure button is pressed, the Scenario Generator will display an error message since there is no need to configure these commands. If the ‘delay’ command is displayed when the configure button is pressed then the user will be presented with a window asking for the maximum and minimum time delay, see Figure 7.5-4.

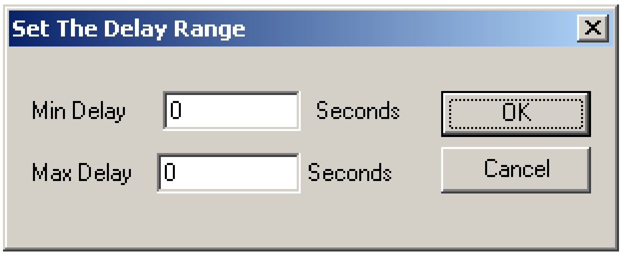


Figure 7.5-4 - Set Delay Range Window

The same window will be displayed if the 'wait' command was selected and the configure button pressed.

Presented in Figure 7.5-5 is the window which would be displayed if the 'Blanket Search' command was selected when the configure button was pressed. The window will ask the user to input the starting location for the blanket search and the zone to be searched. This is the information required by maritimeEXODUS to calculate which compartments to search and in what order, as well as where the dispersal stations will be located. The presented window will also ask the user to input the maximum and minimum time delay to impose on the searching of each individual compartment.

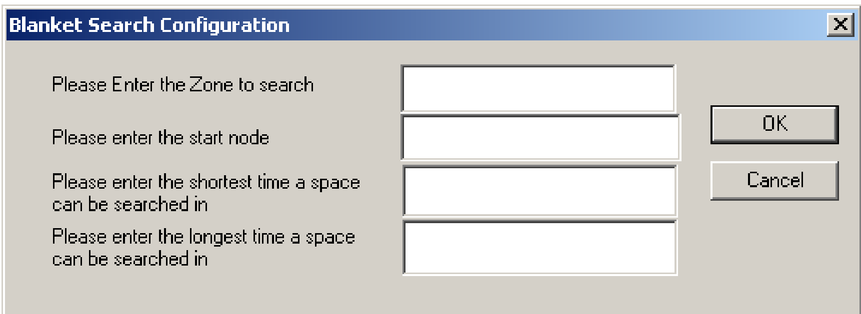


Figure 7.5-5 - Blanket Search Configuration Window

When the 'Repeat' command is selected and the configure button pressed then the user will be prompted with a window where they will be able to define a list of tasks to perform a number of times, as demonstrated in Figure 7.5-6. The window will ask the user to input the number of times these tasks are to be performed. As mentioned earlier in this thesis, if the list of tasks is repeated a large number of times, for instance 999 times, and one of the tasks is 'terminate', then all of the tasks will be repeated continuously until everyone else in the model have completed their tasks.

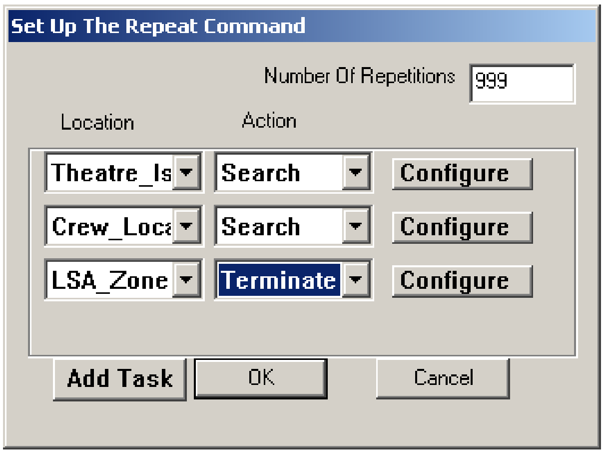


Figure 7.5-6 - Set up the Repeat Command Window

Finally, if the 'search' command is selected when the configure button is pressed then the user will be presented with the window in Figure 7.5-7, which will allow the user to define a list of compartments to search. Within this list, the user can define how long it should take to search each room. When the SSF file is created, the individual(s) with this task will search the compartments in the order that the user placed them in this list.

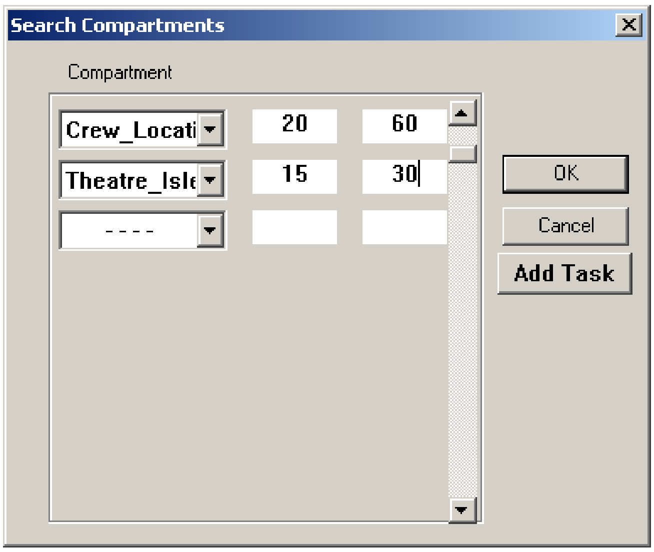


Figure 7.5-7 - Search Compartments Window

The user can define as many itineraries as they desire, but it is recommended that they check everyone is completing the scenario correctly. For example the user may forget to assign a terminate or muster command to groups of people. In these cases the individuals will evacuate which could prolong the simulation and create inaccurate results – for example produce average travel distance and average individual simulation times which are higher than they should be.

These windows can be used to define any number of itineraries for the population; no limit has been found at present. However, this would very much depend on the amount of free memory of the computer running the Scenario Generator. To add additional itineraries the user simply presses the 'Add Itinerary' button; if the user wishes to delete any of the itineraries, they can either set all the values to their default values, i.e. ' - - - ' for all the drop down boxes in the itinerary on the 'Itinerary Set Up' window, Figure 7.5-2. Alternatively, the user can click on any of the drop down boxes for the itinerary and then click on the 'Delete Itinerary' button, again in the 'Itinerary Set Up' window.

Once the population has been defined and the itineraries created, the user may want to configure some of the scenario settings which are not directly related to the population but nonetheless affects them, such as the heel and trim of the vessel.

Some of these attributes can be configured in the 'Scenario Conditions' window, Figure 7.5-8, which can be accessed from the 'Itinerary Set Up' window (Figure 7.5-2) by clicking on the 'Set Scenario Conditions' button.

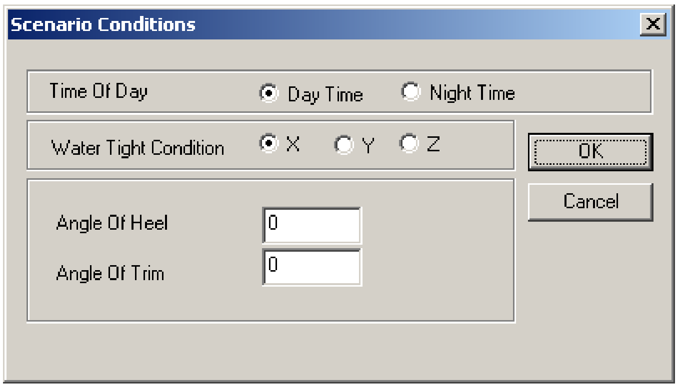


Figure 7.5-8 - Scenario Conditions Window

From here, the user can define the time of day when the scenario is to be performed. This would define what response distribution would be used, if two response curves have been defined. The user can also state the watertight integrity condition of the ship. The Scenario Generator would then take this information and apply it to all the WT doors which it extracted from the MTA file. The Scenario Conditions Window (Figure 7.5-8) can also be used to specify the heel and trim which will act upon the vessel during the scenario simulations.

Once the population and their itineraries have been defined and any specific scenario conditions specified, the user can then generate the SSF file which will then be used in maritimeEXODUS to set up the simulations. To do this, the user would simply click on the 'Produce SSF' button in the 'Itinerary Set Up' window (Figure 7.5-2). This will prompt the user with a 'Save As' dialog box where they can select the destination directory where the file is to be saved and the file name of the SSF file. The Scenario Generator will display a 'Successfully Created' message once the SSF file is created (usually appears instantly).

These are all the windows and procedures required to create a population and their itineraries. It can be seen that the interface created is simple and contains everything the user needs in order to set up the population in one place, solving the previous issue with the user having to search through a number of different windows to create a scenario. The Scenario Generator implementation saves the user a considerable amount of time and effort in setting up the model and provides additional capabilities. In fact the population can very quickly and easily be deleted and reinserted into the model with different attribute values and different starting locations.

7.6 The HPM Analyser

Once the user has set up a model inside maritimeEXODUS and has run a number of simulations for each scenario, they can then analyse the results. Even in a simple case the user will have a large number of simulation output files to analyse. For example, the user may have two designs to assess, each being assessed by 5 evaluative scenarios with each scenario being simulated 50 times. This would lead to 250 simulation output files to be analysed per design and 500 in total.

To simplify the analytical process, it was decided to develop a C++ program which could automate much of this analytical process. The program developed was labelled the '**HPM Analyser**'.

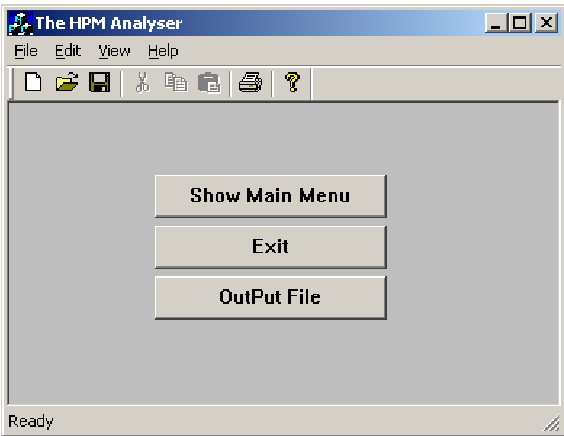


Figure 7.6-1 - Main Screen for the HPM Analyser

The main screen, Figure 7.6-1, has a simple design with just three buttons. The first allows the user to set up the structure of the HPM, the second button allows the user to exit the program and the third button allows the user to produce the required output files containing the results of the HPM. This level of simplicity should make the program very easy to use and significantly reduce the time required to produce the required analytical results.

Once the user clicks on the 'Show Main Menu' button on the main screen (see Figure 7.6-1), they will be prompted with another window where they will have to define the names of the designs to be assessed, see Figure 7.6-2.

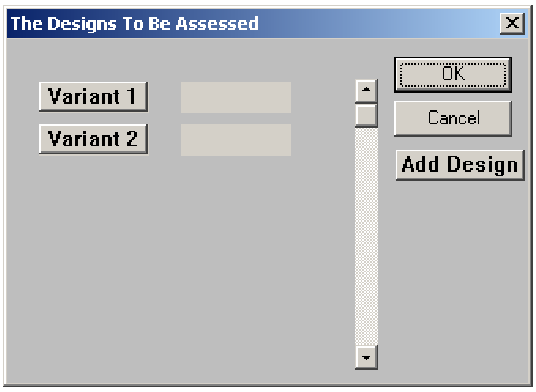


Figure 7.6-2 - Window allowing the definition of the designs

This screen, Figure 7.6-2, is also very simple in design. There are three standard buttons, 'OK', 'Cancel' and 'Add Design'. The 'Add Design' button allows users to define a HPM for an additional design. The program will not produce any results unless there are at least two designs; therefore the user would have to click on this button at least twice in order to assess any designs.

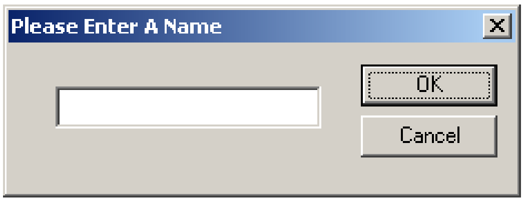


Figure 7.6-3 - Dialog box asking for the name of the HPM component

When the user clicks on the 'Add Design' button, they will be prompted with the above dialog box, Figure 7.6-3, asking for the name of the new design. The user can then assign a name to the design and then when they click 'OK' the window in Figure 7.6-2 will display a new button which will have the name of the new design to be assessed.

Once the designs have been defined, the user can click on the button with their design name, for example 'Variant 1' in Figure 7.6-2. The user would then be prompted with a nearly identical window where they can define the evaluative scenarios for which the design variant will be assessed by, see Figure 7.6-4.

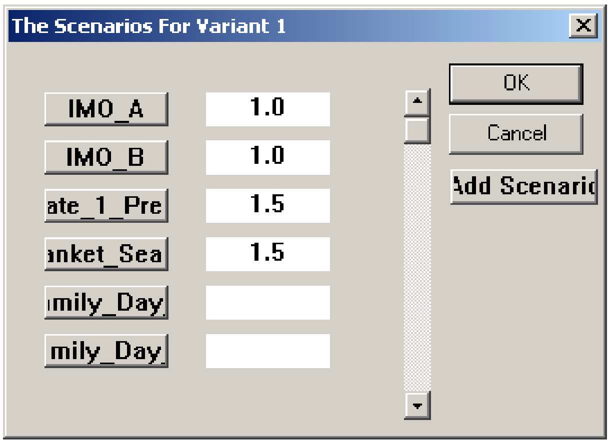


Figure 7.6-4 - Window allowing the definition of relevant ES

While the user can define the scenarios much in the same fashion as defining a design in the previous window, when a scenario is created, they can also assign a weight to it as well. This is done by inserting a number in the text box next to the button with the name of the scenario. By default each scenario will have a weight value of 1.0; therefore in the example screenshot in Figure 7.6-4 the last two scenarios would be given a weight of 1.0.

The user can select one of the buttons with the scenario name in order to define the functional groups which make up that scenario. When they click on the scenario button of their choice, they will be presented with another window, Figure 7.6-5, which is again nearly identical to those displayed in Figure 7.6-2 and Figure 7.6-4. Within this window, the user will be able to define the functional groups.

In addition to the ‘OK’ and ‘Cancel’ buttons, this window also has a button labelled ‘Add Function Group’ and ‘Read In Scenario’.

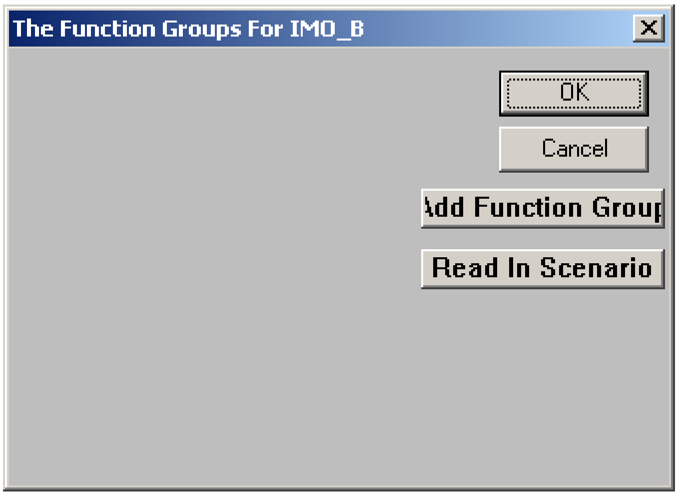


Figure 7.6-5 - Window allows definition of Functional Groups

By pressing the ‘Read In Scenario’ button, The HPM Analyser will ask the user for a representative file with which to complete the rest of the HPM. An open dialog box will be produced from which the user can select the representative output file. The HPM Analyser allows the user to select a number of maritimeEXODUS BMX output files. If the user selects more than one output file then the HPM Analyser will ask the user which files should represent the base line. The utility tool will ask the user whether they require the minimum, average, maximum or 95th percentile file to be used as the representative baseline file. The software will then ask what criteria to base this representative file on, whether this be the final simulation time, average level of congestion (experienced by the entire population), the average personal simulation time or the average distance travelled (in metres by the entire population).

Alternatively, the user can select a single file as the baseline file. The HPM Analyser will then read in the representative file, extract all the functional groups and then populate the performance measures for each functional group with the data from the representative file. This process of selecting a representative file has to then be repeated for every evaluative scenario for every design.

Alternatively, the user could click the ‘Add Function Group’ button in the window depicted in Figure 7.6-5. In this way the user can add their own FG and then they can specify the raw data values for each PM for each FG they create.

Once all the functional groups have been selected, the user can then set the weights for each FG and for each PM within the FGs. The weights are set by placing a number (integer or decimal) in the text box accompanying the component's button in the appropriate window. For example, to set the weight of scenario 'IMO_B' for design 'variant 1' to 1, the number '1' would be typed into the second text box down in the window presented in Figure 7.6-4.

The weight need only be set for the first design; the HPM analyser will use the same set of weights for all the other designs. This reduces the amount of work for the user, saves on implementation time and more importantly keeps a consistency in the structure of each HPM for each design, which will allow for an effective comparison between designs to be made.

Once all the representative files have been selected, the user can click on 'Output File' button on the main screen, as shown in Figure 7.6-1. The user would then be prompted with a 'Save As' dialog box asking where the output files should be saved to as well as the name for the output files. The program will then take the file directory and filename supplied by the user and produce the output files.

The application will firstly normalise the HPMs as described in Chapter 5. The program will then output the results of the HPMs in a text document (with file extension TXT) which can easily be read by the user using such document readers as WordPad or notepad. This output file firstly presents, in an indented list style, the performance measures used to assess each functional group and evaluative scenario, along with the raw data values and the maritimeEXODUS output file used to populate these PM. In the second half of this human readable output file are the results of the HPM. The normalised score for each performance measure along with the weight of the PM are listed as well as the functional group scores, evaluative scenario scores and most importantly the overall vessel performance score for each design.

The HPM Analyser will also output the HPM results via a CSV file (Comma Separated Values) which can then be read into a spreadsheet program such as Microsoft Excel where further analysis can easily be performed on the data. This allows the user to easily produce tables and graphs using the results of the HPM which can then be inserted into reports and presentations.

7.7 Summary

This chapter has described the development / modifications to three software tools which when used together are able to model and successfully assess the human factors performance of a design.

The first tool modified was maritimeEXODUS, which had 6 new behaviours implemented. These were:

- ‘Terminate’,
- ‘Give’ and ‘Receive’,
- ‘Close door’,
- ‘Search Compartment’
- ‘Repeat’

In addition to these new behaviours, the ‘delay’ task within maritimeEXODUS was extended to ‘delay zone’ and the existing ‘wait’ command was modified to send an agent to another location after they have terminated and make them mill. The group behaviours within maritimeEXODUS were also developed such that a group of agents will respond and follow a ‘lead’ agent. These tasks were considered sufficient to model all of the evacuation and normal operational scenarios defined in Chapter 6.

In addition to the development of new behaviours required to model each scenario, new input and output files for maritimeEXODUS were created. The new input file came in the form of an ASCII based script file which will create a population with their itineraries and will also configure the settings for the scenario.

The new outputs files produce the results required for the HPM in a form which can be easily used to fill a HPM. maritimeEXODUS will also produce images and animations illustrating what happened during the simulation. These output files can be very helpful in understanding the human factors performance of a design as well as possibly identifying areas of concern and improvements.

This chapter presented the development of two new software tools aimed at simplifying and semi automating the process of setting up a model and analysing the results of simulations. The first tool, the Scenario Generator, removes the need to use maritimeEXODUS' complex interface for inserting a population with itineraries.

This chapter has also presented the capabilities of the HPM Analyser as a post processed interpreter which will generate the HPM for a number of designs with ease, saving much time in the process. This section has demonstrated how the structure of the HPM can be defined as well as how to import the results from a maritimeEXODUS output file. Presented in this section was how the software tool produces two separate output files aimed at meeting the user's needs. There is the text file format (TXT) which can be opened with any text editor, such as Notepad or Microsoft Word, which can easily be read by humans. There is a comma separated value file format (CSV) which is designed to be imported into a spreadsheet package such as Microsoft Excel. From here further analysis can be performed on the data.

The following chapters use these new developments to assess the human factors performance of two designs and then moves on to implementing these developments into the early stages of the design cycle for new naval vessels.

Chapter 8

Demonstration of Newly Implemented maritimeEXODUS Features

8.1 Introduction

This chapter demonstrates the new capabilities of maritimeEXODUS and its abilities to perform all the behaviours required to simulate the evaluative scenarios defined in Chapter 6. The testing of these new features allows for greater confidence in the software's ability to reliably model the evacuation and normal operation scenarios defined in this thesis.

There are eight newly implemented behaviours which need to be assessed, as well as the development of an additional input and output file. The eight newly implement behaviours are:

1. Terminate,
2. Wait,
3. Search Compartment,
4. Blanket Search,
5. Close WT door,
6. Repeat,
7. Give & Receive itineraries,
8. Enhanced group behaviours.

These newly implemented features within maritimeEXODUS are demonstrated through a number of example cases. Each demonstration case makes use of a hypothetical vessel. The hypothetical vessel consists of two decks, each with a single passageway and a collection of compartments. This hypothetical vessel was constructed using maritimeEXODUS' existing drawing tools and whilst it does not closely resemble a naval vessel, it does contain sufficient complexity to properly test and demonstrate the new features of maritimeEXODUS.

8.2 Demonstration 1 – The Terminate command

Vital for the simulation of general circulation or normal operational scenarios was the ability for maritimeEXODUS to leave people in the geometry at the end of a simulation, as opposed to the population evacuating to a location outside of the geometry. This was achieved in maritimeEXODUS with the novel implementation of the 'Terminate' command. The 'Terminate' command required an agent to stop their involvement in the simulation once they had completed all of their assigned tasks and to remain within the geometry rather than exit as they would in an evacuation simulation. This command will be used in all normal operational scenarios for all agents who are not exiting the geometry.

To demonstrate this new maritimeEXODUS behaviour, a simple scenario has been devised which involves two agents representing crew members. These two agents have been instructed to move to the same compartment (for the purposes of this example this shall be called the medical centre), where they will terminate. Both agents will be given an instant response, i.e. their response time will be 0 seconds. The agents along with their itineraries have been imported in to maritimeEXODUS via an SSF file. Figure 8.2-1 shows the initial set up of the demonstrative case.

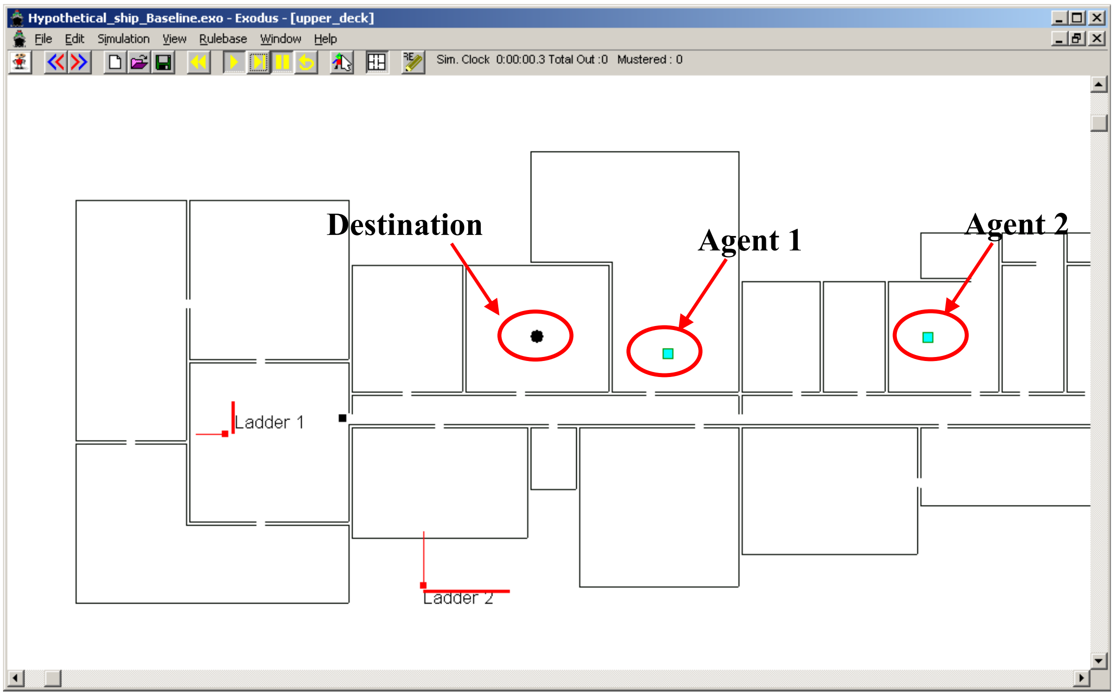


Figure 8.2-1 - Demo 1 – Terminate command: Agent 1 and Agent 2 in their initial locations

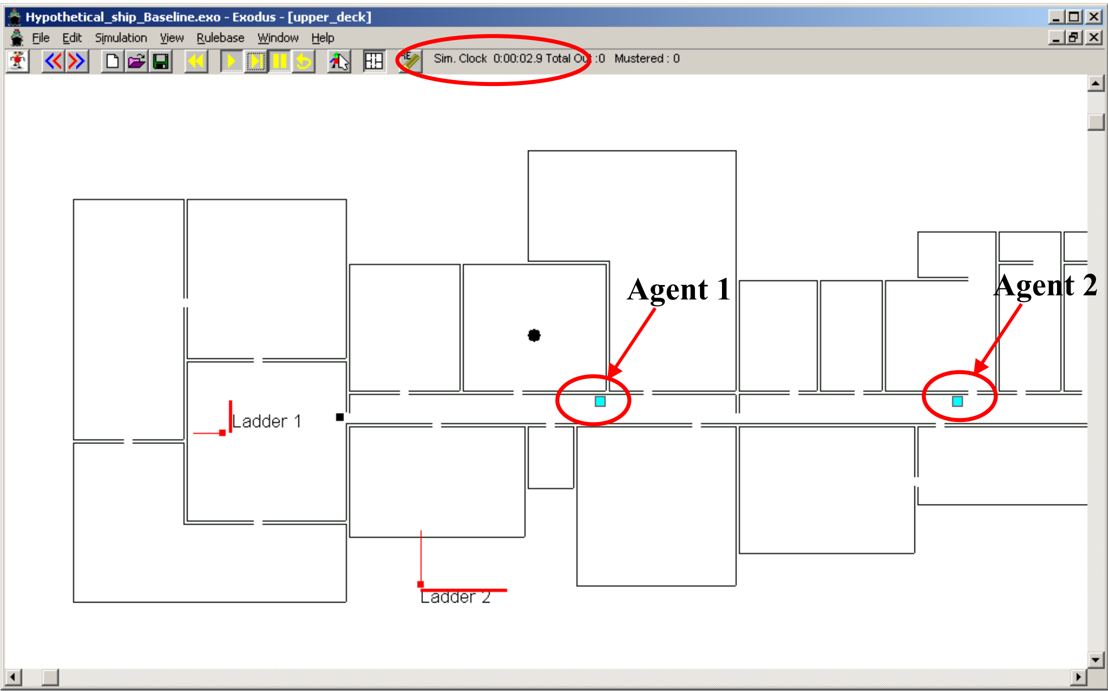


Figure 8.2-2 – Demo 1: Agent 1 and Agent 2 moving along passageway. 2.9 seconds have elapsed

Figure 8.2-2 shows the two agents walking along the passageway towards the destination compartment having left their starting location. Note that 2.9 seconds have elapsed in the simulation.

Figure 8.2-3 shows agent 1 moving into the destination compartment after 6.4 seconds. The properties for agent 1 have been displayed to show changes in their statistics while they are still playing a part in the simulation. The important attribute to note in agent 1's properties is their PET (Personal Elapsed Time), at this stage in the simulation it is 6.5 seconds. Note also in Figure 8.2-3 that Agent 1's PET (Personal Elapsed Time) is 0.1 seconds longer than the overall simulation time. This is not actually true, the agent cannot have been moving for longer than the simulation. This error is caused by one of two things. Firstly, by the screen refresh changing the agents PET before the simulation time (and then the screenshot taken between these screen refreshes), secondly, because there is a difference in rounding the PET and the simulation time. The actual simulation time may have been 6.455 seconds (for example) and the simulation clock on the screen has been cut to 6.4 seconds and the agent's PET rounded up to 6.5 seconds.

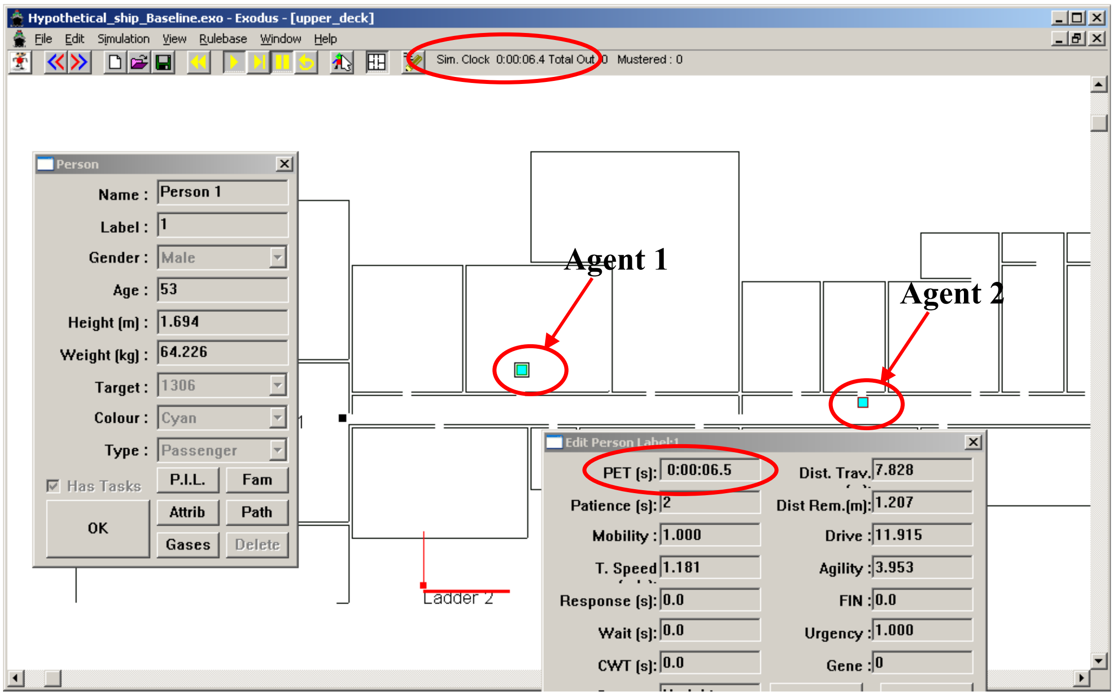


Figure 8.2-3 – Demo 1: Agent 1 arrives in destination compartment. Simulation time is 6.4 seconds and Agent 1's PET time is 6.5 seconds

Agent 1 has arrived at their final destination in Figure 8.2-4 and Agent 2 is still walking along the passageway en-route to the final destination. The simulation time is now 7.6 seconds but Agent 1's PET is 7.4 seconds. The difference in the two times is due to the agent having terminated just before this screenshot was taken.

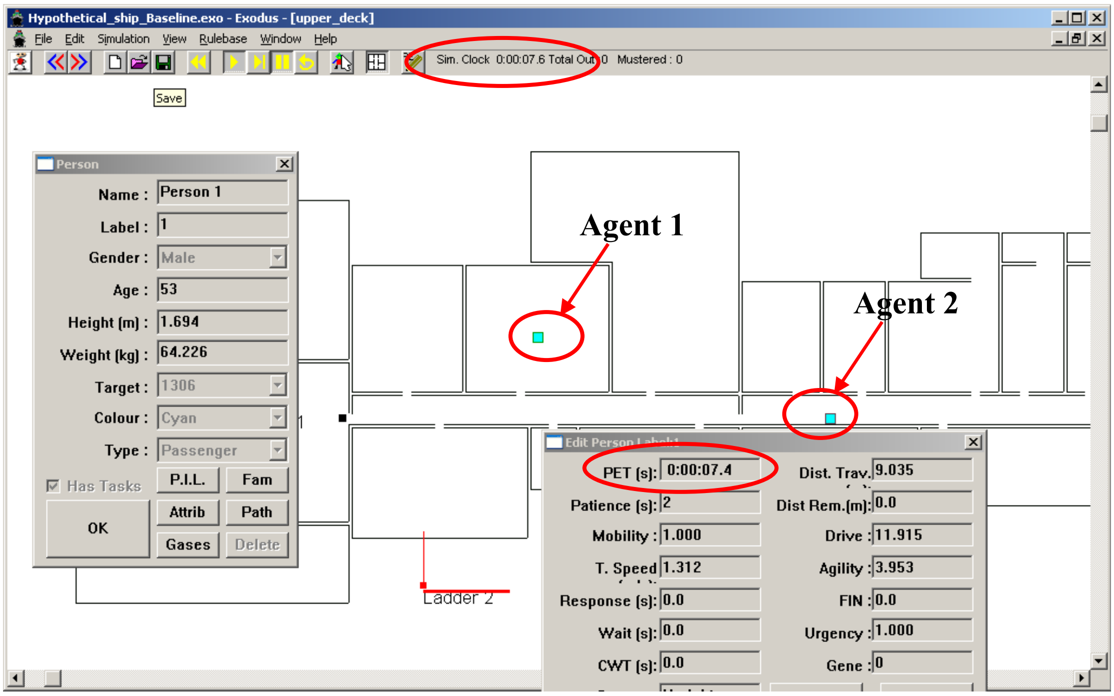


Figure 8.2-4 - Demo 1: Agent 1 arrives at destination and terminates. Simulation time is 7.6 seconds and Agent 1's PET time is 7.4 seconds. Agent 2 transits the passageway

On closer inspection of Figure 8.2-3 and Figure 8.2-4, the changes in Agent 1's properties can be seen as they reach their final destination and terminate. Their PET (Personal Elapsed Time) has increased by 0.9 seconds (from 6.5 seconds to 7.4 seconds) as they travelled the final 1.207 metres to the destination. The "Dist Rem" (distance remaining) attribute went from 1.207 in Figure 8.2-3 to 0.0 in Figure 8.2-4 and the "Dist Trav" attribute (distance travelled) has increased from 7.828 in Figure 8.2-3 to 9.035 in Figure 8.2-4.

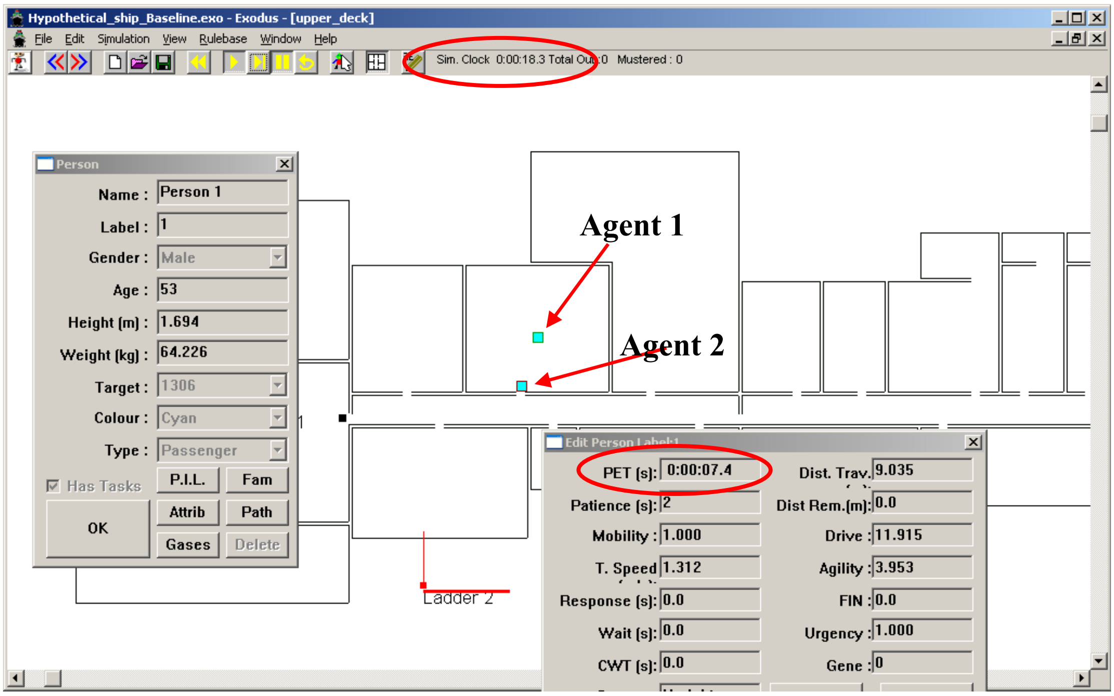


Figure 8.2-5 - Demo 1: Agent 1 remains at destination while Agent 2 arrives in compartment. Simulation time is 18.3 seconds and Agent 1's PET time remains 7.4 seconds

As can be seen from Figure 8.2-5, Agent 1 still has a PET of 7.4 seconds, even though the simulation time is now 18.3 seconds. This demonstrates that agent 1 has terminated and is playing no further part in the simulation. On closer inspection, it can also be seen that the distance travelled by Agent 1 remained at 9.035 metres and the distance remaining continued to be 0.0 metres when Figure 8.2-5 is compared to Figure 8.2-4.

This example has illustrated that the new 'Terminate' command works as required.

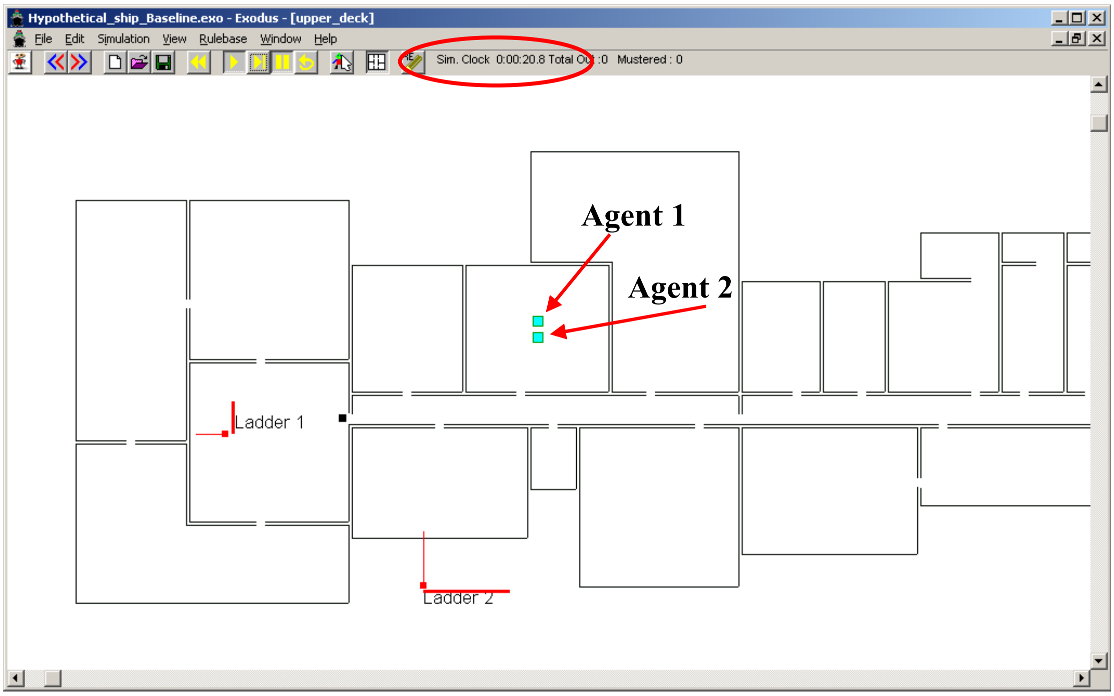


Figure 8.2-6 – Demo 1: Agent 1 and Agent 2 terminate. Simulation ends with simulation time 20.8 seconds

In Figure 8.2-6 it can be seen that the simulation clock has reached 20.8 seconds and Agent 2 has arrived at the centre of the destination compartment (Medical Centre) to join Agent 1. From Figure 8.2-7, it can be seen that the final simulation time was in fact 20.8333 seconds. This demonstrates that Agent 2 must have also terminated at 20.8 seconds and since the entire population had terminated, the simulation also ended.

Figure 8.2-7 displays the new maritimeEXODUS BMX output file. This screenshot shows the output for the functional group ‘Entire Population’. All of the data for this functional group is on separate lines and is indented by one tab. Therefore, from Figure 8.2-7 it can be seen that the ‘Entire Population’ function group consisted of two people (from ‘popSize’) who took 20.83 seconds to complete the scenario (as measured by ‘sim’). It took on average 14 seconds for each agent to complete their part of the scenario (PET) and each crew member experienced a negligible amount of congestion (as measured by ‘CWT’). They each had 2 tasks to perform (‘NoOfTasks’) which they did, whilst not using WT doors (‘WTdoors’) and 8 non WT doors (‘Doors’). The two tasks were to move to another compartment (task 1) and then to terminate (task 2).

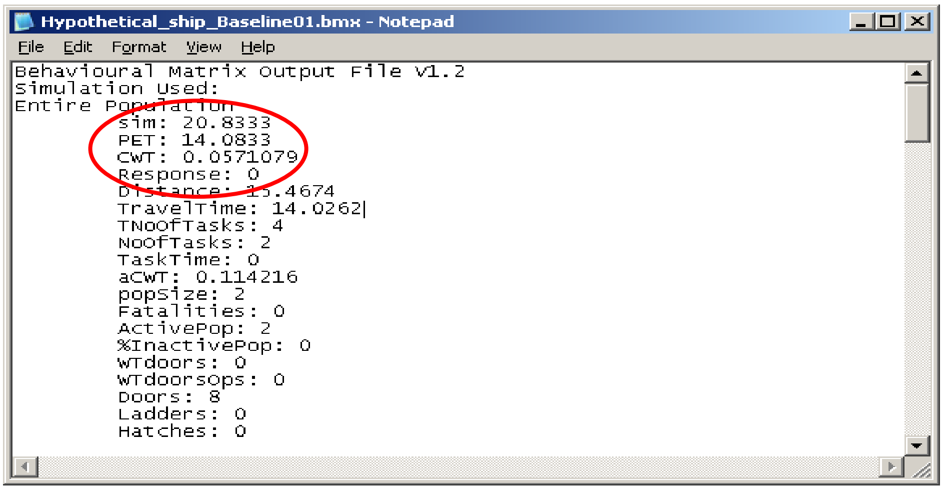

Hypothetical_ship_Baseline01.bmx - Notepad
File Edit Format View Help
Behavioural Matrix output File v1.2
Simulation Used:
Entire Population
sim: 20.8333
PET: 14.0833
CWT: 0.0571079
Response: 0
Distance: 15.4674
TravelTime: 14.0262
TNoofTasks: 4
NoofTasks: 2
TaskTime: 0
aCWT: 0.114216
popSize: 2
Fatalities: 0
ActivePop: 2
%InactivePop: 0
WTdoors: 0
WTdoorsops: 0
Doors: 8
Ladders: 0
Hatches: 0

Figure 8.2-7 – Demo 1: maritimeEXODUS output file, with simulation time output of 20.8333 seconds highlighted

In addition to the test case in this demonstration, other tests were carried out, for example, a simulation should be able to finish with a mixture of agents evacuating and terminating. Although no scenarios required this as part of the work in this thesis, it was considered a worthwhile exercise to ensure that maritimeEXODUS could function correctly with both of these behaviours. Tests of these new capabilities have shown that maritimeEXODUS will now end a simulation once all agents have either evacuated, terminated or a mixture of both.

8.3 Demonstration 2 - TerminateMill command

As described in Chapter 7.2, after initial testing of the ‘Terminate’ command, it was found that problems could arise with agents terminating on a particular node and blocking the thoroughfare for other agents. The solution to this was to introduce a milling behaviour into the terminate command.

In a similar fashion to Demonstration 1, a test case scenario was set up to demonstrate an agent’s new ability to ‘mill’ after terminating their involvement in the simulation. The scenario involved two agents, representing crew members, starting in different locations (see Figure 8.3-1), and they both move to the Medical Centre. Both agents have an instant response time and both are given the command to ‘TerminateMill’ in the Medical Centre. As with Demonstration 1, the agents along with their itineraries have been created within maritimeEXODUS using an SSF file.

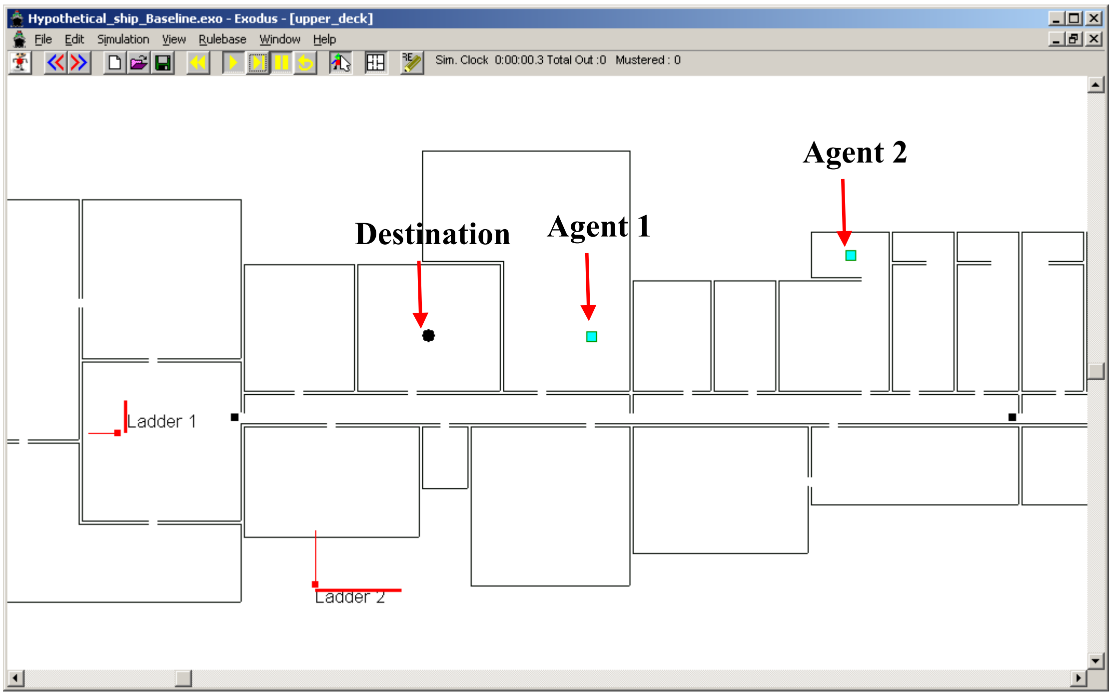


Figure 8.3-1 – Demo 2 – TerminateMill command: Agent 1 and Agent 2 in their initial locations

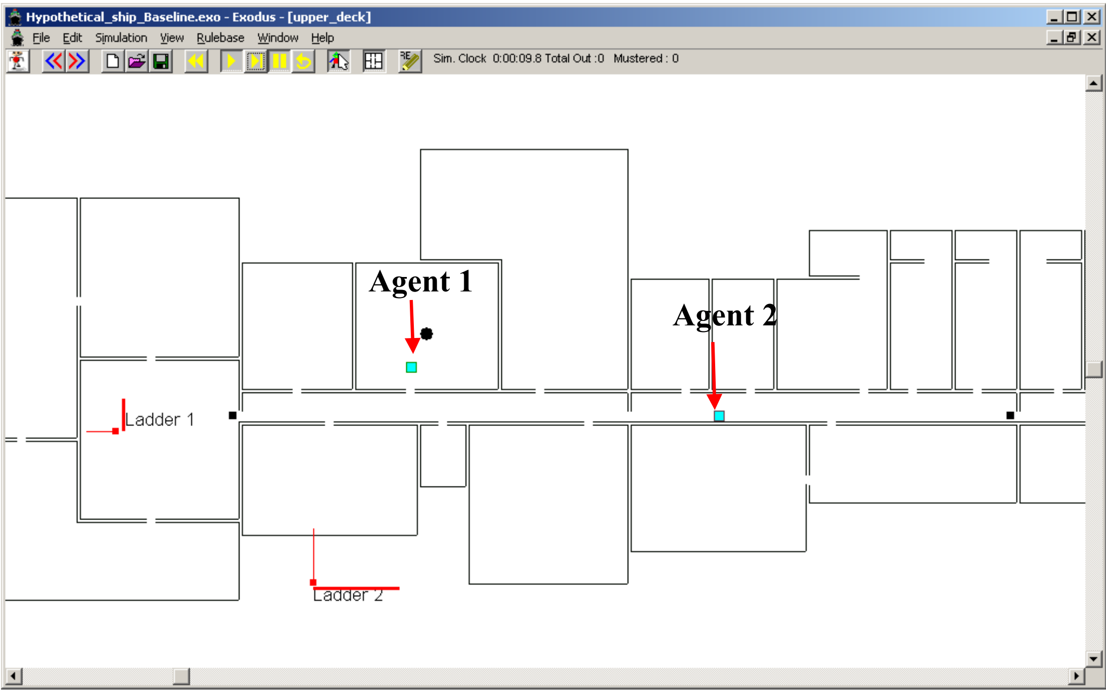


Figure 8.3-2 - Demo 2: Agent 1 enters destination compartment and Agent 2 begins to traverse the passageway

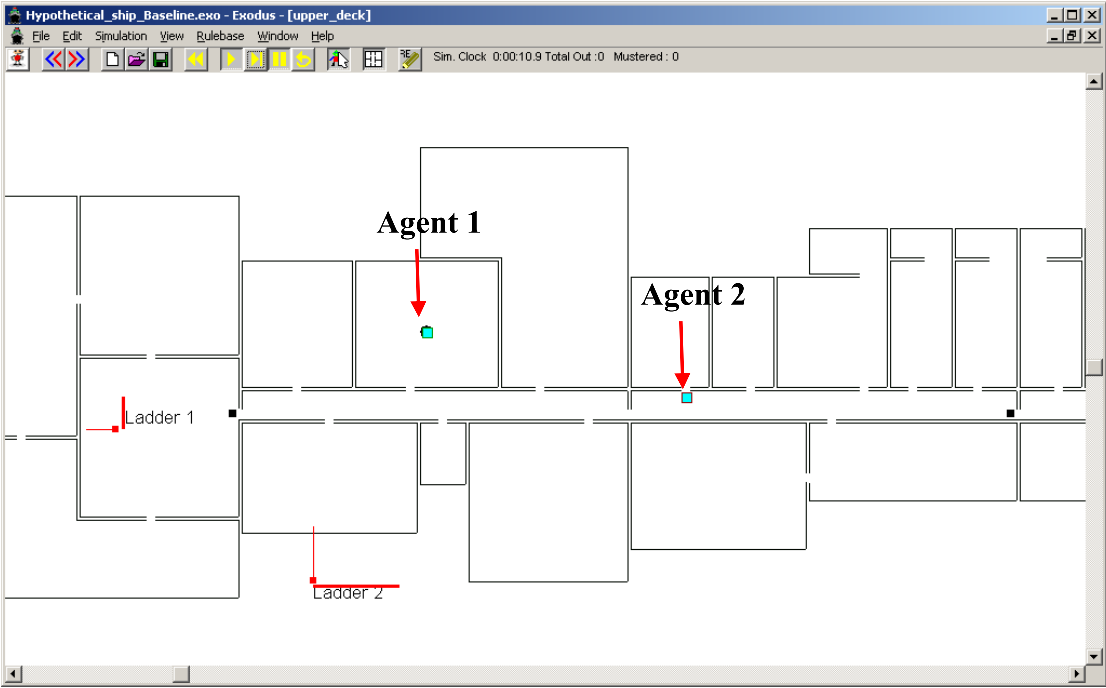


Figure 8.3-3 – Demo 2: Agent 1 arrives at destination and terminates. Agent 2 continues along passageway

Figure 8.3-2 shows Agent 1 arriving in the destination compartment and heading to the target node. At the same time, Agent 2 begins to traverse the passageway. Figure 8.3-3 shows Agent 1 arriving at the centre of the Medical Centre and reaching his destination. Meanwhile, Agent 2 still has quite a distance to travel in order to reach the Medical Centre. While Agent 1 is waiting for the simulation to end, he randomly moves around the compartment, 'Milling', as demonstrated in Figure 8.3-4 to Figure 8.3-7.

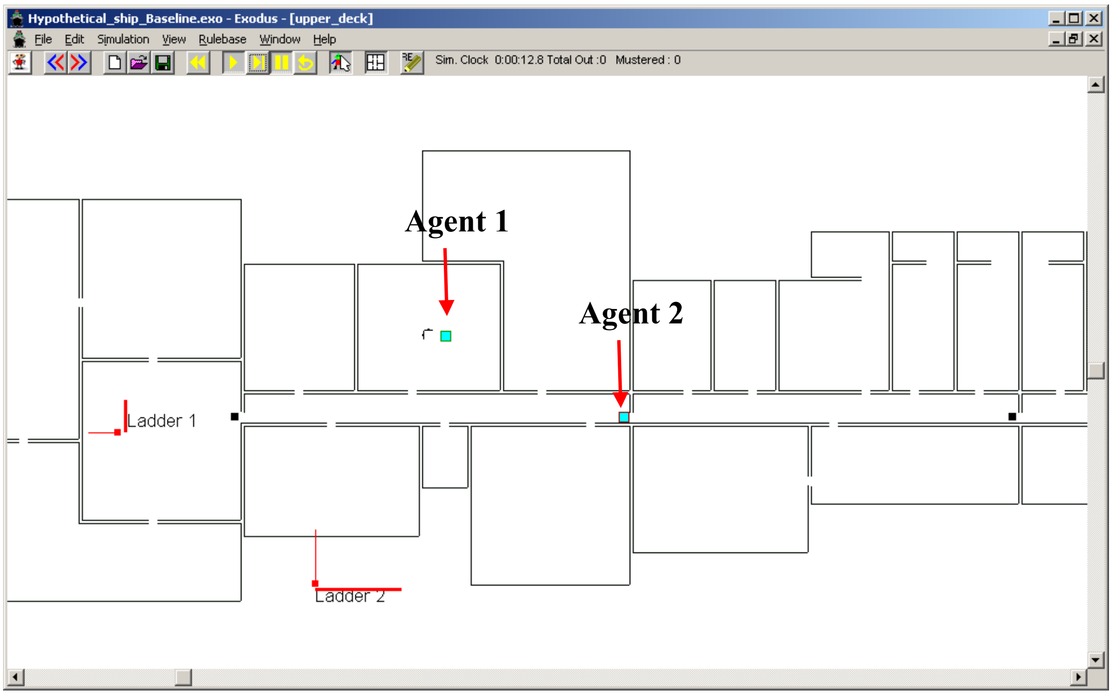


Figure 8.3-4 – Demo 2: While Agent 1 waits for Agent 2 to arrive at the destination, Agent 1 'Mills'. Agent 1 takes a random step to the right of their final location

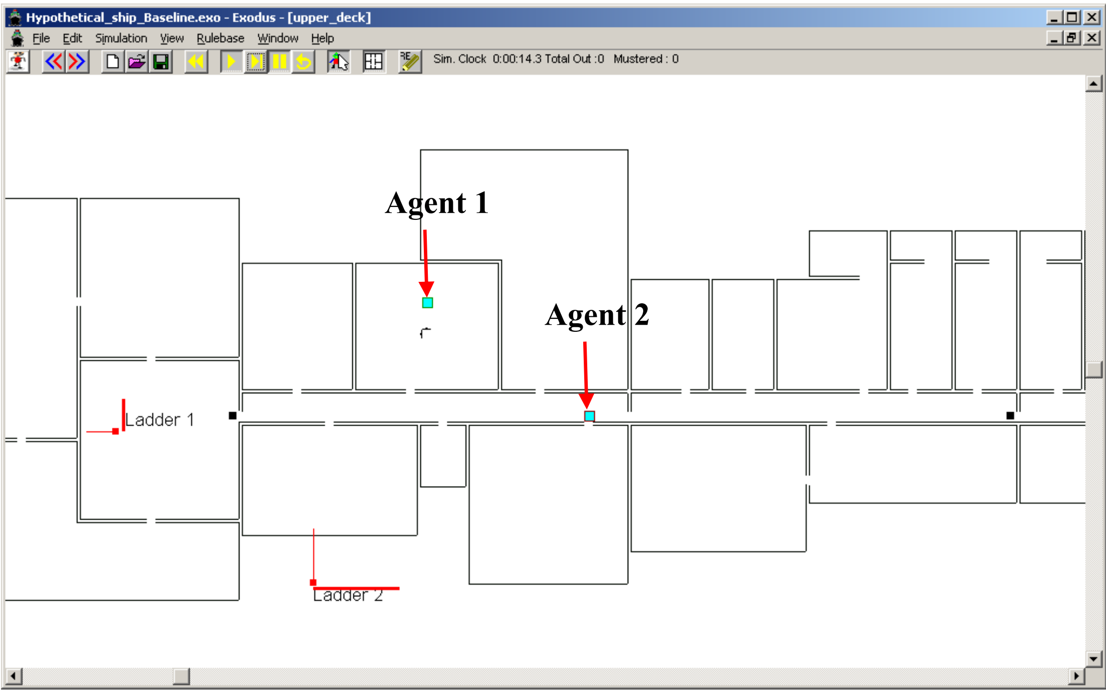


Figure 8.3-5 - Demo 2: While Agent 1 continues to wait for Agent 2 to arrive at the destination, Agent 1 'Mills'. Agent 1 takes a random step north of the destination location

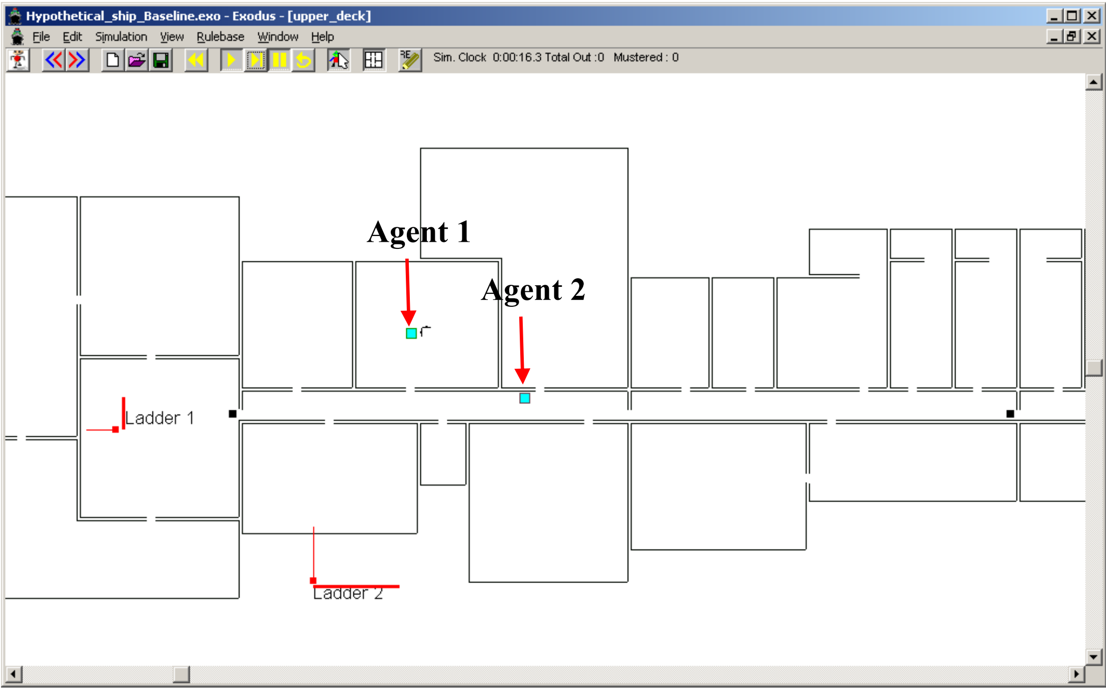


Figure 8.3-6 - Demo 2: While Agent 1 continues to wait for Agent 2 to arrive at the destination, Agent 1 'Mills'. Agent 1 takes a random step to the left of the destination location

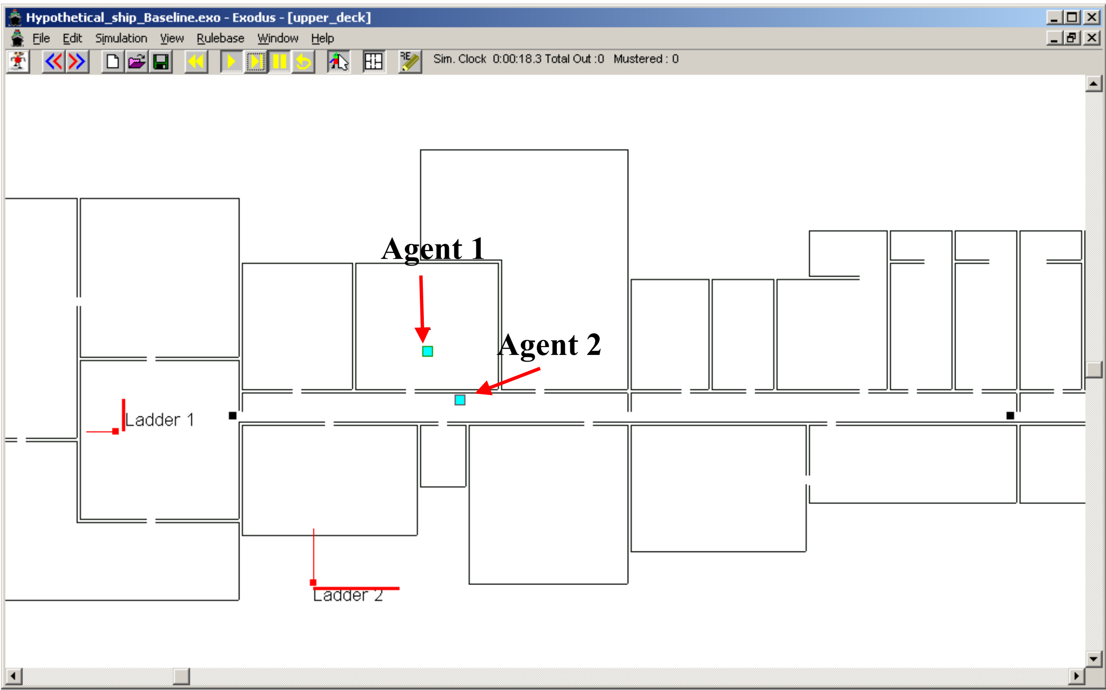


Figure 8.3-7 - Demo 2: While Agent 1 continues to wait for Agent 2 to arrive at the destination, Agent 1 'Mills'. Agent 1 takes a random step to the south of the destination location

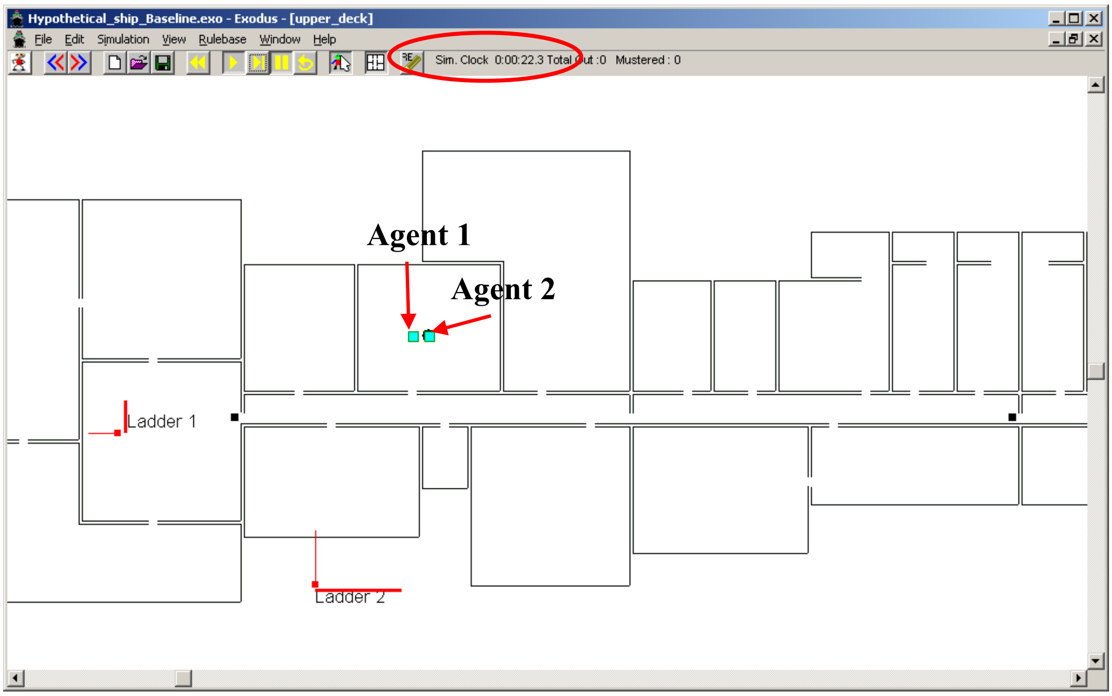


Figure 8.3-8 – Demo 2: Agent 2 arrives at destination and terminates. The simulation ends with a time of 22.3 seconds

Figure 8.3-8 shows Agent 2 arriving at his destination, i.e. the centre of the Medical Centre, where he too carries out the 'TerminateMill' command. Since there are only two agents in the simulation and both of them have reached the terminate command, the simulation ends. It can be seen that Agent 2 arrives at the centre of the compartment with 22.3 seconds on the simulation clock (see Figure 8.3-8) and the final simulation time in the output file for this simulation was 22.3333 seconds, see Figure 8.3-9.

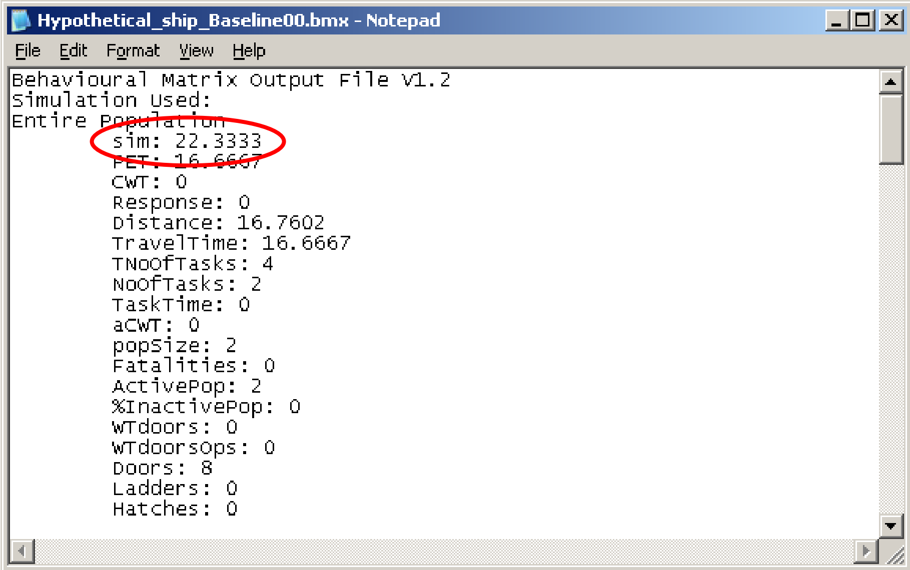


Figure 8.3-9 – Demo 2: maritimeEXODUS Output file, with simulation time output of 22.3333 seconds highlighted

8.4 Demonstration 3 - Wait command

The ‘wait’ command was intended to accompany the ‘Terminate’ action as a way of moving the agent to a position where they will not interfere with others after the agent has terminated. In this respect, the demonstration of the new command will involve two agents (see Figure 8.4-1); who will move to the officers’ mess. The first agent will have an instant response and will move to the centre of the officers’ mess where they will terminate. Once they have terminated, Agent 1 will move to the bottom right corner of the compartment where they will ‘wait’ for Agent 2 to complete their assigned tasks. Agent 2 will be given an arbitrary response time of two minutes; this is more than sufficient time to demonstrate Agent 1 waiting. When Agent 2 eventually responds, they will move to the centre of the officers’ mess where they will ‘terminate’. Agent 2, has also been given the command to ‘wait’, however, they will not have to wait since everyone else in the simulation, i.e. Agent 1, has terminated. As with the previous two demonstrations, these agents and their itineraries have been imported into maritimeEXODUS using an SSF file.

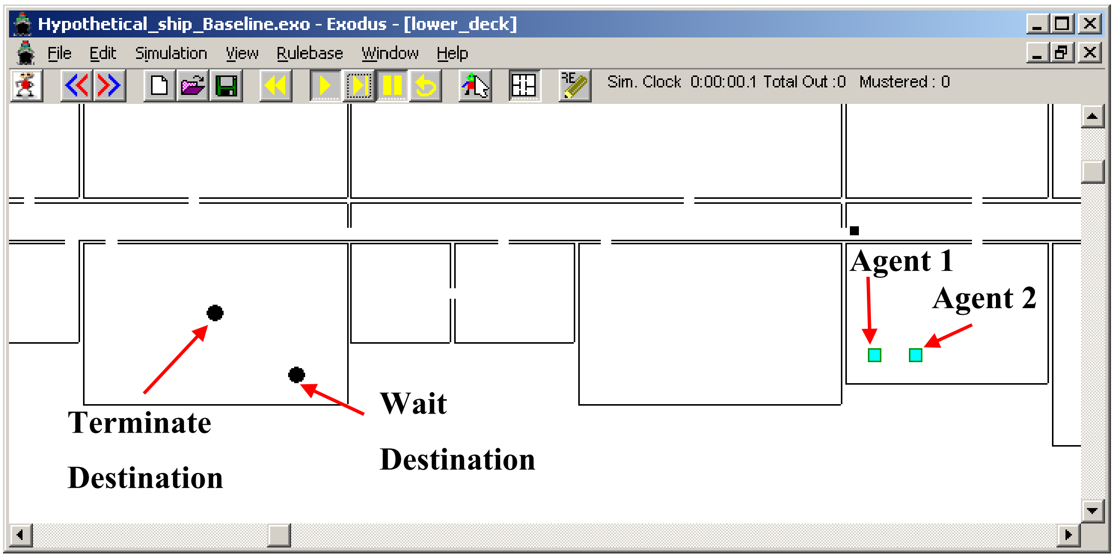


Figure 8.4-1 – Demo 3 – Wait command: Agent 1 and 2 in their initial locations. Location of agents' termination and wait destination identified

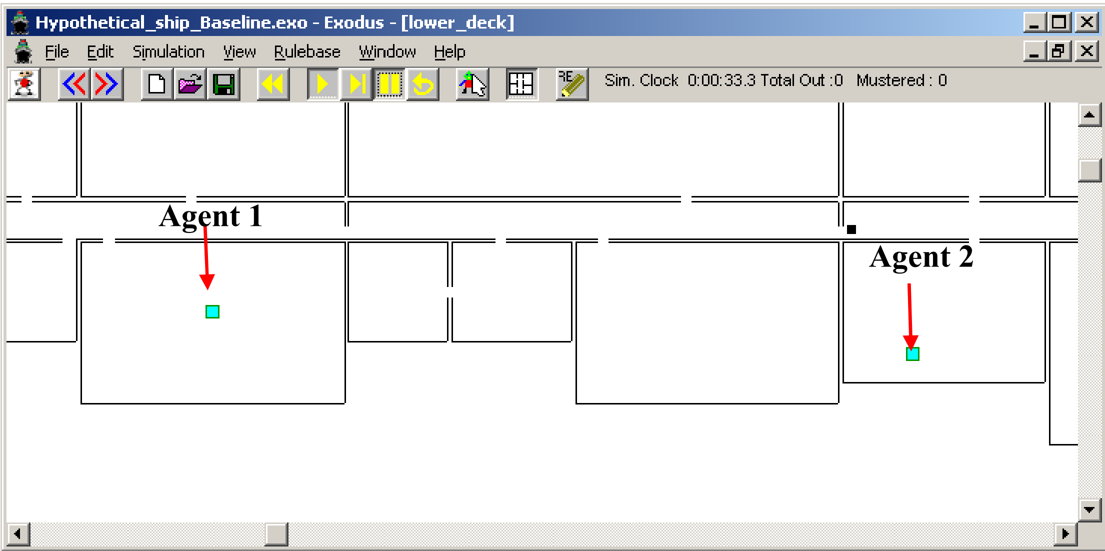


Figure 8.4-2 – Demo 3: Agent 1 arrives at destination and terminates. Agent 2 remains in their initial location

Figure 8.4-2 shows Agent 1 arriving at the centre of the officers' mess where they terminate. As the 'terminate' task is followed by the 'wait' command, Agent 1 will now move to the bottom right corner of the compartment, as specified in the wait command, see Figure 8.4-3.

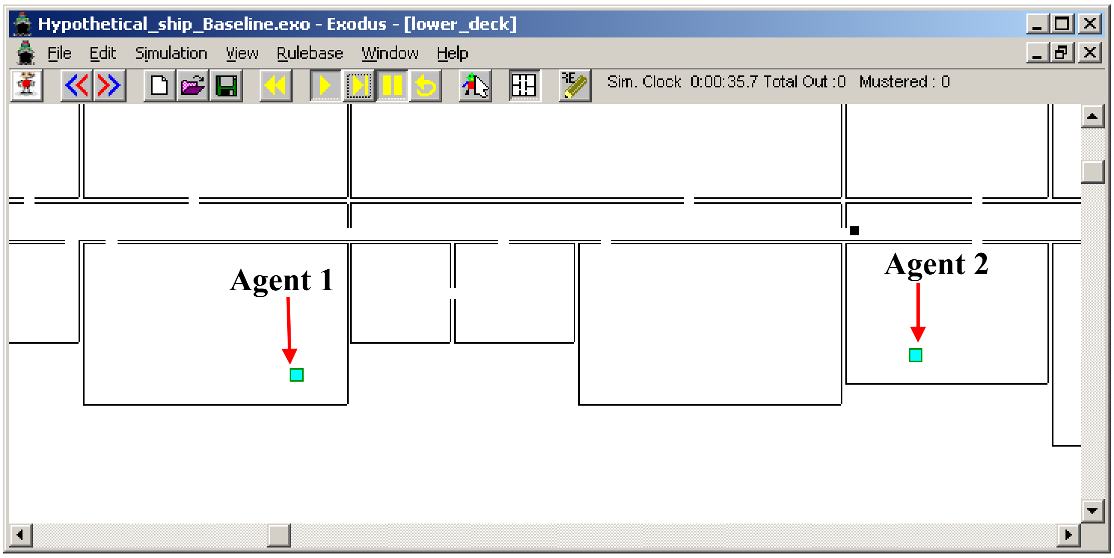


Figure 8.4-3 – Demo 3: After terminating, Agent 1 moves to the specified location and 'Waits' for the simulation to end. Agent 2 remains at their initial location.

Once Agent 1 arrives here, they will randomly move about within a specified range (set at a radius of 2 metres for this demonstration). Figure 8.4-4 shows Agent 1 moving one node to the right of their destination, Figure 8.4-5 shows the agent moving 1 node to the left of their destination and Figure 8.4-6 shows the agent moving one node to the left and 1 node up from their destination.

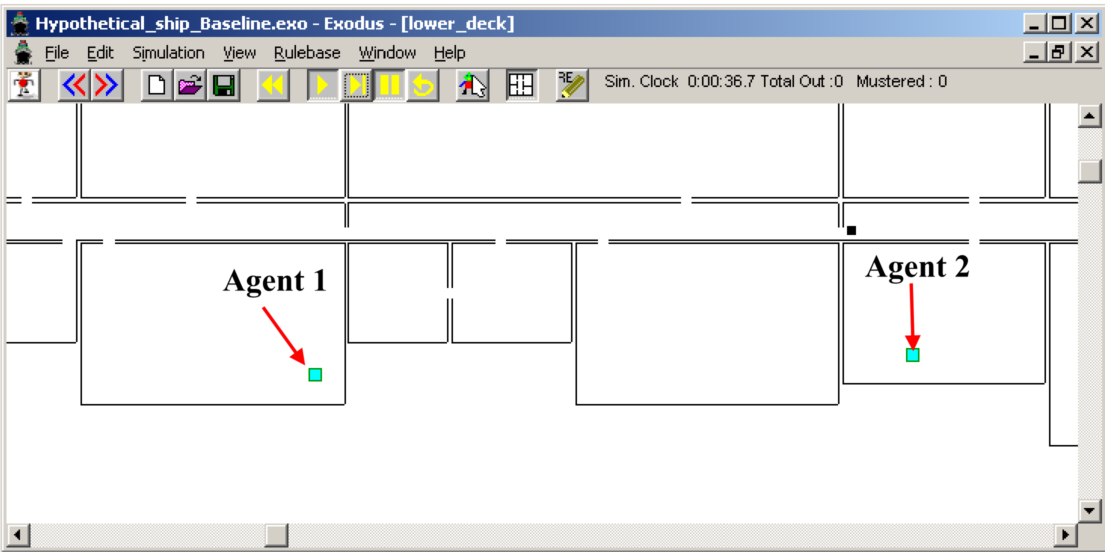


Figure 8.4-4 – Demo 3: Agent 1 'mills' about specified location while waiting for end of simulation. Agent 2 still in initial location

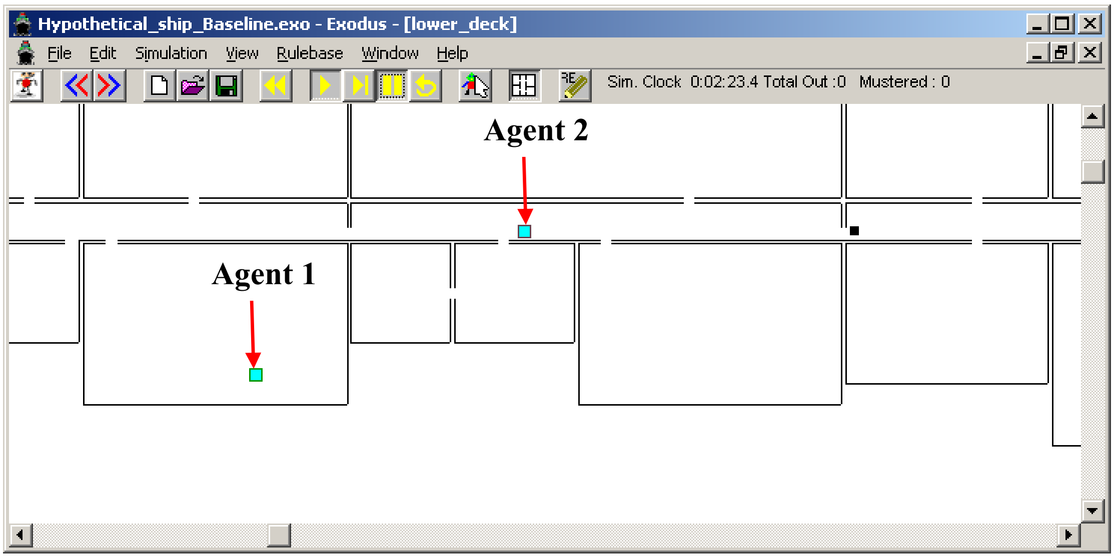


Figure 8.4-5 – Demo3: Agent 2 traverses the passageway towards destination compartment. Agent 1 continues to wait for end of the simulation

After 2 minutes, Agent 2 has finished their previous tasks and has responded (see Figure 8.4-5). In Figure 8.4-6 Agent 2 has arrived at the centre of the officers' mess where they have terminated. At this point Agent 1 also terminates and the simulation ends.

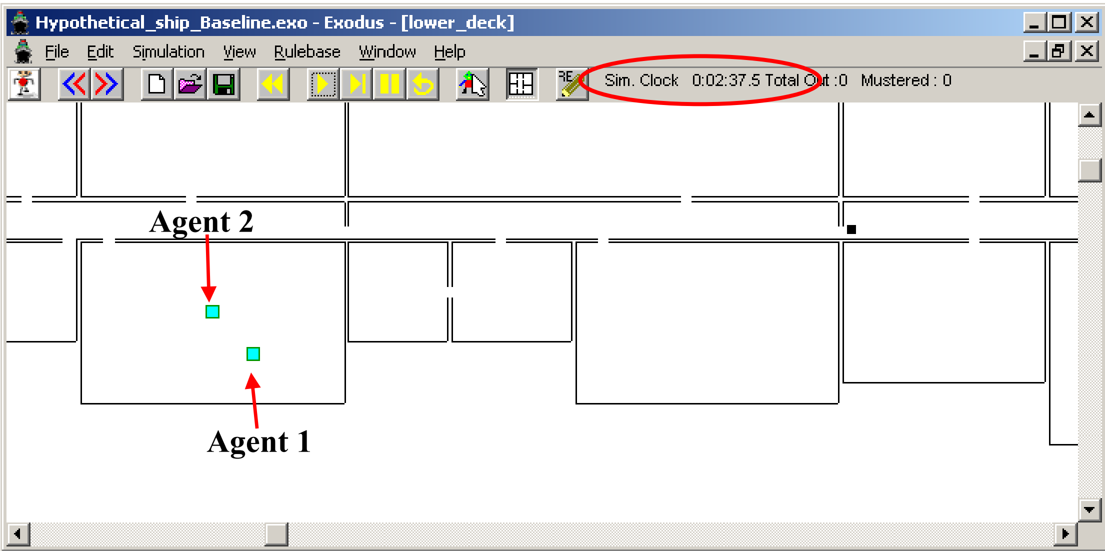


Figure 8.4-6 – Demo 3: Agent 2 arrives at destination and terminates. Agent 1 will also terminate and the simulation ends with a simulation time of 2 minutes 37.5 seconds

Figure 8.4-6 shows that the final simulation time was 2 minutes 37.5 seconds (or 157.5 seconds), this is corroborated by the BMX output file shown in Figure 8.4-7 which shows the final simulation time ("sim") as 157.5 seconds.

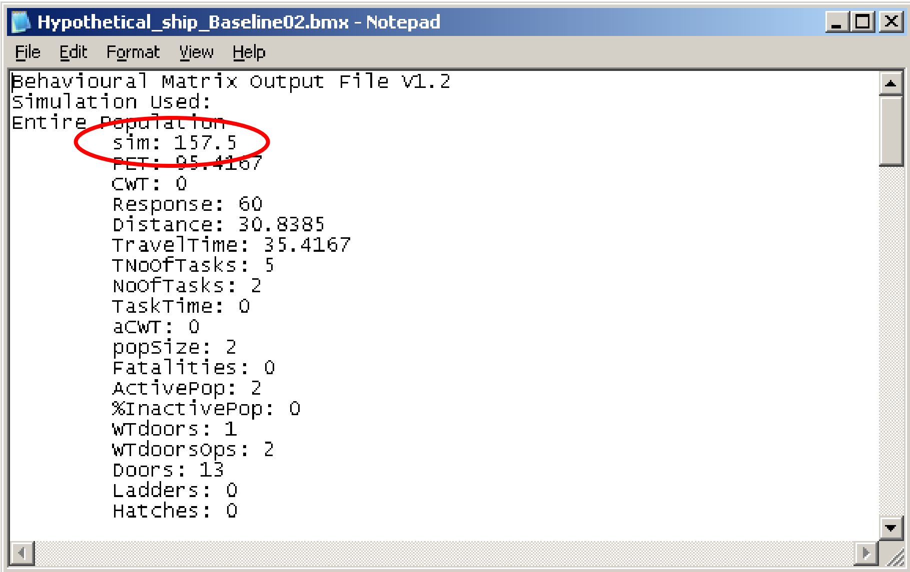


Figure 8.4-7 – Demo 3: maritimeEXODUS Output file, with simulation time of 157.5 seconds highlighted

8.5 Demonstration 4 – Search Compartment Command

The Search Command was developed as a requirement for the State 1 Preps and the Blanket Search Scenario. This command involves the crew member assigned this task to enter a room and spend a specified amount of time in there, which represents them either searching the compartment for damage (in the case of the 'Blanket Search' scenario) or checking the room for loose / dangerous items (in the case of the 'State 1 Preps' scenario). The agent carrying out this task does not actually do anything except remain in the compartment for a specified time.

This command may be developed further in the future to more accurately meet the requirements of specific scenarios. For example, when searching a compartment as part of the 'Blanket Search' scenario, an agent may be told to walk around the perimeter of the compartment. This would more accurately represent a crew member searching the compartment thoroughly. Alternatively, an agent may move to the centre of the compartment and experience a time delay. This could represent a crew member checking equipment as part of a search.

To demonstrate the newly implemented 'Search Compartment' command, a test case was devised which involved a single agent placed in the hypothetical ship (see Figure 8.5-1). This agent is assigned the task to enter another compartment and search it for between 10 and 20 seconds, after which they return to their initial location where they will terminate.

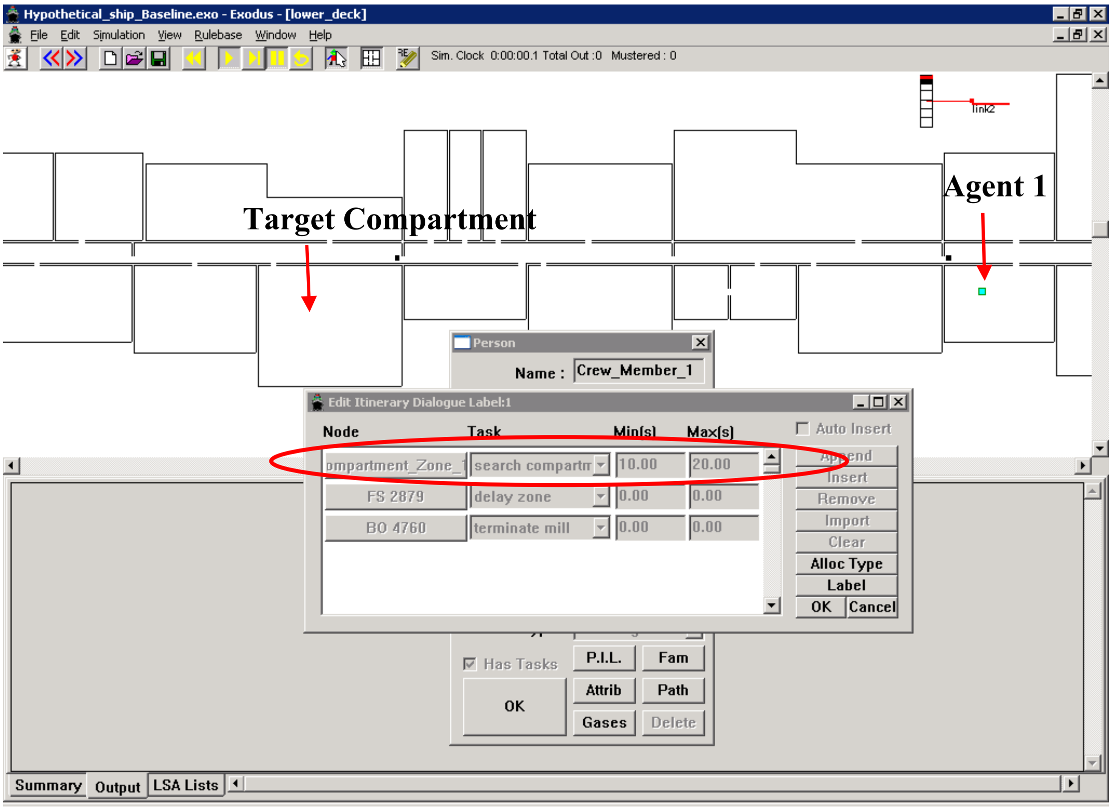


Figure 8.5-1 - Demo 4: Search Compartment command: Agent 1 at their initial location. Agent 1's itinerary displayed with the 'Search Compartment' task and their target compartment highlighted

Figure 8.5-1 shows the agent's (called 'Crew Member 1') itinerary. As can be seen, the agent has been assigned three tasks. The first of which (highlighted in Figure 8.5-1) involves searching a compartment for between 10 and 20 seconds. The second instructs the agent to delay in a different zone for 0 seconds (effectively sending the agent to another location) and the final task is to terminate in that location.

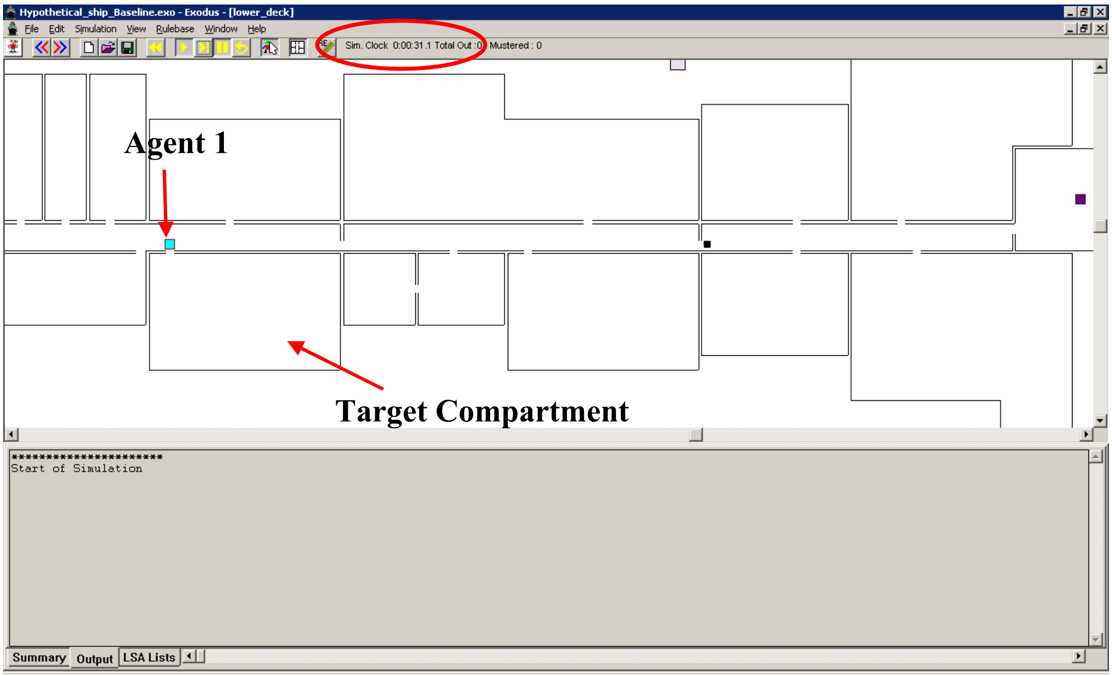


Figure 8.5-2 - Demo 4: the agent is about to enter the compartment. The simulated time is 31.1 seconds

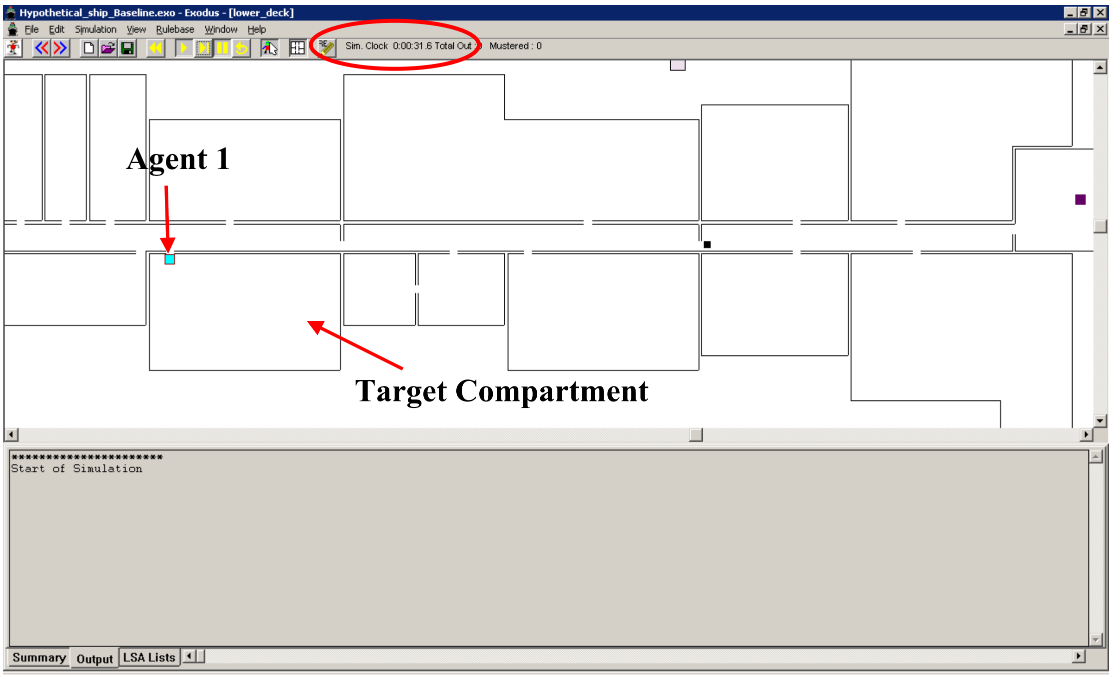


Figure 8.5-3 - Demo 4: agent enters the target compartment after 31.6 seconds. The search compartment task has not began yet

Figure 8.5-2 shows the agent after responding to the scenario, approaching the target compartment. They arrive at the entrance to the target compartment after 31.1 seconds. The agent enters the compartment 31.6 seconds into the simulation (see Figure 8.5-3) and has started the search compartment task by 32.1 seconds (see Figure 8.5-4).

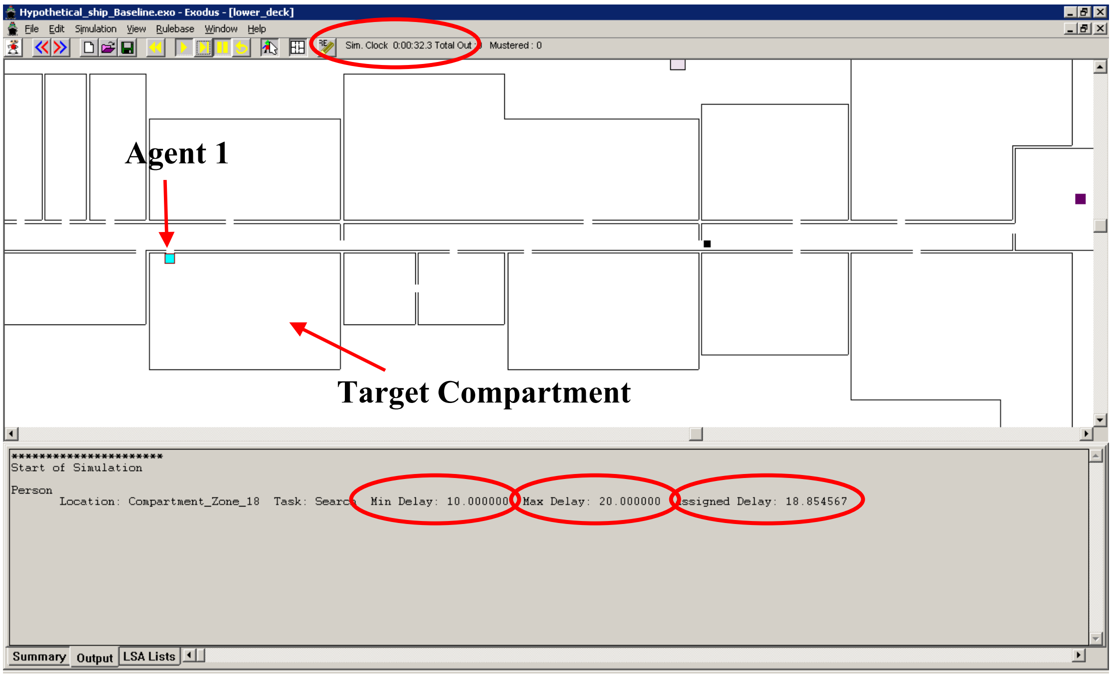


Figure 8.5-4 - Demo 4: search compartment command commenced. The task details are highlighted, including the minimum and maximum delay as well as the actual delay task assigned to the agent. The simulation time has reached 32.3

The details of the search compartment task can be seen in Figure 8.5-4. The agent has been assigned the task 'search' which they have to carry out at the location 'Compartment Zone 18'. The task carries a minimum delay of 10 seconds and a maximum delay of 20 seconds. The actual time assigned to the agent in this simulation is 18.85 seconds. Using this information and knowing that the agent had entered the compartment 31.6 seconds into the simulation, it is known that the agent will complete the search compartment task at 50.45 seconds (31.6 + 18.85).

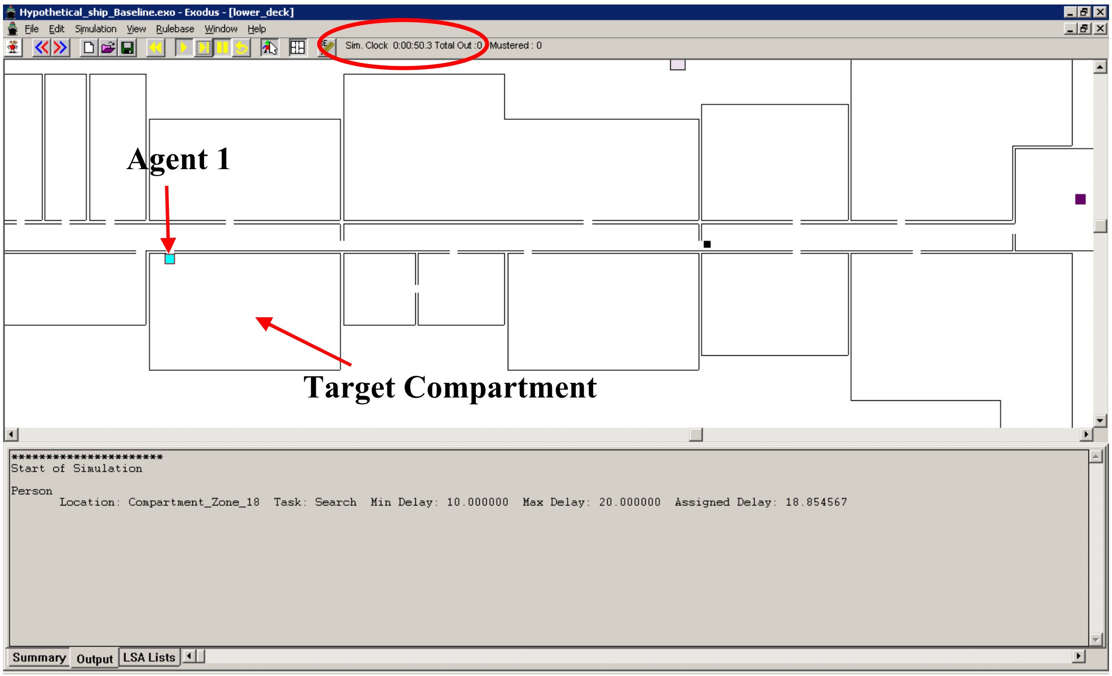


Figure 8.5-5 - Demo 4: Agent 1 continues to search the compartment. The simulation time is 50.3 seconds

The agent approaches the end of the ‘search compartment’ task in Figure 8.5-5 with the simulation clock on 50.3 seconds. The agent should complete the ‘search’ task at 50.45. When the simulation clock reaches 50.8 in Figure 8.5-6, the agent has completed the ‘search’ task and has moved out of the compartment en-route to their final destination. This shows that the task has worked correctly.

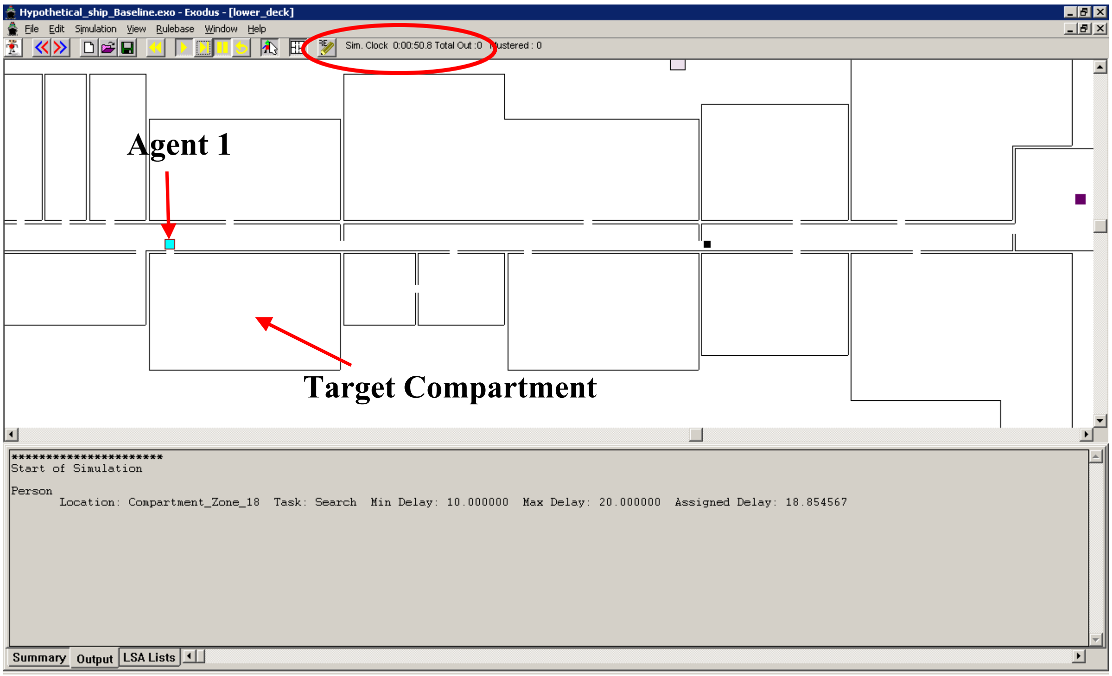


Figure 8.5-6 - Demo 4: The agent finishes the search compartment task and moves out of the compartment en route to their final destination. The simulation time is 50.8 seconds

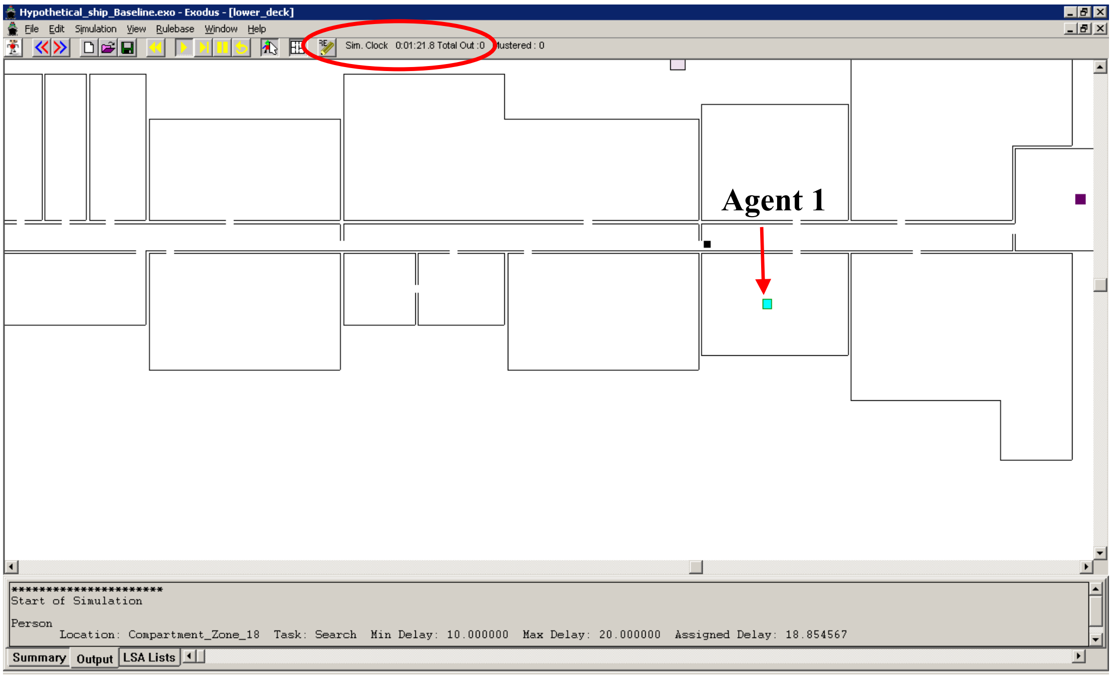
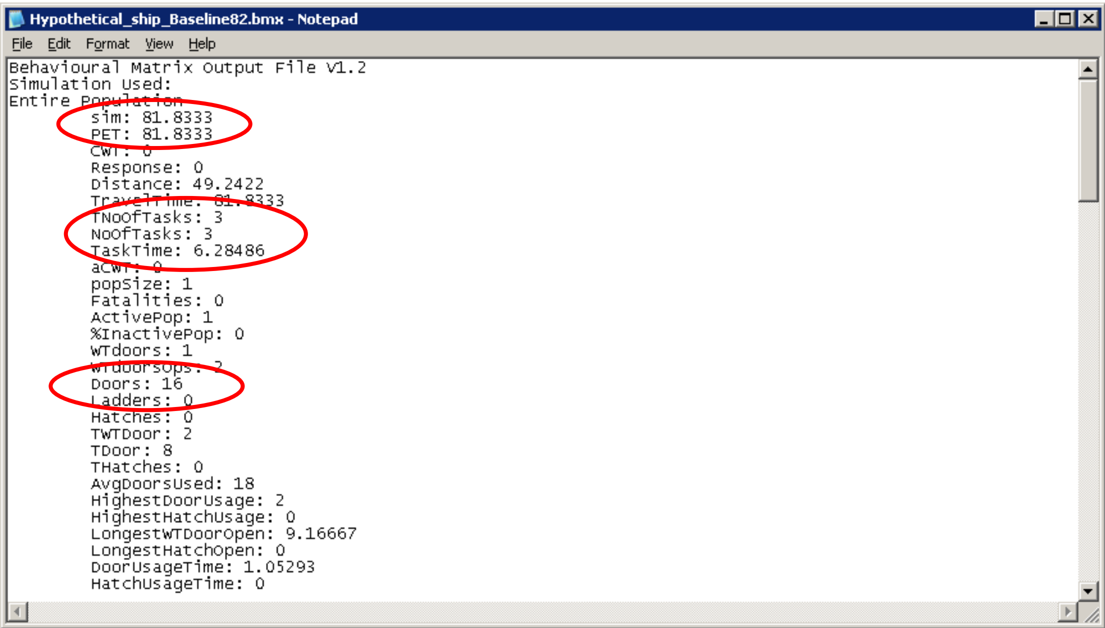


Figure 8.5-7 - Demo 4: The agent arrives at their final destination and terminates. The simulation ends with a time of 1 minute 21.8 seconds

In Figure 8.5-7, the agent has reached their final destination and terminated with a simulation time of 1 minute 21.8 seconds (81.8 seconds). This is the same as the simulation time recorded in the BMX output file displayed in Figure 8.5-8, as shown by the line "sim: 81.8333". The output file also shows how there were three tasks performed which compares well against the screenshot in Figure 8.5-1, which also shows three tasks assigned to the agent. In addition to the correct number of tasks performed, the output file also registers an average task time of 6.28 seconds. Since two of the tasks do not require any time to complete, then the average task time must be the length of time to complete the search compartment task. This time is therefore divided by 3 (tasks). As the search compartment task took 18.85 then the average task time would be 6.28 seconds (18.85 / 3).

Also highlighted in the output file, see Figure 8.5-8, is the number of doors used, which in this demonstration is 16 (from the line "Doors: 16"). The agent had to use 4 doors to get from their starting location to the compartment which they searched, and then used 4 doors to get to their final destination. Thus 8 doors were used in total, all of those were closed when the agent approached them which meant that the agent had to firstly open each door and then close each door behind them, which for 8 doors equates to 16 door operations. This is further validation showing that the outputs from the model are working correctly.


Hypothetical_ship_Baseline82.bmx - Notepad
File Edit Format View Help

```
Behavioural Matrix Output File V1.2
Simulation Used:
Entire Population
        sim: 81.8333
        PET: 81.8333
        CWT: 0
        Response: 0
        Distance: 49.2422
        TravelTime: 81.8333
        TNoofTasks: 3
        NoofTasks: 3
        TaskTime: 6.28486
        aCWT: 0
        popSize: 1
        Fatalities: 0
        ActivePop: 1
        %InactivePop: 0
        WTdoors: 1
        WTdoorsOps: 2
        Doors: 16
        Ladders: 0
        Hatches: 0
        TWTDoor: 2
        TDoor: 8
        THatches: 0
        AvgDoorsUsed: 18
        HighestDoorUsage: 2
        HighestHatchUsage: 0
        LongestWTDoorOpen: 9.16667
        LongestHatchOpen: 0
        DoorUsageTime: 1.05293
        HatchUsageTime: 0
```

Figure 8.5-8 - Demo 4: The output file for the simulated test case. The simulation time (81.8333), number of tasks performed (3), average task time (6.28486) and number of doors used (16) highlighted.

8.6 Demonstration 5 - Blanket Search command

The Blanket Search command was developed for the evaluative scenario of the same name. The purpose of the action is to search every unoccupied compartment on board the vessel. As explained in greater detail in Chapter 7, crew members selected to carry out the search of the vessel would be assigned a list of compartments to search and then sent to dispersal stations. These dispersal stations would be the furthest point away from their current position, usually a FRPP (Fire Repair Party Post), and would be the first compartment which they search. Once the crew arrives at the dispersal stations, an arbitrary time elapses before the blanket search commences. For the purposes of modelling the scenario, this delay will be zero seconds. At which point, the crew will start searching their assigned compartments.

To demonstrate this command, two agents will be sent to a FRPP, located in the compartment at the end of the passageway. From here they will be assigned a dispersal station and a list of compartments to search. They will then head to the dispersal station and once both agents are there, they will start the search. A third agent is located in the geometry to represent an occupied compartment which the other agents do not need to search. The initial state of the scenario can be seen in Figure 8.6-1. The third agent can be seen in the space labelled “Occupied Compartment”. In this figure, the dispersal station has not yet been defined.

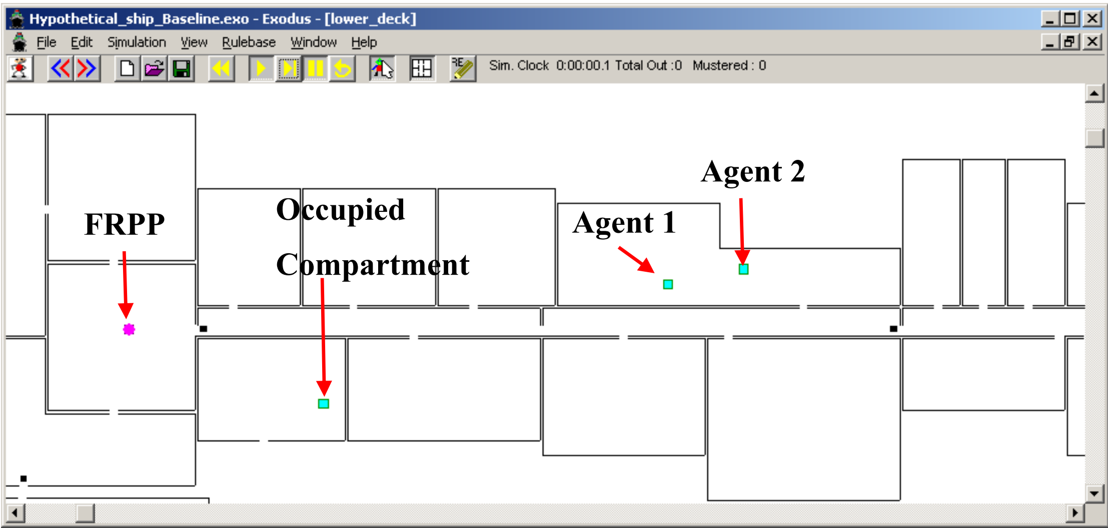


Figure 8.6-1 - demo 5: Blanket Search command; Initial state of test case showing Agent 1 and Agent 2 in their initial locations, the FRPP (action station) at the other end of the passageway and an agent occupying a compartment.

Figure 8.6-2 shows the two agents arriving at the FRPP (their assigned action station) and receiving the list of compartments which they need to search. maritimeEXODUS uses a dot placed in the centre of a compartment to represent compartments that have to be searched. The dispersal station is highlighted in Figure 8.6-2, using a pink dot to represent the designated dispersal station.

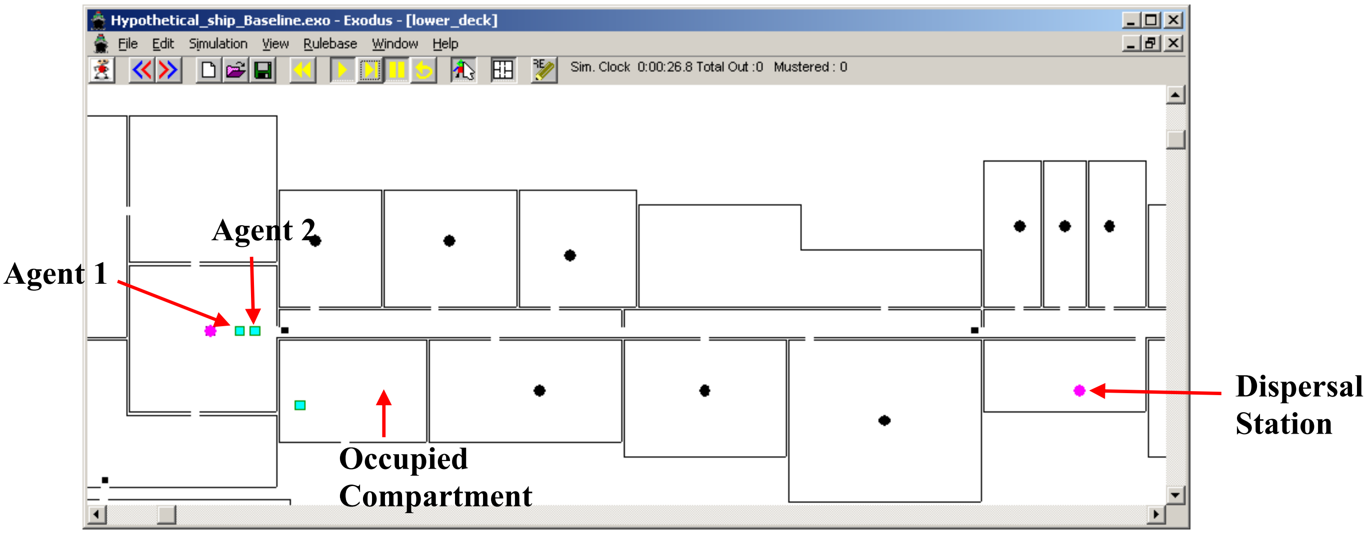


Figure 8.6-2 - Demo 5: Agent 1 and Agent 2 at the FRPP, are assigned compartments to search and given location of dispersal station. Note that they are not assigned the compartment which is already occupied

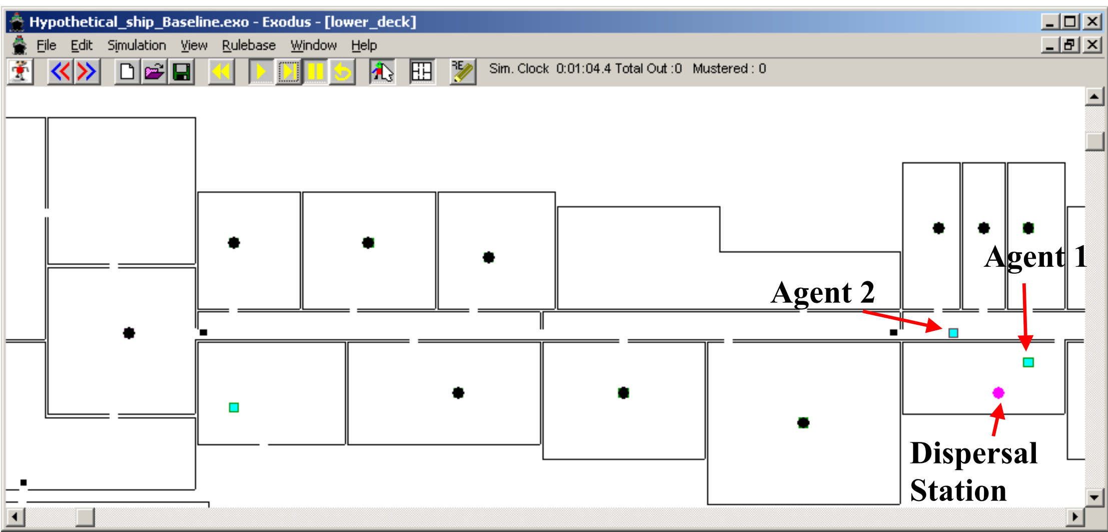


Figure 8.6-3 - Demo 5: Agent 1 arrives at dispersal station and waits for Agent 2 to arrive before proceeding with the blanket search

Figure 8.6-3 shows how Agent 1 has arrived at the dispersal station and is waiting for all other crew members (i.e. Agent 2 in this case) to reach their dispersal stations and for the call to ‘blanket search’.

Agent 2 arrives at the dispersal station in Figure 8.6-4 where Agent 1 is already located. Since all crew members assigned the task to blanket search have arrived at dispersal stations, the order to ‘blanket search’ is given.

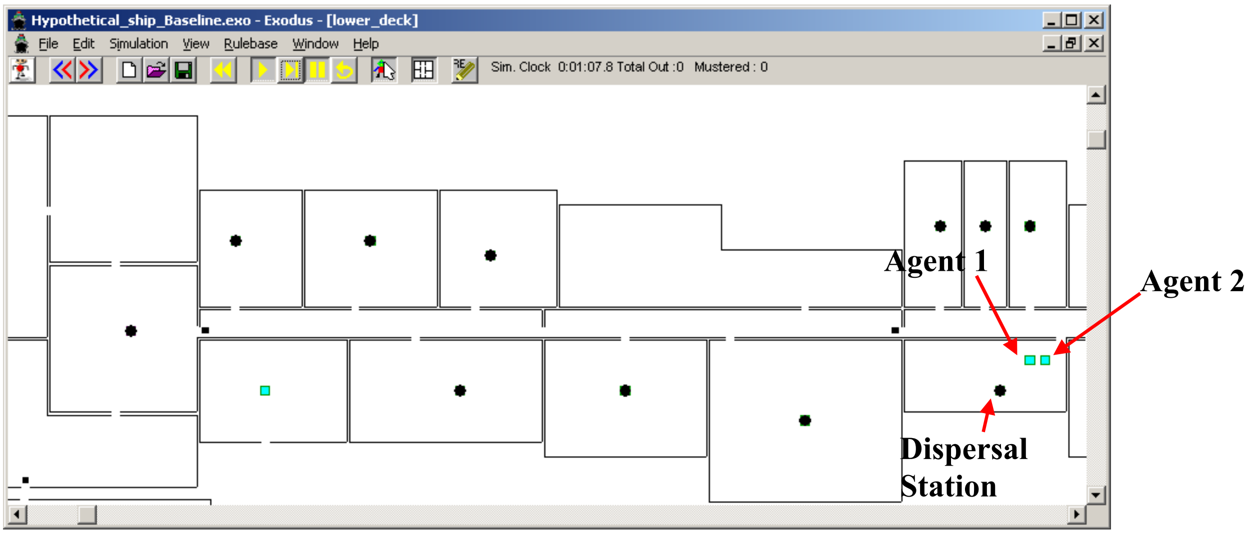


Figure 8.6-4 - Demo 5: Agent 2 arrives at dispersal station where Agent 1 is already stationed. This sparks the start of the blanket search

Figure 8.6-5 shows the two agents checking the first two compartments in their itinerary for signs of damage. Note that they do not check the same compartments as each other and are therefore, in adjacent compartments.

Figure 8.6-6 and Figure 8.6-7 show the routes taken by each agent during the Blanket Search scenario. The routes show how each agent searched alternate compartments starting at the furthest point from the FRPP and working towards it. There were many possible routes which the agents could have taken, for example one agent could have searched all compartments on the left side of the passageway whilst the other agent searched the compartments on the right hand side. Alternatively, each agent could have started at either end of the passageway and worked inwards searching each compartment along their way.

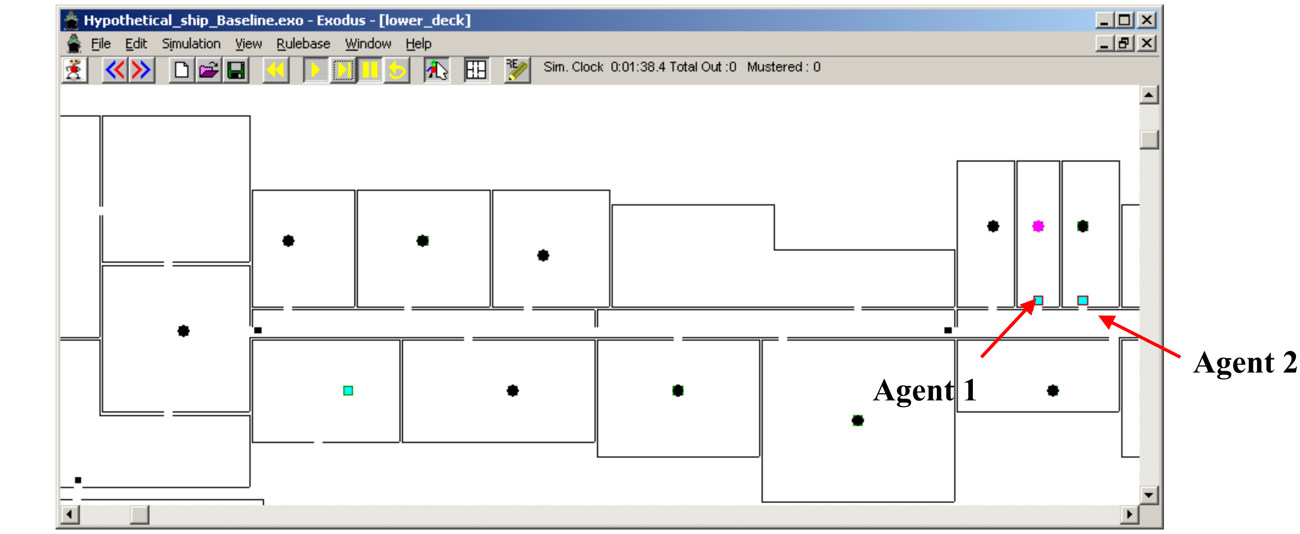


Figure 8.6-5 - Demo 5: Agent 1 and Agent 2 start searching assigned compartments. Note they are in adjacent compartments

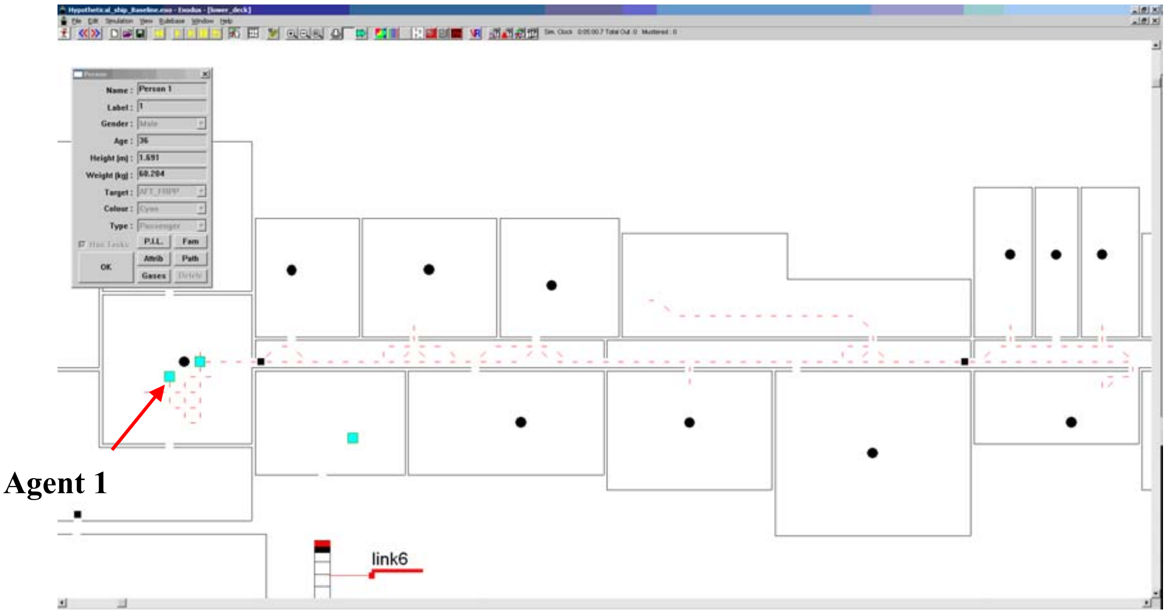


Figure 8.6-6 - Demo 5: the route taken by Agent 1 during the Blanket Search scenario

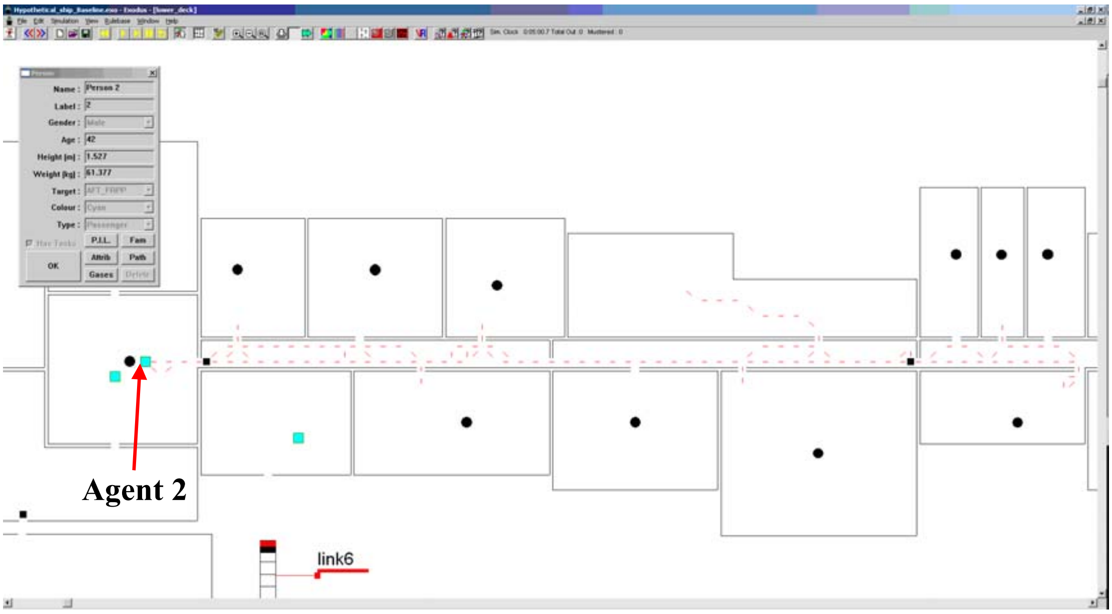


Figure 8.6-7 - Demo 5: the route taken by Agent 2 during the Blanket Search scenario. Once Agent 2 arrives, the simulation ends

Once both crew members have reported their findings to the FRPP (see Figure 8.6-7), the agents terminate and the simulation ends.

This demonstration shows how maritimeEXODUS is capable of simulating the Blanket Search scenario. The agents can be sent to an action station and be assigned a dispersal station and a list of compartments to search. The agents will then head off in pairs to the dispersal stations and wait for all other agents to reach their assigned dispersal stations before starting the search of all the unoccupied compartments.

In addition to the test case demonstrated here, other aspects of this behaviour were assessed. It was essential that agents waited for all other agents to reach the dispersal stations before setting off to search compartments. Tests were performed where agents were held back while other agents arrived at the dispersal stations before setting off to their dispersal station. These tests demonstrated that the other agents did wait for the slower agent to reach their dispersal station before setting out on the blanket search and were therefore successful.

A requirement of the Blanket Search scenario on board a naval vessel was to search all the compartments within a single WT zone before moving into the next WT zone. This is carried out to minimise the amount of time WT devices (such as WT doors or hatches) are open.

During tests it could be seen that the agents would start at the bottom of the furthest WT zone (from the FRPP / action station). They would also work their way up to the top of the WT zone before moving into the next WT zone.

This behaviour may be different on board different naval vessels. For example, crew may not need to report to an action station / FRPP. They may be using radios or internal intercoms to receive the orders and report any findings. Also crew members may not move in pairs, they may be on their own or even in small groups. In this sense they may be searching all or no compartments in a passageway rather than every other one. What was successfully modelled for this work was considered representative of a basic Blanket Search scenario.

8.7 Demonstration 6 - Close WT door command

The 'Close Door' command was designed for the 'State 1 Prep' scenario, where the vessel needs to close up ready for battle. This command instructs the crew member to approach the WT door and close it; by doing so this helps the ship reach watertight integrity condition Z. If the door is already closed, the crew member will still approach the door and will check that it is securely closed.

To demonstrate the 'Close Door' command, an agent placed in the hypothetical ship will be assigned the instruction to close the WT door 'WTD6', see Figure 8.7-1. This WT door will initially be set in the open state. An SSF file has been used to set the initial state of the WT door as well as to created the agent and give them the command to close the WT door.

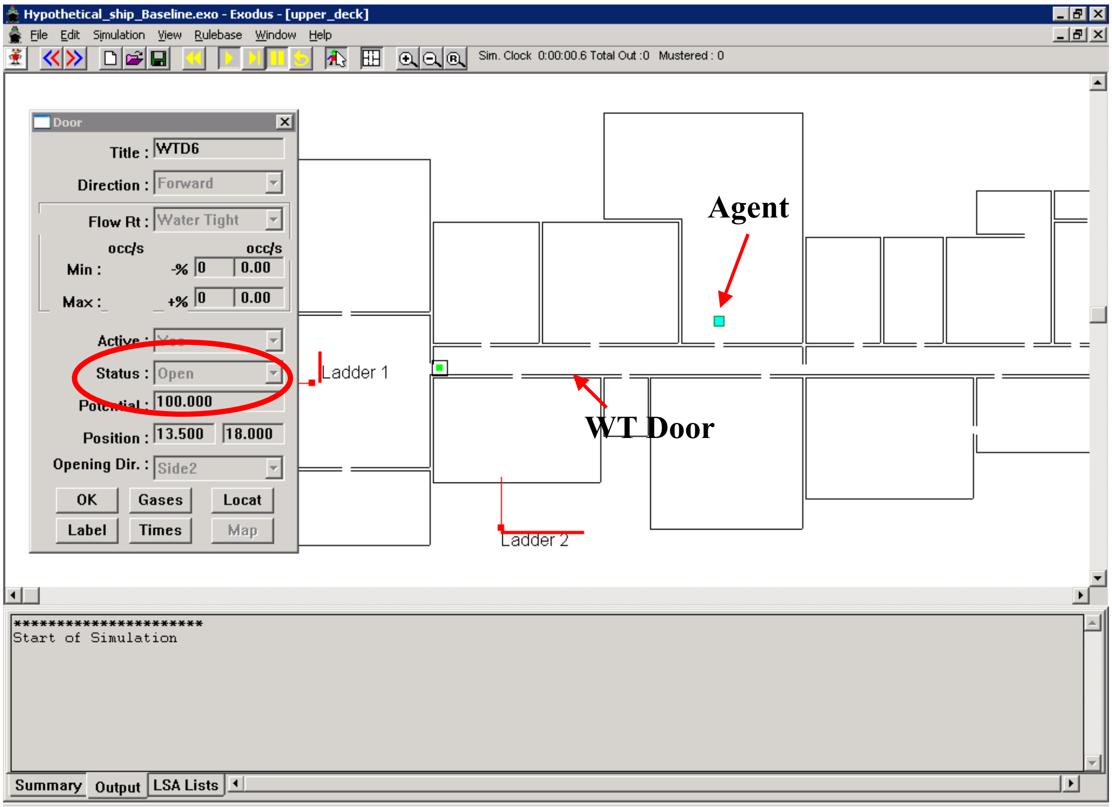


Figure 8.7-1 - Demo 6: The Close WT Door command – screenshot of maritimeEXODUS showing the initial state of the demonstrative case with an agent assigned the command to close a WT Door

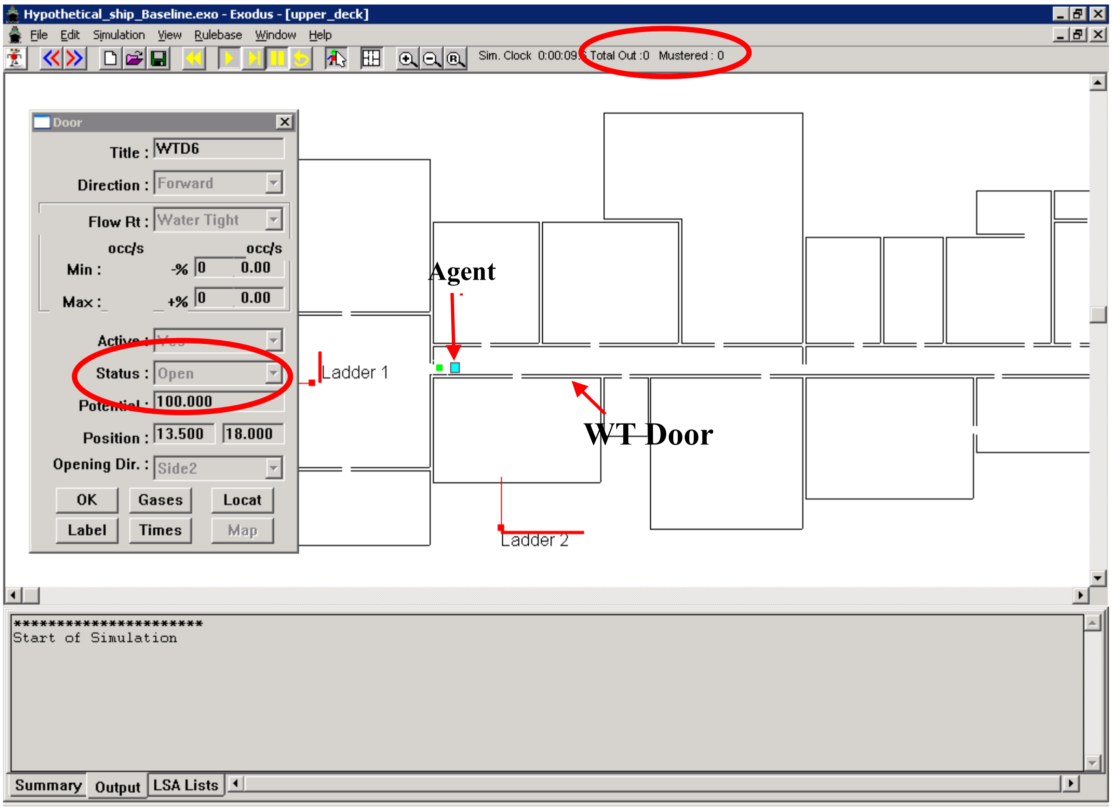


Figure 8.7-2 - Demo 6: The agent reaches the node before the WT door. The door is still open and the simulation time is 9.6 seconds

In Figure 8.7-2 the agent is still approaching the WT door and the WT door remains open. Note that the simulation clock time is at 9.6 seconds. In Figure 8.7-3, the agent has arrived at the WT door and is starting to close it. At this stage maritimeEXODUS considers the WT door to still be open.

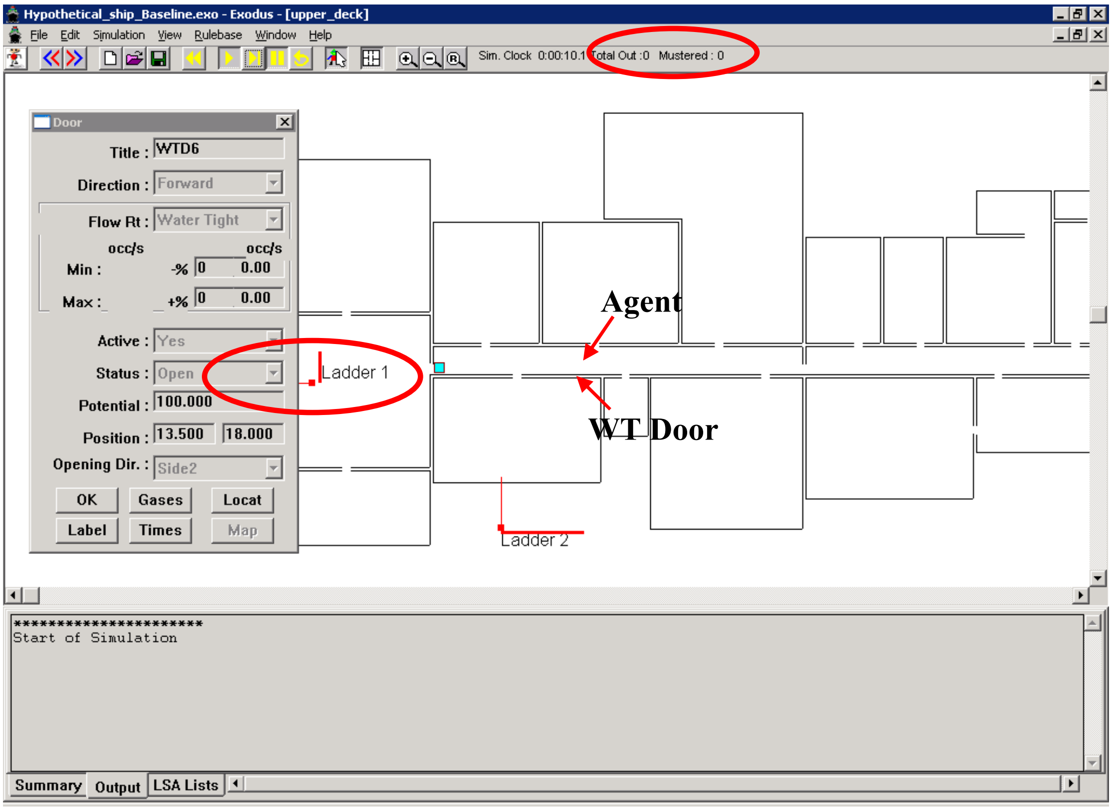


Figure 8.7-3 - Demo 6: The agent steps onto the WT door node. The door is still open and the simulation time is 10.1 seconds. The agent begins to shut the door.

The crew member remains at the door and experiences a time delay which represents them shutting the WT door. When the agent has completed this part of the task, the door node in maritimeEXODUS will change from a green colour (as in Figure 8.7-3) to a brown colour (as in Figure 8.7-4), and the status of the door will now read as ‘Closed’.

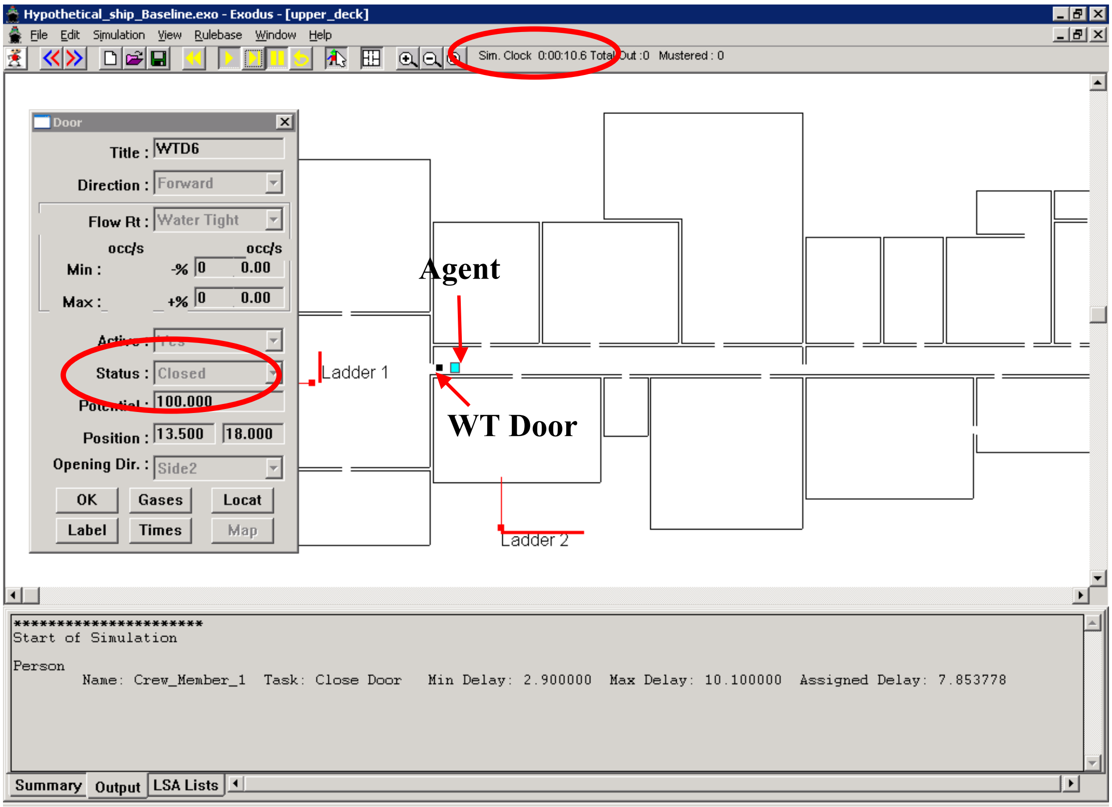


Figure 8.7-4 - Demo 6: The agent steps off the WT door node and the status of the door changes to closed. Simulation time is 10.6 seconds Agent assigned a 7.86 second delay for closing WT door

At this stage, see Figure 8.7-4, the agent has stepped off the door node, however although the status of the door is now closed, the agent will now experience the actual delay associated with closing the door. This delay represents the agent securing the WT door (closing the clips). In situations where the WT door was already closed, this delay would represent the agent checking that the door was properly secured.

maritimeEXODUS outputs the details of this task to show how long the agent should spend carrying out the 'close WT door' command. It can be seen from Figure 8.7-4 that the simulation time is 10.6 seconds and the time assigned for the task is 7.85 seconds. Therefore the agent should complete the task at 18.45 seconds. It can also be seen that the range of times the task could have taken was between 2.9 and 10.1 seconds.

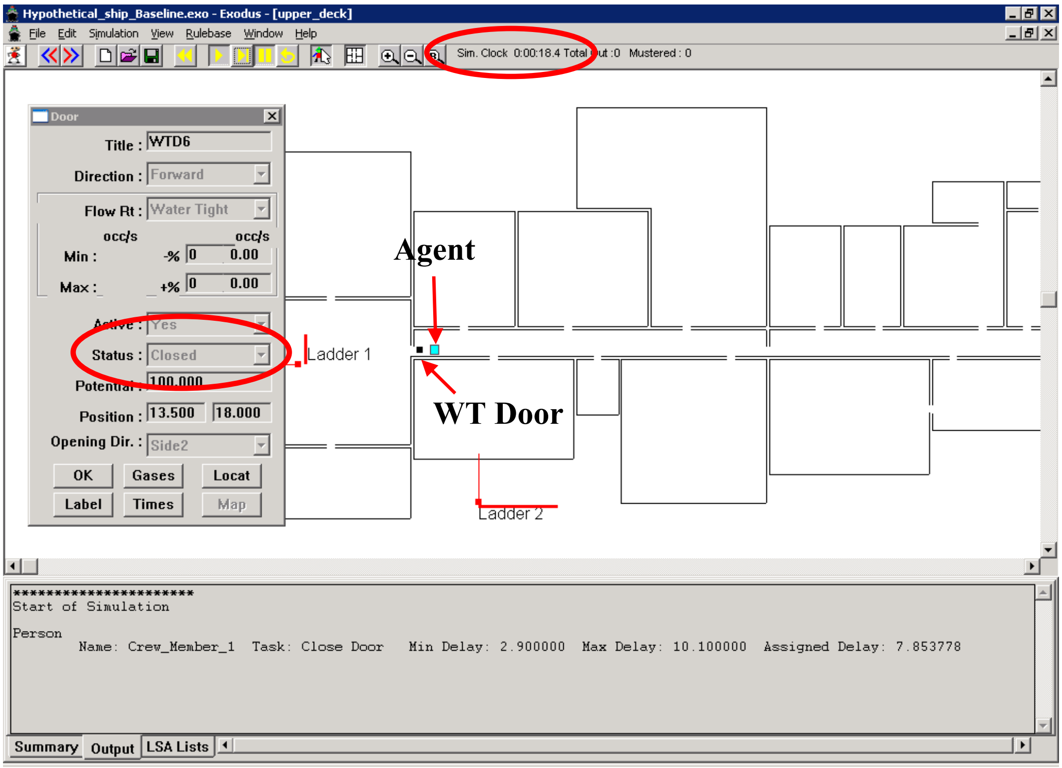


Figure 8.7-5 - Demo 6: The agent is still in the process of closing / securing the WT door, the simulation time is now 18.4 seconds

In Figure 8.7-5, the simulation clock has reached 18.4 seconds and the agent is still carrying out the 'close WT door' task. It was expected that the agent would finish at 18.45 seconds. In Figure 8.7-6, the simulation clock has reached 18.8 seconds and the agent has finished the 'close WT door' and has moved onto the next node on their quest to reach their next waypoint. This illustrates how maritimeEXODUS can successfully order an agent to approach and close a WT door or check that it is closed.

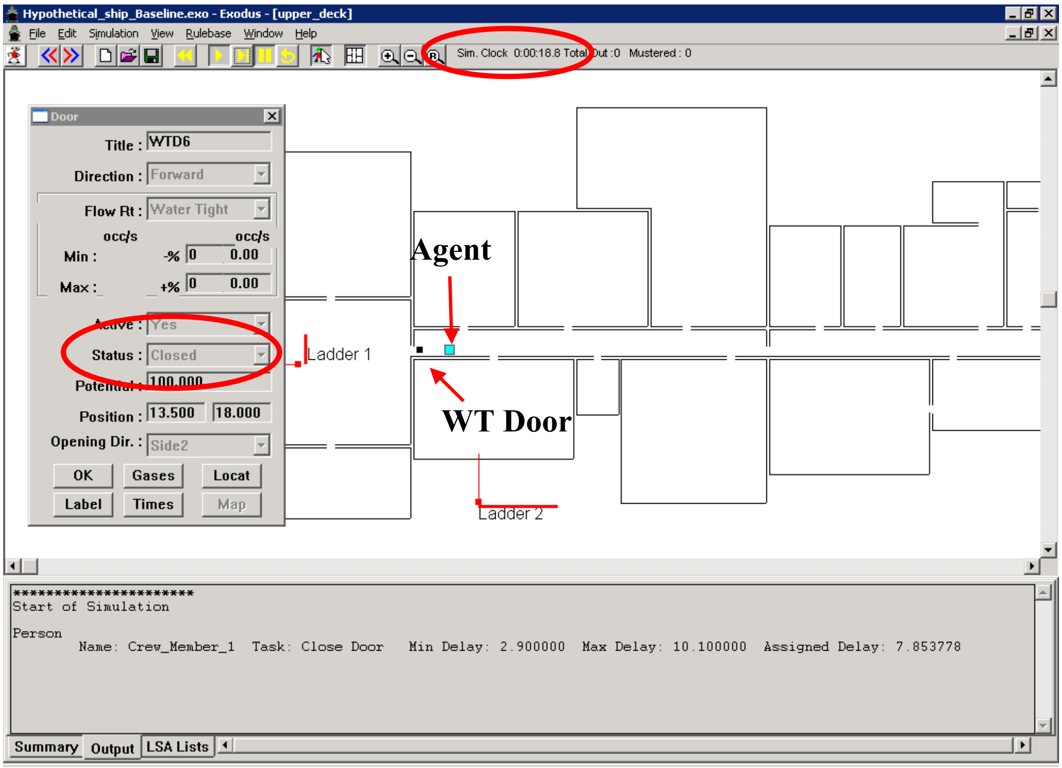


Figure 8.7-6 - Demo 6: The agent has finished closing the WT door and moves on. Simulation time is now 18.8 seconds

In addition to the test case demonstrated here, further tests were required with this new behaviour. Namely, these tests assessed the agent's ability to close the WT door from both sides when the door is open and assess the agent's ability to check that the WT door is closed when approaching from either side (when the WT door is already closed). Tests for this capability within maritimeEXODUS were successful.

8.8 Demonstration 7 - Give and receive

In this demonstration two behaviours will be validated; the 'Give' action and the 'Receive' action. As was discussed in Chapter 7, these two commands together simulate a commanding officer (CO) issuing orders to the nearby crew.

Chapter 7 identified an issue of the commanding officer not being able to reach the action station, represented by a redirection node in maritimeEXODUS, due to it being surrounded by agents. Therefore, the test case employed for this demonstration will involve 20 crew members moving to the action station where they will surround it. The commanding officer will then approach the crowd of crew and attempt to make his way through to the action station.

The commanding officer, shown in green, is located to the far left end of the passageway in Figure 8.8-1, and is given a response time of between 30 and 40 seconds. This should be sufficient time for the rest of the crew, with an instant response time, to assemble around the action station.

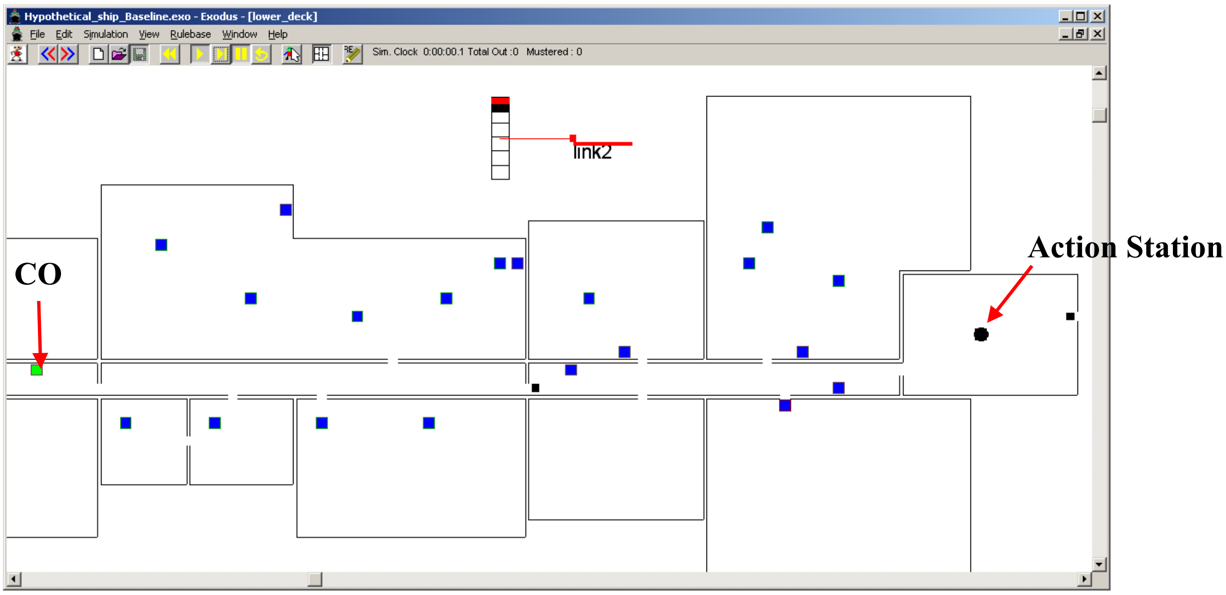


Figure 8.8-1 - Demo 7: The Give and Receive commands– screenshot of maritimeEXODUS showing the initial state of the demonstrative case with a commanding officer at one end of the passageway and the action station at the other end. 20 crew members randomly distributed in geometry

After 41 seconds, it can be seen in Figure 8.8-2 that the crew have crowded around the action station and the commanding officer is on their way to the station.

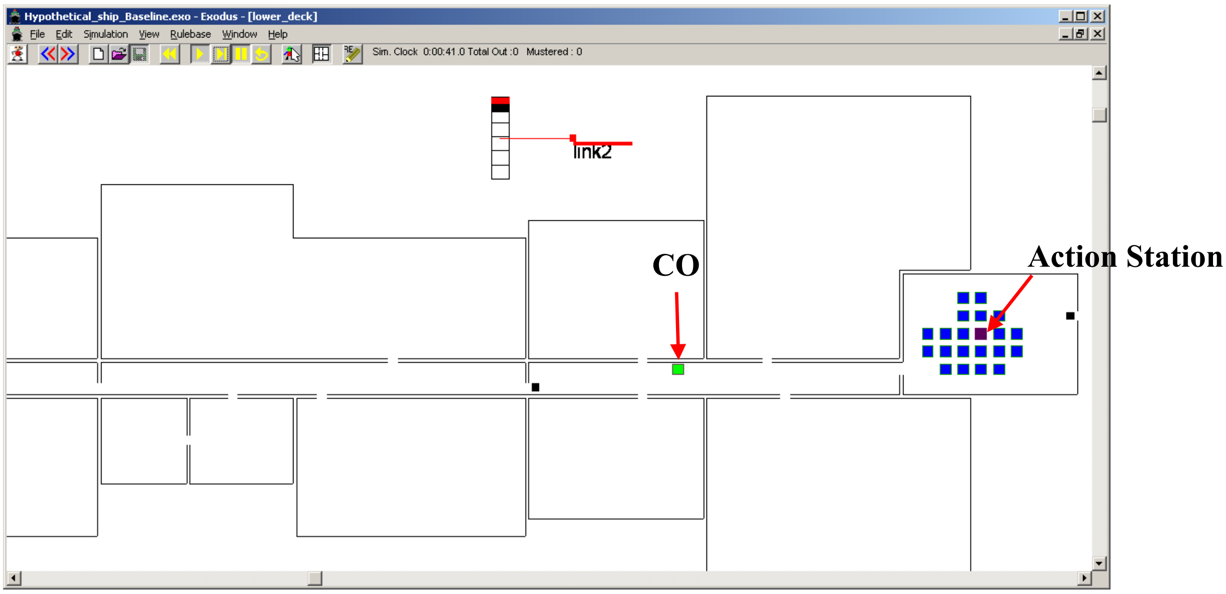


Figure 8.8-2 - Demo 7: the 20 crew members have arrived at the action station and await orders. The CO is approaching the action station

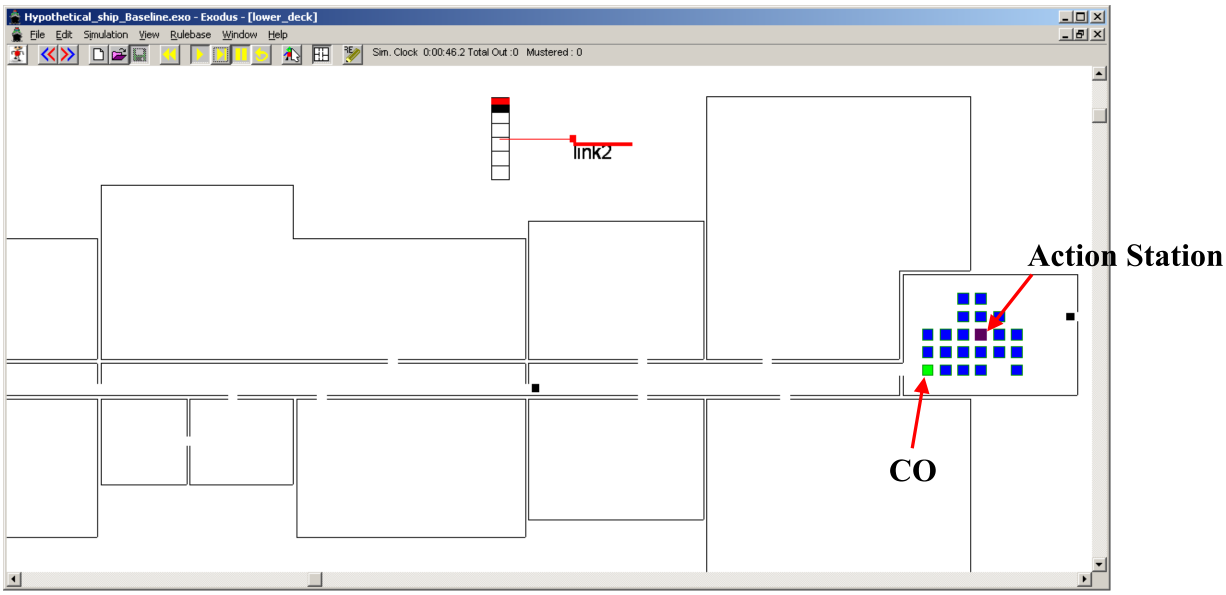


Figure 8.8-3 - Demo 7:The CO arrives in the compartment containing the action station but cannot reach their final destination

The commanding officer arrives in the compartment in Figure 8.8-3, but cannot reach the action station. He will need to reach the action station to enable him to issue the orders. The commanding officer then moves to where the crowd is rather less dense, as shown in Figure 8.8-4, in an attempt to make his way through the crowd.

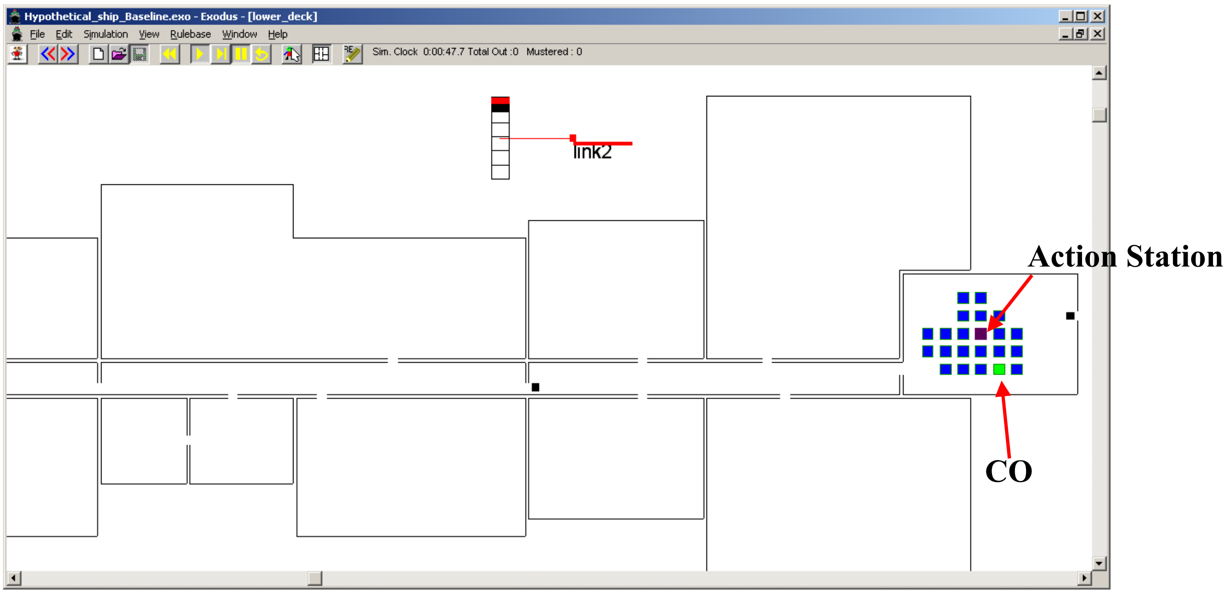


Figure 8.8-4 - Demo 7: The CO attempts to reach the Action Station

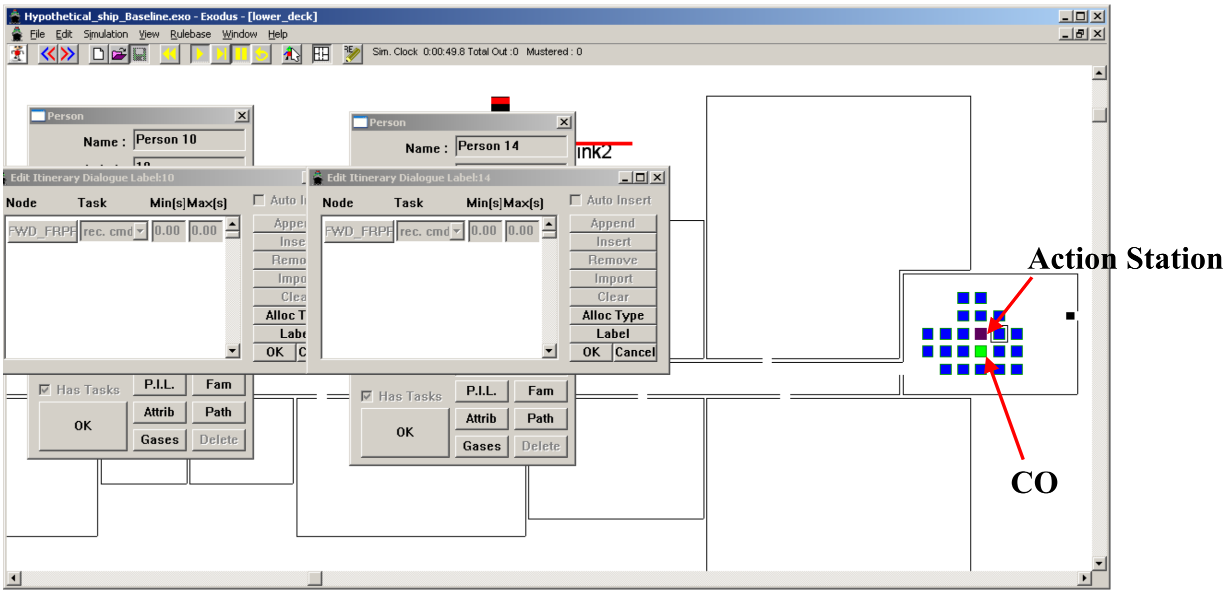


Figure 8.8-5 - Demo 7: the commanding officer works their way through the crowd. Itineraries for two random crew members, 'Person 10' and 'Person 14', are shown

In order to reach the action station, the commanding officer (CO) effectively orders a crew member to step back so that they can pass them. This can be seen in Figure 8.8-5 where the CO is now only one node away from the action station and is surrounded by crew members. In Figure 8.8-5 two random crew members have been selected and their itineraries displayed.

It can be seen that these two crew members only have one task each, which is the ‘receive’ task.

Figure 8.8-6 shows the commanding officer having reached the action station. At this point they start distributing orders to the surrounding crew whom have the ‘receive’ command. The same two crew members have been selected, and it can be seen that they have both collected two additional tasks. These two additional tasks send the crew to an adjacent compartment where they will terminate. This demonstrates maritimeEXODUS’ new ability for individuals to ‘give’ commands to other individuals who will ‘receive’ new tasks.

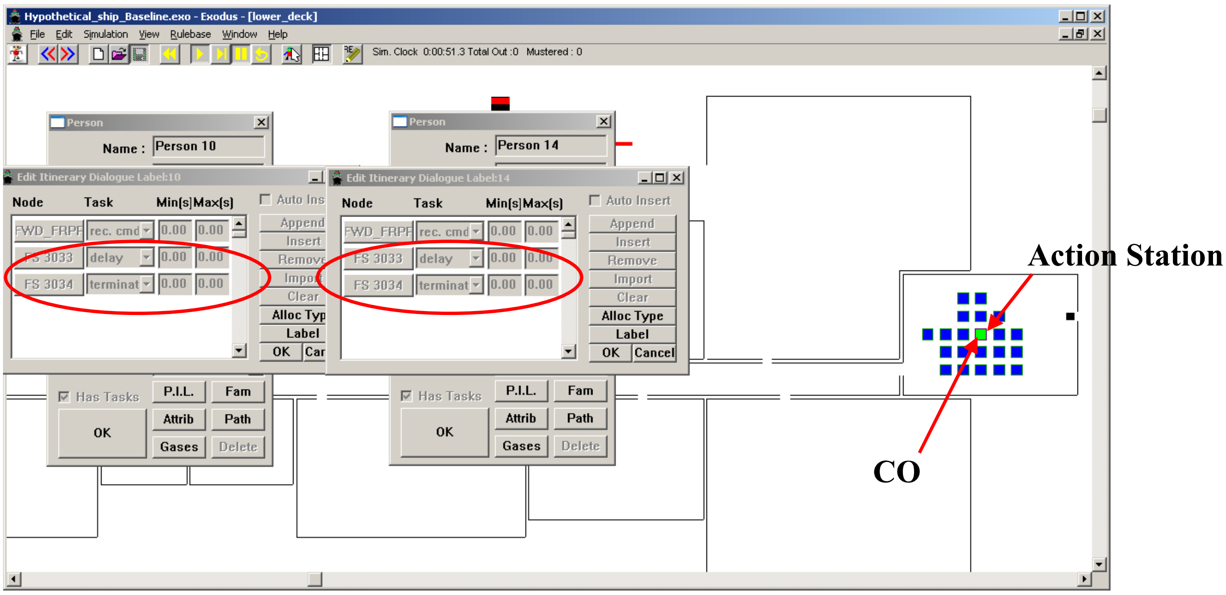


Figure 8.8-6 - Demo 7: the commanding officer arrives at the action station and issues new orders to crew. Itineraries for Person 10 and Person 14 are shown with extra tasks.

With all the tasks distributed by the commanding officer, all the crew move to the adjacent compartment and the commanding officer moves away from the action station, walking along the passageway to their next destination, as illustrated in Figure 8.8-7.

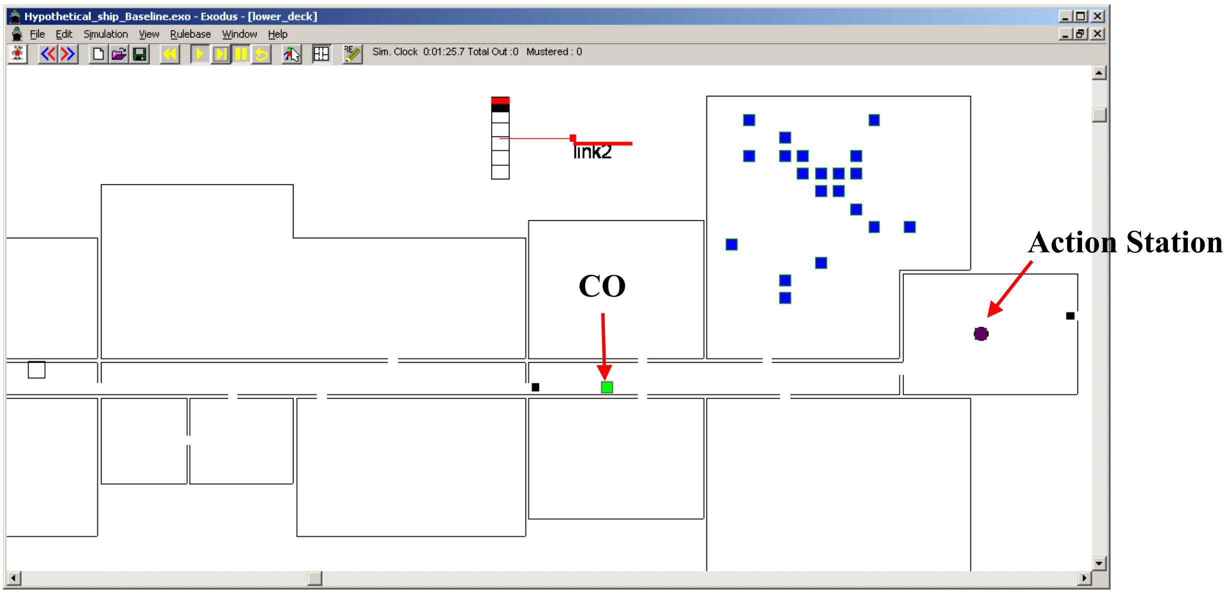


Figure 8.8-7 - Demo 7: Crew members disburse and follow their new orders. The CO moves away from the action station to their next destination.

This test case successfully demonstrates maritimeEXODUS' ability for agents to give other agents additional itinerary tasks. It has also demonstrated higher ranked agents' abilities to move through a crowd of other agents in order to reach their target. This is an important behaviour for maritimeEXODUS to exhibit on naval vessels where orders are always being issued.

8.9 Demonstration 8 - Repeat command

The repeat command was developed within maritimeEXODUS to represent crew performing a patrol about the naval vessel. During evaluative scenarios such as 'State 1 Preps', some crew members would be issued a route which they would have to follow a number of times.

For the demonstration of this new command, an agent will follow a route which will move them around four compartments repeatedly until the second agent has completed their tasks. The second agent has been given an artificially high response time (of approximately 4 minutes) as a way to allow the first agent to repeat their tasks a number of times. The initial locations of the agents can be seen in Figure 8.9-1 and the four compartments which Agent 1 will visit have been highlighted with a small black circle in the middle.

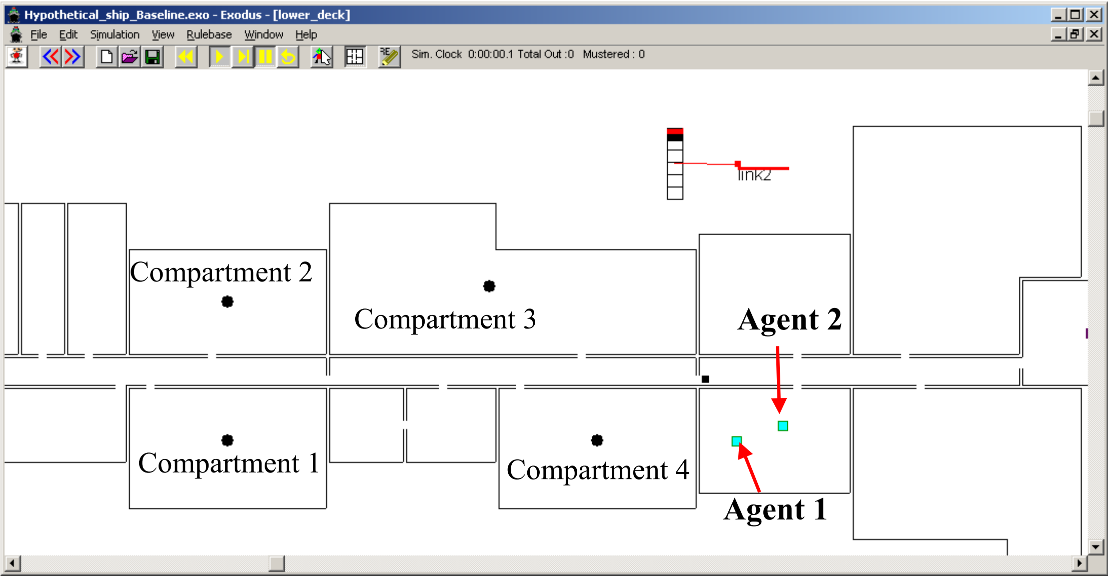


Figure 8.9-1 - Demo 8: The Repeat command screenshot of maritimeEXODUS showing the initial state of the demonstrative case with two agents. Agent 1 is given a route to repeat and Agent 2 given a large response time

When the simulation commenced, the first agent, who is assigned the repeat command, moves to the first assigned compartment where they experience a delay of between 0 and 10 seconds. This can be seen in Figure 8.9-2.

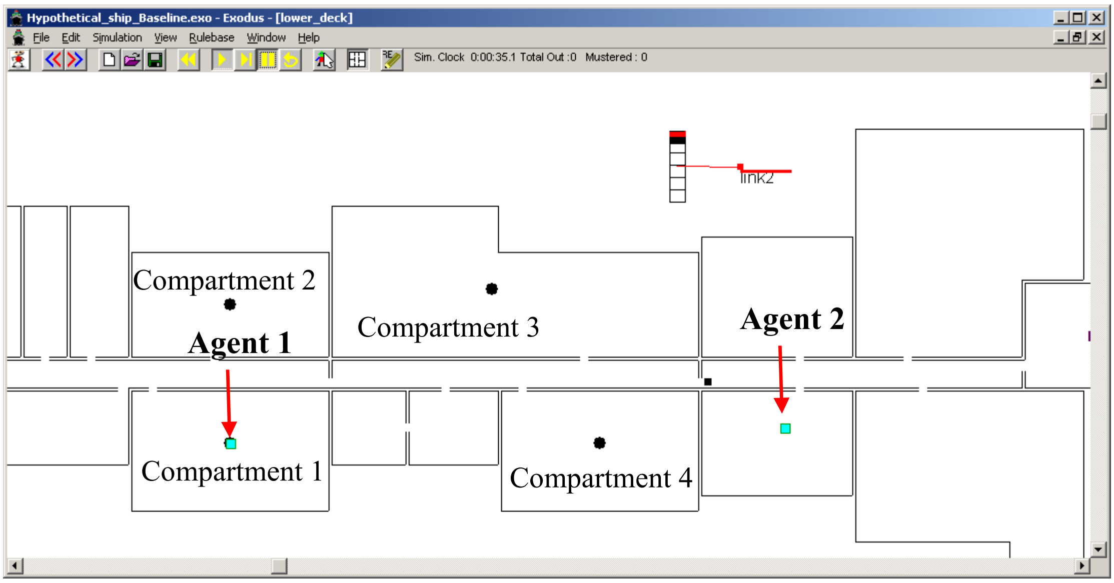


Figure 8.9-2 - Demo 8 :Agent 1 moves to the first compartment to start their assigned route

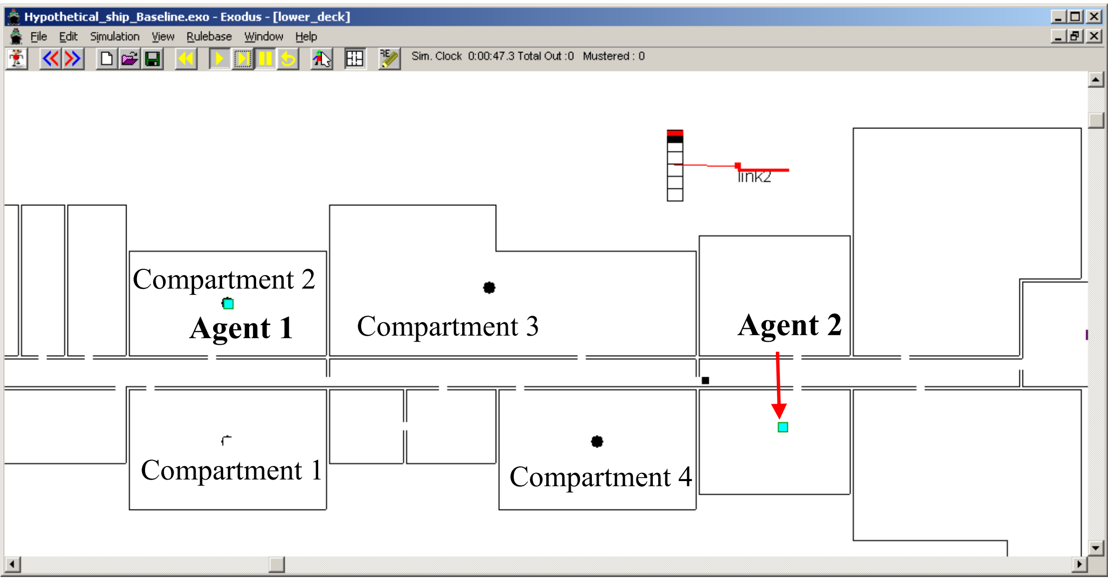


Figure 8.9-3 - Demo 8: Agent 1 moves to the second compartment on their route

Figure 8.9-3 to Figure 8.9-5 shows Agent 1 moving between the four compartments on their first lap of the assigned patrol. In the meantime, Agent 2 remains in their initial location while they experience a lengthy delay. This delay could be a task which they were carrying out prior to starting the current scenario tasks.

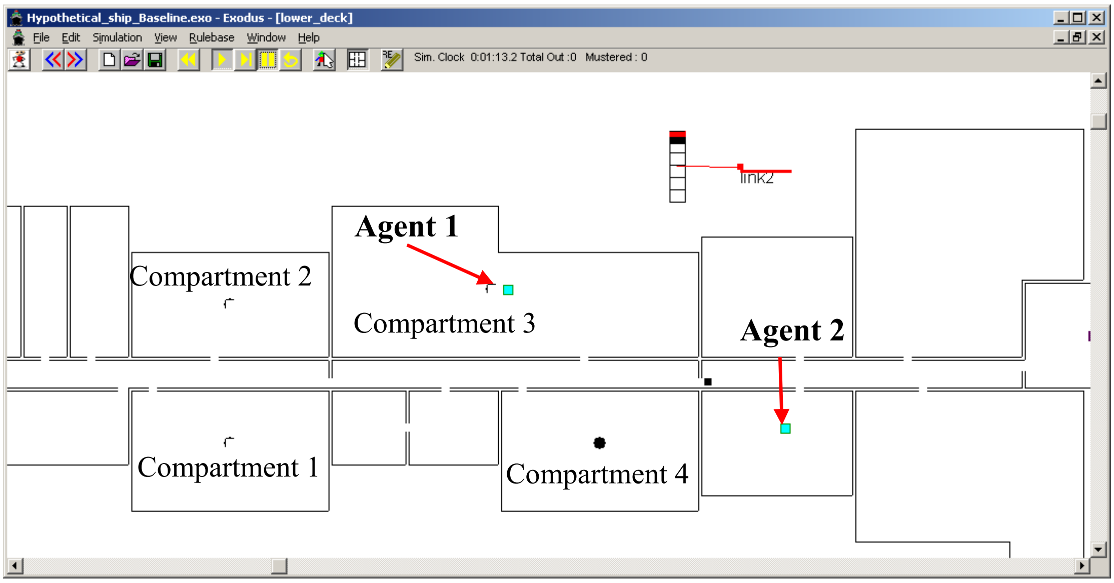


Figure 8.9-4 - Demo 8: Agent 1 moves to the third compartment on their route

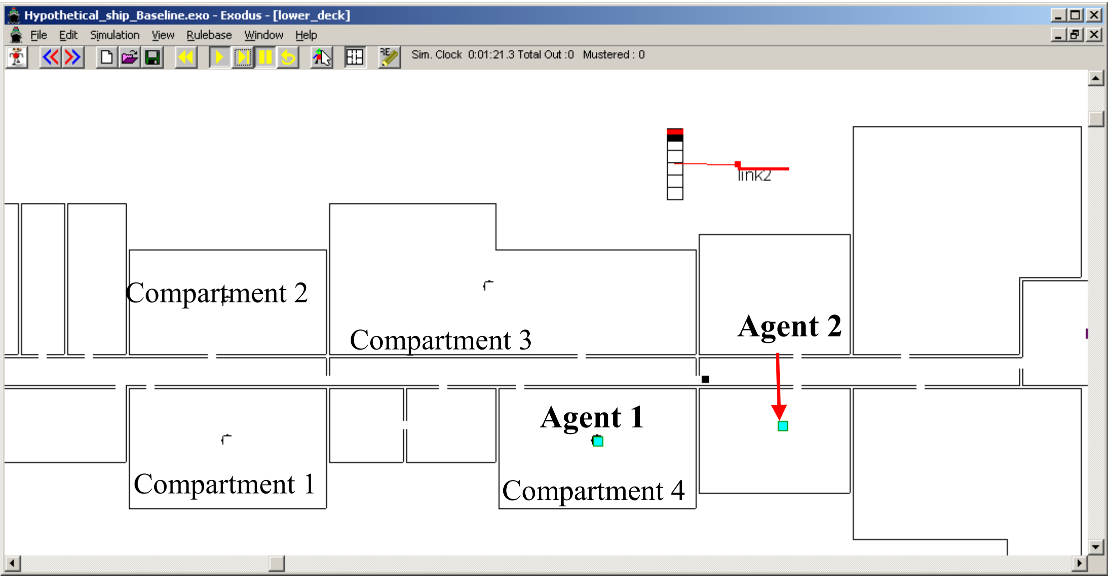


Figure 8.9-5 - Demo 8: Agent 1 moves to the fourth compartment on their route

Once Agent 1 has arrived at Compartment 4 and experienced their set delay (as they have done in Figure 8.9-5), they have completed one lap of the patrol. The next task in their itinerary is to repeat the last four tasks 999 times. This effectively means that the agent continues repeating the previous four tasks until all the other agents in the simulation have either terminated or evacuated.

Figure 8.9-6 and Figure 8.9-7 shows Agent 1 starting to repeat the lap of compartments by visiting Compartment 1 and Compartment 2 for a second time. In the meantime, Agent 2 still remains in their initial location

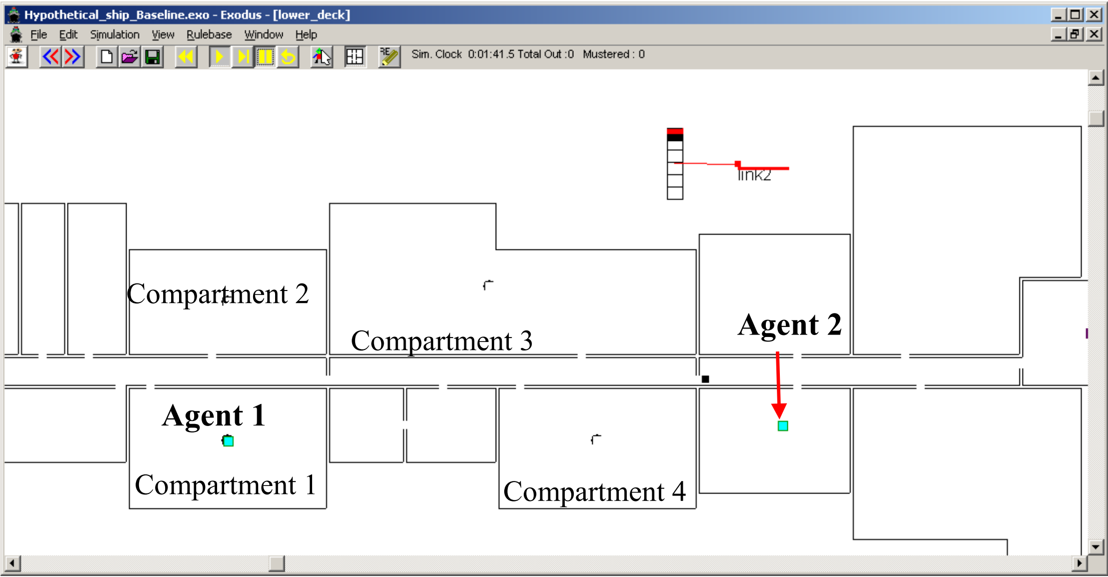


Figure 8.9-6 - Demo 8: Agent 1 starts repeating their route by moving to the first compartment in their itinerary.

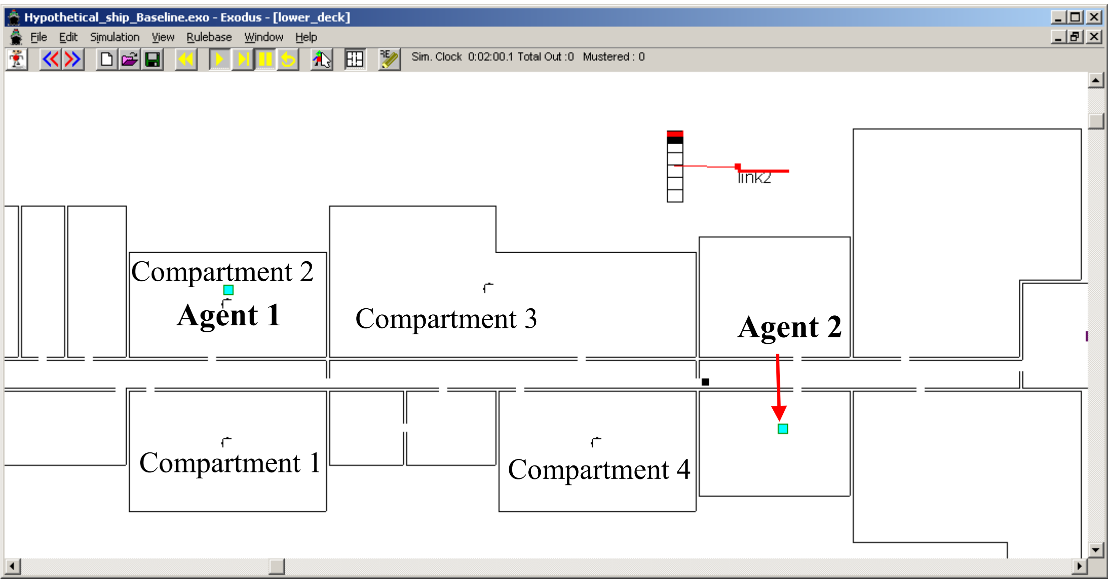


Figure 8.9-7 - Demo 8: Agent 1 moves to the second compartment for the second time

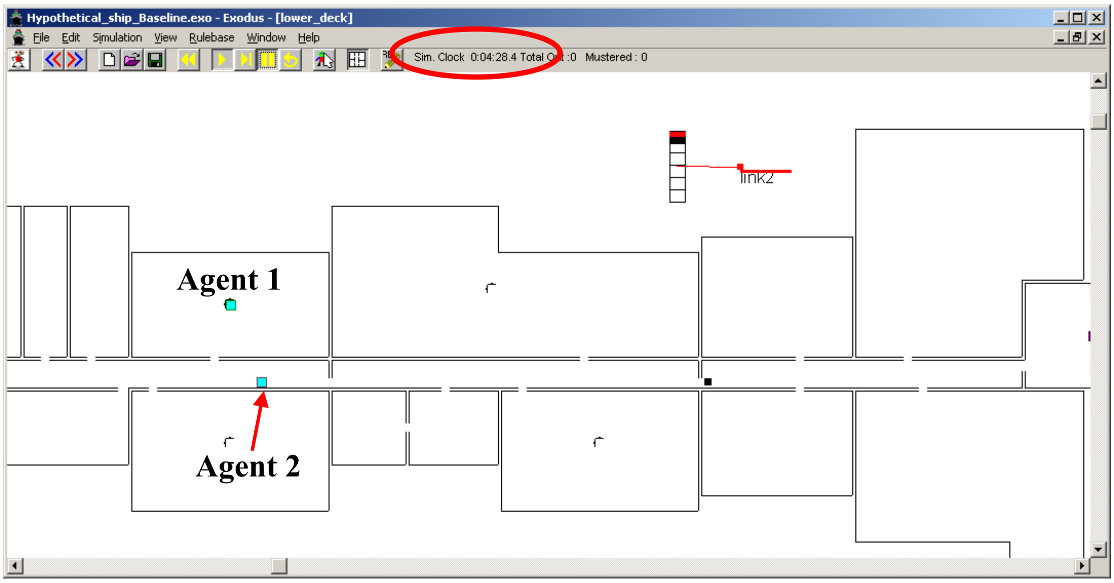


Figure 8.9-8 - Demo 8: After 4 minutes 20 seconds, Agent 2 has responded and moves towards their final destination, meanwhile Agent 1 continues repeating their tasks.

In Figure 8.9-8, the second crew member has finally started their assigned tasks for this scenario. This involves moving to the first compartment of the patrol, where they will terminate. Meanwhile, the first crew member continues to patrol the four assigned compartments.

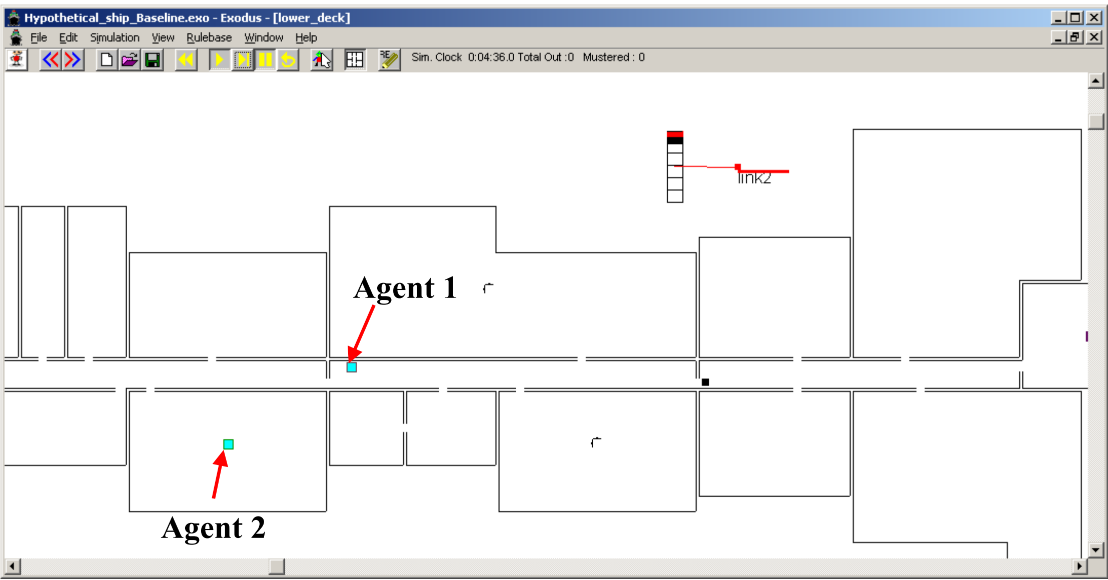
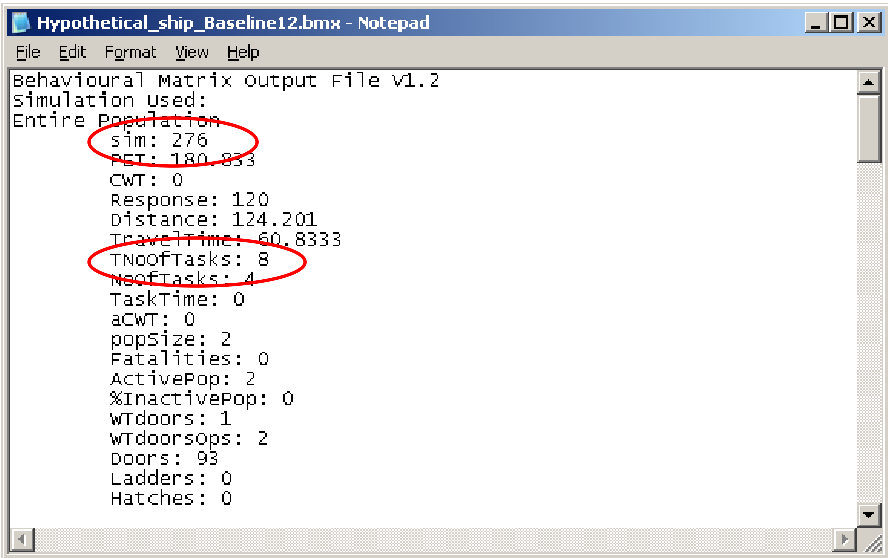


Figure 8.9-9 - Demo 8: Agent 2 arrives at their final destination and terminates. Agent 1 stops repeating their tasks and also terminates. The simulation ends.

Agent 2 finally arrives at their destination where they terminate, as shown in Figure 8.9-9. Since all other agents in the simulation have terminated, i.e. Agent 2, Agent 1 breaks out of the patrol task and terminates. This then ends the simulation since all agents have terminated. The simulation time in maritimeEXODUS is 4 minutes 20 seconds (from Figure 8.9-9) which is the same as the simulation time listed in the output file in Figure 8.9-10 ('sim' = 276 seconds). From the output file it can also be seen that the total number of tasks is 19, since both agents had the task to terminate and Agent 2 had the task to move to their final destination therefore Agent 1 performed 16 other tasks. This means that they must have repeated the 4 assigned tasks 4 times.



```
Behavioural Matrix output File v1.2
Simulation Used:
Entire Population
        sim: 276
        PET: 180.833
        CWT: 0
        Response: 120
        Distance: 124.201
        TravelTime: 60.8333
        TNoofTasks: 8
        NoofTasks: 4
        TaskTime: 0
        aCWT: 0
        popSize: 2
        Fatalities: 0
        ActivePop: 2
        %InactivePop: 0
        WTdoors: 1
        WTdoorsOps: 2
        Doors: 93
        Ladders: 0
        Hatches: 0
```


Figure 8.9-10 - Demo 8: the output file for demonstrative case highlighting the simulation time (276 seconds) and the number of tasks (8)

8.10 Demonstration 9 - Group behaviour

The Family Day scenario involved a number of untrained civilians on board the vessel when an incident occurred. The scenario required assigned crew members to escort the civilians to a point of relative safety, i.e. the muster stations.

This required an individual to be assigned a crew type and be able to collect individuals assigned as civilians. This was implemented in the SSF file and although this can be set up using the maritimeEXODUS interface, is more efficiently implemented using the SSF file. The process involves giving civilians a common gene number which represents their group, the assigned crew member also carries the same gene number, allowing them to be assigned to that group of civilians.

To demonstrate the newly developed group behaviour, an agent (Agent 1 aka 'Person 1') has been given crew status and instructed to collect a group of agents with civilian status from the mess room and escort them to a safer location. The configuration of this demonstration can be seen in Figure 8.10-1, with the agent assigned as crew on the right of the screen and the group of 20 civilian agents on the left of the screen.

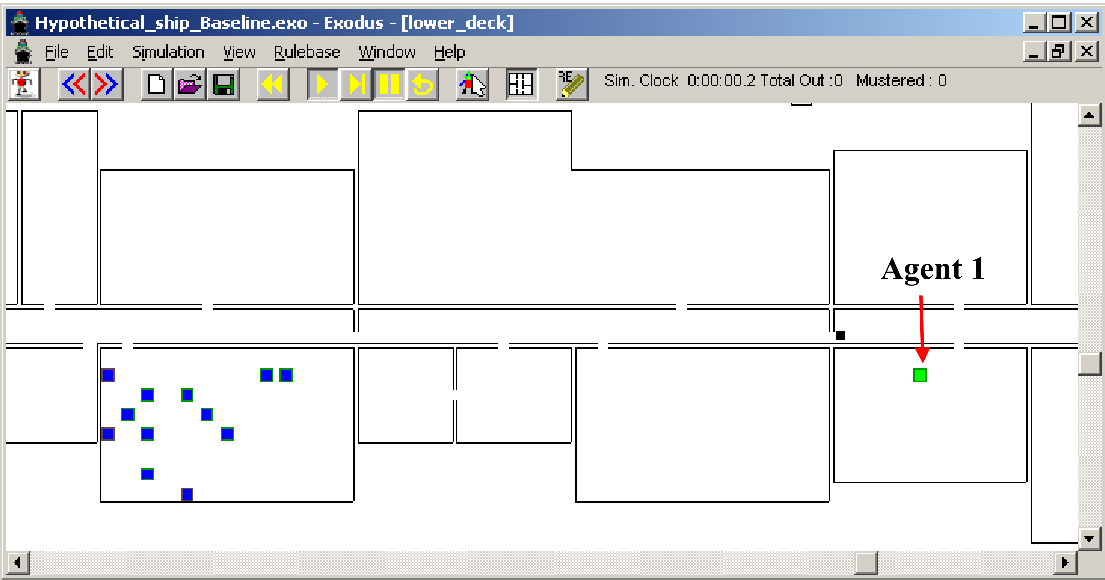


Figure 8.10-1 - Demo 9: Group behaviours - screenshot of maritimeEXODUS showing the initial state of the demonstrative case with an agent (Agent 1) assigned as a crew member and 20 agents assigned as civilians. Agent 1 is assigned the task of collecting the civilians and taking them to a location of relative safety.

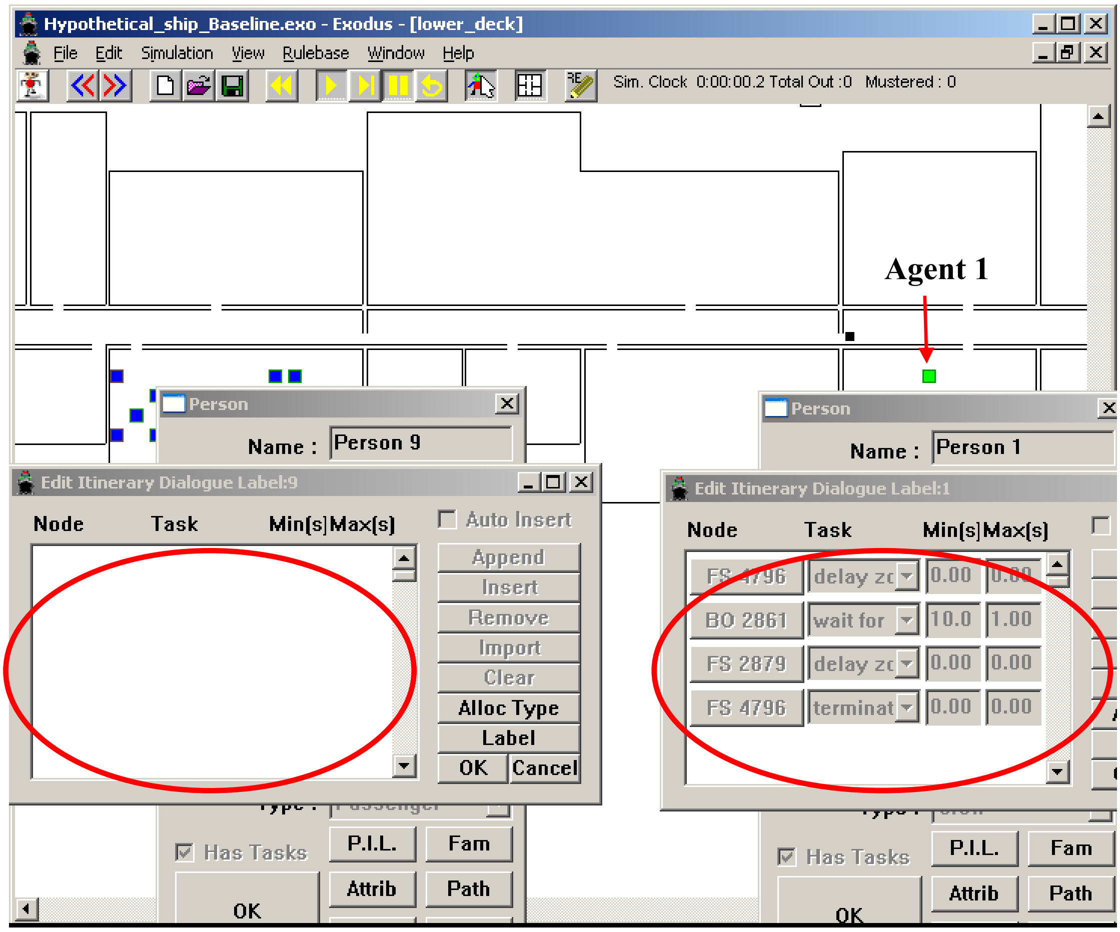


Figure 8.10-2 - Demo 9: The initial itineraries for Agent 1 (Person 1) and a civilian (Person 9)

Figure 8.10-2 illustrates the itineraries for both the agent with crew status (Person 1) and an example of one of the agents with civilian status (Person 9). Although not displayed in the Itinerary window, , the crew member is assigned the task of going to the compartment where the civilian agents are located (top task 'delay zone'), collecting the civilian agents ('wait for members') and then returning to the crew's starting location ('delay zone') where they will terminate. The civilian agents have not got any tasks to perform.

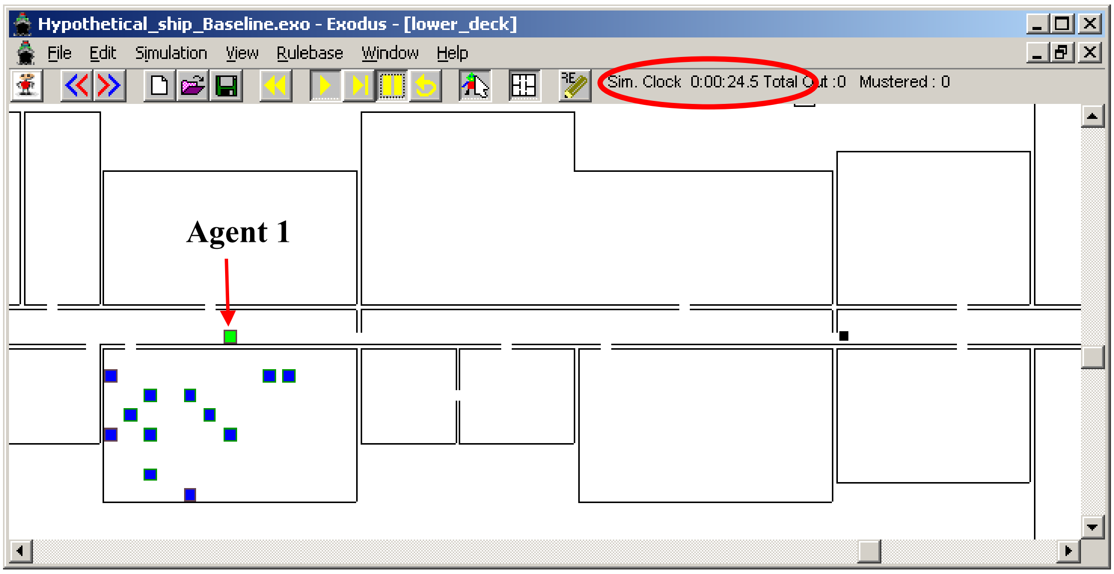


Figure 8.10-3 - Demo 9: After 24 seconds Agent 1 approaches the compartment containing the civilians

When the simulation starts, the agent with crew status walks along the passageway (as seen in Figure 8.10-3) to the compartment where the civilian agents are located. Once there (Figure 8.10-4), the crew agent overrides the civilian agents' response time and instructs them to follow him.

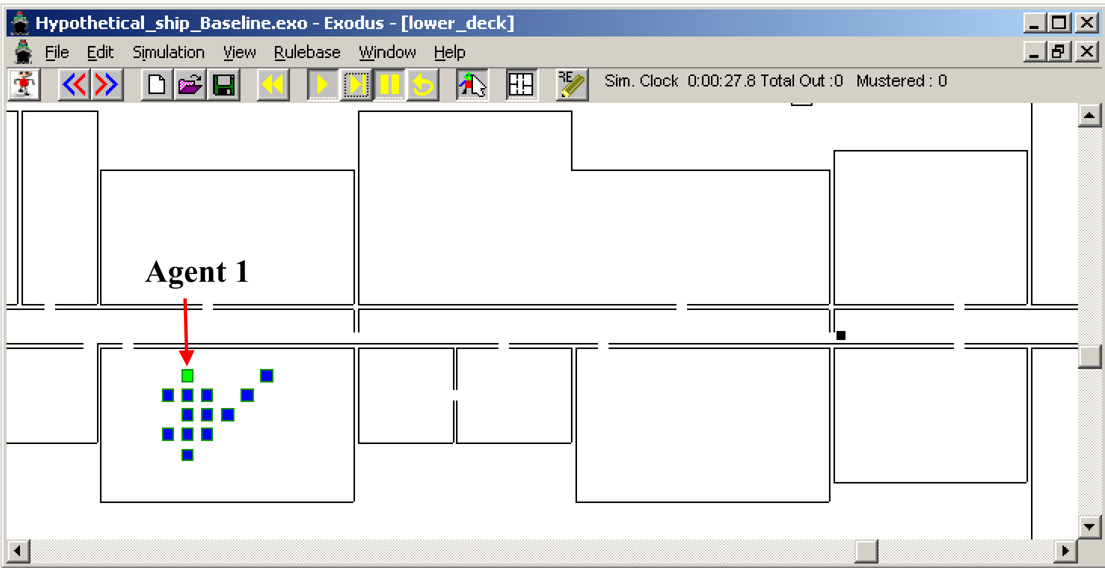


Figure 8.10-4 - Demo 9:Agent 1 arrives in the compartment with the civilians and instructs them to follow him

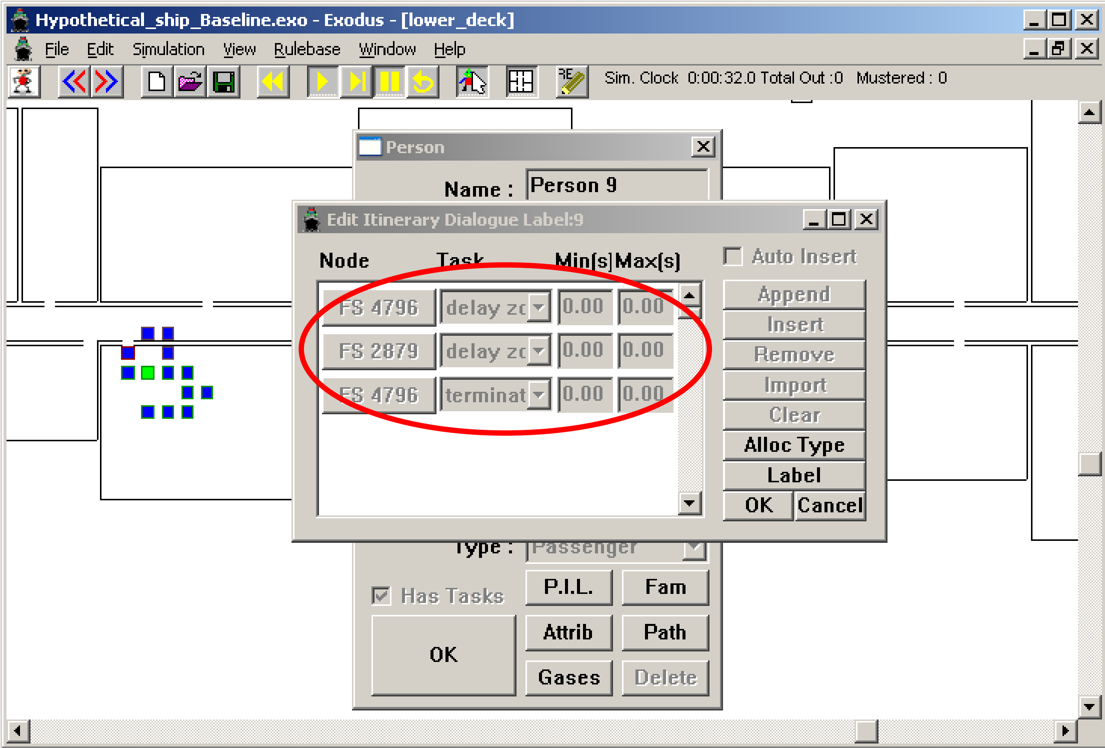


Figure 8.10-5 - Demo 9: Screenshot showing a civilian's (Person 9) new itinerary

Figure 8.10-5 shows the crew member having met the civilians and overridden their response time, causing them to respond instantly. The figure also displays Person 9's new itinerary items. The civilian now has to move to another compartment ('delay zone') where they will terminate.

Figure 8.10-6 shows the civilians following the crew member to the assigned compartment, where they terminate (Figure 8.10-7).

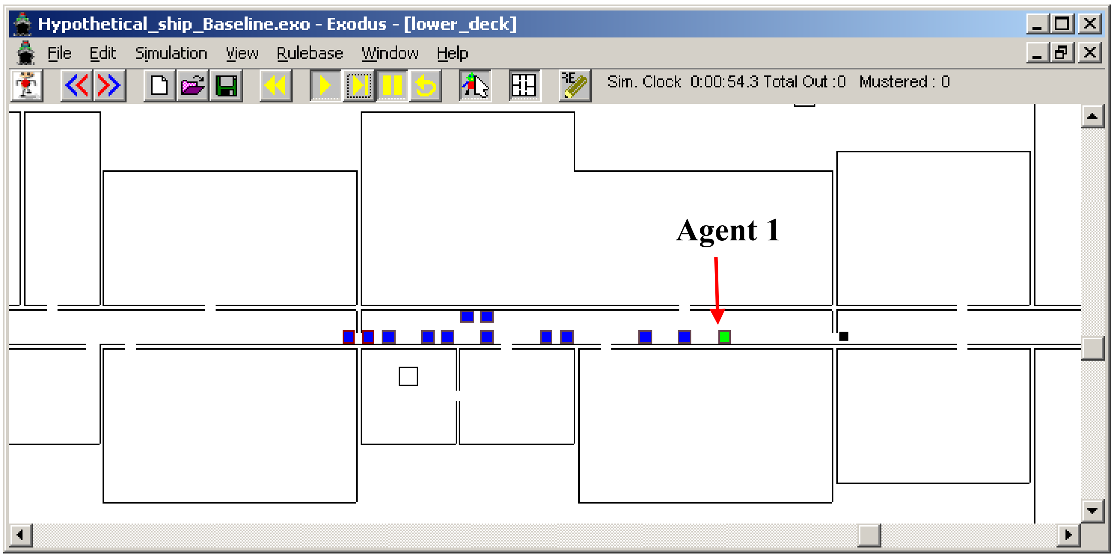


Figure 8.10-6 - Demo 9: The civilians follow Agent 1 to a location of relative safety

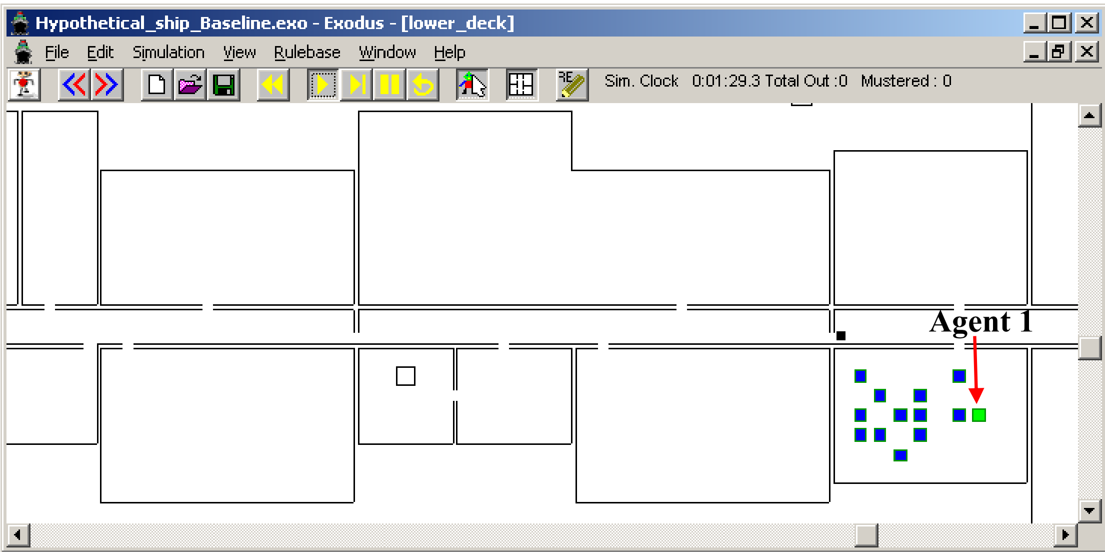


Figure 8.10-7 - Demo 9: Agent 1 and the civilians reach their final destination and terminate.

In addition to the example case shown here, tests were carried out to check that the group of civilian agents do in fact move as a group. In the Family Day scenario, many of the civilians will be related in some way, either family or friends of crew members, and as such will usually move about the vessel as a group. Tests were carried out to make sure that the civilians remained as a group. Initially they did not, but after some development of the behaviours, any fast moving group members will only move away from the group a set distance before stopping and waiting for the rest of the group to catch up.

Other tests involved checking that the agent with crew status would collect all member of the assigned group who are in the compartment zone, before they continue. It is possible for group members to be in different compartments, in which case the agent with crew status should be instructed to enter these other compartments to 'collect' members of the group. For the purposes of the work carried out in this thesis, it was assumed all members of a group would be in the same compartment.

8.11 Summary

This chapter has demonstrated the newly implemented features within maritimeEXODUS. The newly implemented behaviours consisted of:

- Terminate
- TerminateMill
- Wait (following a Terminate task)
- Repeat
- Search Compartment
- Blanket Search
- Close WT door
- Give and Receive itineraries
- Group Behaviours

This chapter has made use of nine demonstrations to cover all of these new features. These demonstrative cases not only verified the implementation of the innovative behaviours of the simulated crew but also presented the novel input and output files implemented for ease of use of the software. These demonstrations made use of a hypothetical naval vessel which will be used in much greater detail in the following chapter. This hypothetical vessel was created within maritimeEXODUS using the software's built-in drawing tools and consisted of two decks.

Chapter 9 makes use of this hypothetical vessel along with a real design of a Royal Navy frigate to provide example applications that demonstrate the capabilities of the Human Performance Metric.

Chapter 9

Demonstration of the HPM Technique as a Stand Alone System

9.1 Introduction

This chapter will demonstrate the innovative Human Performance Metric (HPM) concept using two example applications. These example applications will make use of the newly created / modified software tools to demonstrate the whole system, including the scenario generator, maritimeEXODUS and the HPM Analyser. This chapter aims to show all three tools working together in assessing the Human Factors (HF) performance of a design. The concept of the human performance metric will be evaluated in its ability to assess the HF performance of a design.

In the first of the two example applications, two variants of a hypothetical ship design will be utilised. These design variants have been created to be simplistic in structure but sufficiently complex to affect the HF performance. For simplicity, only two Evaluation Scenarios (ES) are considered for this example application, 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 best design can be identified.

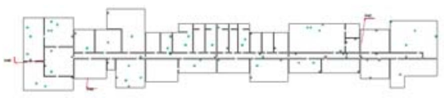
The second of the two example applications involves the Type 22 Batch III frigate as explored in Chapter 6. This example will make use of two variants, the first of which will have a single passageway running from the fore part of the vessel to the aft. The second design variant will make use of two passageways which run in parallel from the fore of the vessel to the aft. Both designs will be assessed across the seven ES as described in Chapter 6.

9.2 First Example Application – Assessing human factors performance of a hypothetical vessel

9.2.1 The geometry

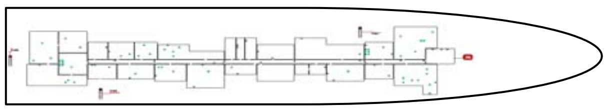
The baseline vessel design (variant 1) consists of 61 compartments spread over two decks, with 27 compartments plus a passageway on the lower deck and 34 compartments plus a passageway on the upper deck. The two decks are connected via three ladders; two located in the aft and one in the fore of the 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 fore of the vessel on both decks (see Figure 9.2-1a and Figure 9.2-1c). 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 upper deck. The key difference between the two designs is that variant 2 has two passageways running in parallel from the aft to the fore end of the vessel on both decks (see Figure 9.2-1).

The design was created within the maritimeEXODUS interface using its built-in drawing functions. The passageways on each deck were created and then random blocks were placed alongside the corridor to represent compartments of various different shapes and sizes. These blocks were then replicated and placed randomly along the passageway until all the spaces along the corridor had been filled. Some of the blocks were then subdivided to produce compartments which could resemble smaller spaces on board a naval vessel, such as cabins. When creating the second variant of the design, the central passageway in variant 1 was shifted to the top of the design and the lower compartments were moved to fill the space left by the passageway. The passageway was then duplicated and placed at the lower part of the design, as seen in Figure 9.2-1. Some of the compartments had to be reshaped in order to fill empty spaces or to allow the passageways to be placed flush to every compartment.

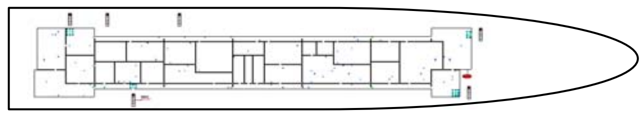


(a) Upper Deck of variant 1

(b) Upper Deck of variant 2



(c) Lower Deck of variant 1



(d) Lower Deck of variant 2

Figure 9.2-1 - Layout of variant 1 ((a) and (c)) and variant 2 ((b) and (d)).

9.2.2 The scenarios

Each vessel design, from Figure 9.2-1, was given a complement of 150 crew members which was considered an adequate number to demonstrate any flaws within the structure of the design.

For simplicity, the crew were initially scattered randomly throughout the vessel. In this example application each variant was assessed using two Evaluation Scenarios (ES). These are the naval evacuation ‘normal day cruising’ and normal operational (NOP) ‘State 1 Preps’ (which were labelled ES_2 and ES_4 respectively in Chapter 6) scenarios.

The NOP scenario (ES_4) involves the entire complement moving to designated locations throughout the vessel and changing into appropriate clothing. In addition, two teams of five fire fighters in the damage control and fire fighting function group (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 watertight doors (WTD) on the vessel bringing it to watertight integrity 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 at 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.

Since the Naval Ship Code (NATO, 2006) does not specify what response time distribution or travel speeds to assign to the population of a naval vessel (as identified in Chapter 2), in both scenarios, crew were given response times and travel speeds as stipulated in the IMO MSC 1238 guidelines(IMO, 2007). Since the main aim of this chapter is to demonstrate the HPM concept, the exact data used to represent the movement and behaviour of the naval personnel is not paramount. As identified in Chapter 2, there are no validated data sets which provide the response times of naval personnel; therefore since the data is essential for the modelling of HF, the response time distribution from passenger vessels (IMO, 2007) was considered a step in the right direction. The response time distribution for a naval vessel is likely to have lower limits; however, it would still expect to follow a lognormal distribution.

The travel speeds of naval personnel would expect to be slightly quicker than that of passengers on board a civilian vessel. However, as with the response time distributions, there is not sufficient data available to currently model crew on a naval vessel. This is essential data required to model the movement of the naval personnel, and therefore has to come from somewhere. It was considered to use the validated data from passenger vessel evacuation analysis guidelines (IMO, 2007), since although this may not be completely representative of naval personnel, it does represent humans moving about a vessel.

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.

9.2.3 The software and methodology

The ship evacuation model maritimeEXODUS (Boxall et al, 2005) was used to perform the simulations. Both vessels were created within the maritimeEXODUS software as described earlier in this chapter. Once they were created, the geometry was saved as an MTA file.

The Scenario Generator was then employed to create the population and their itineraries. The Scenario Generator first loaded the geometry as produced by maritimeEXODUS, allowing the extraction of the compartment zones information. Using this data, the Scenario Generator then allowed the user to define the population, including their initial location and their itinerary. Once the population was defined, the Scenario Generator produced a SSF file (Scenario Specification File) for every scenario defined. These SSF files could then be imported back into maritimeEXODUS where the scenarios could be modelled.

Each scenario was simulated 50 times for each vessel design as specified in the IMO guidelines (2007). Once the simulations had been run, a representative output file was selected for detailed analysis.

The HPM Analyser was used to select the representative output file for each scenario and to produce the HPM for each design. When the HPM Analyser tool was launched, the structure of the HPM was defined as described in the next section. Once the structure for the HPM had been defined, the representative maritimeEXODUS output file was used to populate the PM. When selecting the representative output file, the user could select all 50 simulations for the ES in question, the HPM Analyser then asked the user what criteria should be used to select the representative output file. In both ES, the representative file was selected based on its final simulation time. For the evacuation scenario (ES_2), the IMO guidelines (2001) 95^{th} percentile case was used to select the representative simulation. While for the NOP scenario (ES_4), the representative output file was considered to be the case producing the maximum simulation time.

After these files had been selected and imported into the utility tool, the user defined the HPM for each design. The utility tool then set about normalising the matrices and then produced the relevant output files, as described in Chapter 6 (Defining a HPM for a naval vessel). These output files were then checked for correctness and then interrogated. This analysis is reported in Section 9.2.5.

9.2.4 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 matrices, one for variant 1 (single passageway vessel) and one for variant 2 (two passageway vessel).

9.2.4.1 The Evacuation Evaluation Scenario ES_2

The evacuation evaluation scenario (ES_2) consists of a single functional group, FG_1 (Entire population). 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; number of severe congestion regions, C_2; severity of worst congestion region and G_4; the average time spent in congestion by the population);
- General performance of the crew (G_1; the average time required by each individual to complete their tasks, G_2; average time spent in transition, G_3; time to complete the scenario and G_5; average distance travelled by the population)
- Structural interaction (M_1; the number of WT door used, M_8; number of times the population moved between decks and M_{11}; the most times a WT door was operated).

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 used in this example application 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 are based solely on the interpretation of the author of this thesis. There was no client involved in this example application since this case was simply used to test the HPM concept and not to validate it. 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 important to the client, or by a community of experts, possibly using the Delphi method (Harmathy, 1982). A client is used to set the weights later in this thesis in Chapter 11; however, such techniques as the Delphi method were not required since there was only one person making the decision about the assignment of the weights.

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 9.2-1.

9.2.4.2 The NOP Evaluation Scenario ES_4

The NOP evaluation scenario (ES_4; State 1 Preps) requires two functional groups, FG_1 (entire population) and FG_2 (damage control and fire fighting group). 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. However, in addition, the various FGs must perform various tasks and so the PMs related to completing tasks (P_1; Total number of tasks completed by the FG, P_2; Average number of tasks completed by each member of the FG, and P_3; Average time to complete each FG task) are also used. For this ES, the main performance measure (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 criterion 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 has been applied to both the FGs in this scenario.

The final array of weightings used for evaluation scenario ES_4 is displayed in Table 9.2-1.

Table 9.2-1 - 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

9.2.4.3 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 NOP scenario (ES_4) is given 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).

9.2.5 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 by the HPM Analyser and used to construct the HPM for each variant. The HPM Analyser produced the relevant output files from which the PMs, FGs and ES were analysed for each. The final HPM constructed for each variant are shown in Table 9.2-2 and Table 9.2-3.

Table 9.2-2 - Human Performance Matrix for variant 1

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 9.2-3 - Human Performance Matrix for variant 2

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 Table 9.2-2 and Table 9.2-3, 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 HF performance according to the measures identified, producing an overall vessel performance that is some 26% better than variant 1. Furthermore, it must be noted 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 vessel's 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.

With these conclusions drawn, it would be very interesting to see how these results were formulated, what caused them and of far greater interest; how could the design be improved in terms of its human factors. This is where the capabilities of the HPM concept comes in to its own. Not only has it provided a framework for assessing a design across a number of different scenarios but it will also provide a means for showing why a design performed in the way that it did.

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

Table 9.2-4 - Comparison of results for FG_2 in ES_4 between variant 1 and variant 2

ES_4					
	FG_2				
		Variant 1		**Variant 2**	
Performance Measure	**Weight**	**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

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 9.2-4, 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 PMs 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 respectively.

The poor return produced for M_1 is due to the dual corridor system having eight more WT doors than the single corridor variant. The increase in the number of WTDs is due to the requirement to maintain watertight 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. 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 the scenario much quicker than variant 1.

This analysis suggests that it is difficult to further improve the performance of FG_2 in ES_4 for variant 2. This is primarily due to the requirement for additional WTDs in variant 2. If improvements were desired to the variant 2 design, an examination of the other evaluation scenario (ES_2) could be made to see if there is any scope for improvements.

Table 9.2-5 - Comparison of results for FG_1 in ES_2 between variant 1 and variant 2

ES_2					
	FG_1				
		Variant 1		**Variant 2**	
Performance Measure	**Weight**	**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

From Table 9.2-5, 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 PMs 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 9.2-5 a serious failing of variant 1 is that it does not meet the Naval Ship Code (NATO, 2006) concerning regions of critical congestion, with three regions displaying serious congestion as measured by the 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. NB: the normalising factor for G_3 is 3000; this is the regulatory specified time limit (in seconds) for a vessel of this size.

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. **Nor**, 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 behind them. 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 watertight 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 watertight integrity and this increases the number of tasks that must be performed to complete State 1 Preps.

9.2.6 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. This analysis involved setting the Evaluative Scenarios (ES) weights, Functional Group (FG) weights and Performance Measure (PM) weights each to 1.0 in turn. This would determine how much of an impact each set of weights had on the overall HPM, and it could possibly highlight areas of the design which could have been improved but were overlooked due to its low importance to the human factors performance of the design in question.

With each ES given equal importance, the vessel performance (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 have been 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.

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 has a significant effect on 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.

9.3 Second Example Application – Assessing human factors' performance of a Type 22 Batch III frigate

This second section of the chapter will make use of the HPM concept to evaluate the relative performance of two designs of a naval vessel, based on the UK Royal Navy's Type 22 Batch III frigate. For this example, seven evaluation scenarios were considered; three evacuation scenarios and four normal operational scenarios (NOP). It must be stressed, the geometry used in this example is not a Type 22 Batch III frigate, it is a fictitious design which resembles the real vessel. The compartment names are fabricated and the procedures employed are also fictitious although the procedures were deemed representative enough to demonstrate the capabilities of the new methodology. The aim of this analysis was to determine which design variant was the most efficient in terms of its HF performance and whether any improvements to the winning design could be identified.

9.3.1 The Geometry

The baseline vessel design (variant 1) consists of 453 compartments spread over eight decks. Decks No 1 and No 2 (deck 4 and 5 respectively) have a single central passageway connecting the aft to fore section of the deck (see Figure 9.3-1). This feature led to this design variant being labelled the single passageway variant. The second variant design (variant 2) consists of 445 compartments spread over eight decks as in variant 1. The key difference between the two designs is that variant 2 has two passageways running in parallel from the aft to the fore of the vessel on both decks (see Figure 9.3-1). This feature meant that the variant 2 design was also known as the double passageway variant.

The No 4 deck is the lowest of all the decks on both variant designs and 03 deck is the highest. No 1 Deck is the highest level in the hull of the vessel; it has an outer deck which contains the vessel's helicopter pad and a large gun. The 01 Deck is the first level above the hull of the vessel. This deck contains the most space outside and is where much of the exterior equipment, such as machine guns, are located. The majority of cabins are located in the lower decks although the officers' cabins can be found on No 1 Deck. Other compartments of note are the operations room which is located on the 01 Deck, the bridge which is located on the 02 deck, the hangar located over No 1 Deck and 01 Deck, and the fore and aft FRPP (fire repair party post) which are both located on No 1 Deck.

Both design variants consist of four watertight zones, of which there are three vertical zones stretching the breadth of the vessel under the waterline and a single WT zone consisting of all the compartments above the waterline, i.e. the 01 Deck and above.

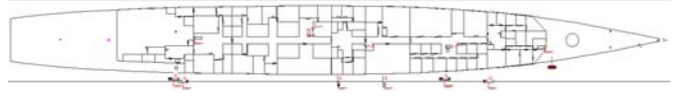
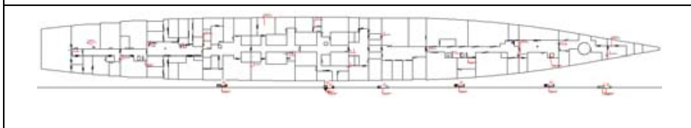
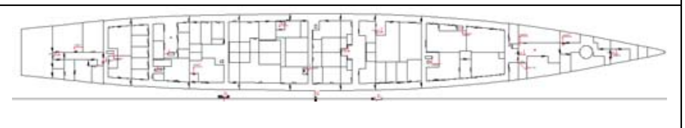
	
(a) No 1 Deck of variant 1	(c) No 1 Deck of variant 2
	
(b) No 2 Deck of variant 1	(d) No 2 Deck of variant 2

Figure 9.3-1 - Layout of variant 1 (a, b) and variant 2 (c, d).

9.3.2 The Scenarios

Each vessel was given a complement of 262. The crew were initially located in the compartments where they would be expected to be at the start of each scenario as determined by the "state" of the vessel. Crew members not on watch were located in their cabins. In this example each variant is assessed using seven ESs. These are the naval evacuation scenarios; 'Normal Day Cruising A', 'Normal Day Cruising B', 'Action Station Evacuation' (ES_1, ES_2, and ES_3 respectively) and normal operational (NOP) scenarios; 'State 1 Preps', 'Blanket Search', 'Family Day A' and 'Family Day B' (ES_4, ES_5, ES_6 and ES_7 respectively) scenarios. These scenarios have all been described in some detail in Chapter 6, so a short description of each will now be provided.

The NOP scenario 'State 1 Preps' (ES_4) involves the entire complement moving to designated locations across the vessel and changing into appropriate clothing. 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, four crew members from FG_2 close all WTD on the vessel. The 'Blanket Search' scenario involves the crew searching the entire vessel for damage. Each crew member searches the compartment they currently occupy while eight crew members search all the unoccupied compartments. 'Family Day A' involves a number of civilians on board the vessel when an incident occurs. The civilians are ushered to the muster stations while the crew move to their emergency stations in preparation to tackle the incident. In 'Family Day B', the incident engulfs the entire vessel and the command is given to evacuate, at which point the crew move to join the civilians at the muster stations. In both designs, the same procedures are employed so the results produced from the HPM will be a direct result of the differences in vessel layout. The evacuation scenario ES_1 involves the complement moving from their cruising locations towards their designated emergency stations ready for the call to abandon ship. The evacuation scenario ES_2 then involves the complement moving from their emergency stations to the muster stations where they will collect vital life saving equipment prior to evacuating. The evacuation scenario ES_3 involves the ship's complement moving from their action stations to the muster stations.

In all the scenarios, crew were given response times as stipulated in the draft Naval Ship code (NATO, 2006). 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.

9.3.3 The weights

Typical ES and PM weights used in the analysis are shown in Table 9.3-1. The weights were derived in consultation with the industrial partner (MoD). It should be noted that the NOP scenarios are given higher weights than the evacuation scenarios. This does not mean that the evacuation scenarios are not important but merely that they are perceived to be less important to a naval vessel than NOPs. It must also be emphasised that the evacuation ES are considered pass/fail scenarios, i.e. the vessel must meet the required evacuation standards if they are to be considered acceptable.

Table 9.3-1 - Weightings assignment for the PMs associated with each ES

Performance Measure	Normal Day Cruising A (ES_1)	Normal Day Cruising B (ES_2)	Action Stations Evacuation (ES_3)	State 1 Preps (ES_4)		Blanket Search (ES_5)	Family Day A (ES_6)		Family Day B (ES_7)
	FG_1	FG_1	FG_1	FG_1	FG_2	FG_1	FG_1	FG_3	FG_1
C_1	8	8	8	3	0	0	8	0	8
C_2	3	3	3	3	0	0	3	0	3
G_1	4	4	4	6	6	6	4	4	4
G_2	3	3	3	5	5	5	3	3	3
G_3	8	8	8	8	8	8	8	8	8
G_4	3	3	3	6	6	6	3	3	3
G_5	4	4	4	2	2	2	4	4	4
P_1	0	0	0	3	3	3	0	0	0
P_2	0	0	0	4	4	4	0	0	0
U1	0	0	0	0	0	7	0	0	0
U2	0	0	0	0	0	7	0	0	0
M_1	2	2	2	4	4	4	2	2	2
M_2	2	2	2	4	4	4	2	2	2

M_3	2	2	2	2	2	2	2	2	2
M_5	1	1	1	1	2	2	1	1	1
M_6	0	0	0	4	0	0	0	0	0
M_7	0	0	0	4	0	0	0	0	0
M_8	2	2	2	4	4	4	2	2	2
M_{10}	2	2	2	3	3	3	2	2	2
M_{11}	4	4	4	3	3	3	4	4	4
M_{12}	3	3	3	3	3	3	3	3	3
M_{13}	3	3	3	3	3	3	3	3	3
M_{14}	3	3	3	3	3	3	3	3	3
M_{15}	3	3	3	3	2	2	3	3	3
M_{16}	0	0	0	0	6	0	0	0	0
M_{17}	0	0	0	0	6	0	0	0	0
M_{18}	0	0	0	0	0	6	0	0	0

As has been stated, these weights were assigned in collaboration with our MoD partners. Initially the author of this thesis created the original set of weights. This set was then presented to our partner for their opinions. In doing this, the MoD could better understand the meaning of the weights and also did not have to create the weights from scratch which may have been harder to conceive.

9.3.4 Results of HPM analysis

With the simulations performed for both the single passageway variant 1 design and the double passageway variant design, the HPM was created by the HPM Analyser and the results of which are shown in Table 9.3-2 and Table 9.3-3. It can be seen from Table 9.3-2 that variant 1 produces an overall vessel performance score of 523.7 and from Table 9.3-3 that variant 2 produces an overall vessel performance score of 531.2. This illustrates that the single passageway variant design is marginally the best design in terms of its human factors' performance returning a 1.41% better vessel performance score.

Table 9.3-2 - HPM for variant 1

Variant 1 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	46.14	0	0	0	0	46.14	1
Normal Day Cruising B	1	50.81	0	0	0	0	50.81	1
Action Stations Evacuation	1	51.45	0	0	0	0	51.45	1
State 1 Preps	0.5	67.01	0.5	67.91	0	0	67.46	1.5
Blanket Search	0	0	1	78.04	0	0	78.04	1.5
Family Day A	0.5	55.88	0	0	0.5	41.43	48.65	1.5
Family Day B	1	56.03	0	0	0	0	56.03	1.5
Overall Performance of Functional Groups	324.61		167.99		31.07			
			Overall Performance of design				523.7	

Table 9.3-3 - HPM for variant 2

Variant 2 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	44.33	0	0	0	0	44.33	1
Normal Day Cruising B	1	46.79	0	0	0	0	46.79	1
Action Stations Evacuation	1	46.70	0	0	0	0	46.70	1
State 1 Preps	0.5	75.20	0.5	75.74	0	0	75.47	1.5
Blanket Search	0	0	1	84.29	0	0	84.29	1.5
Family Day A	0.5	51.05	0	0	0.5	43.35	47.20	1.5
Family Day B	1	55.32	0	0	0	0	55.32	1.5
Overall Performance of Functional Groups	315.49		183.24		32.51			
			Overall Performance of design				531.2	

Having seen the final HPMs for both design variants and having identified variant 1 as being marginally the better design, it would be useful to further analyse the matrices to see if there are any interesting results from the HPM sub components which could be used to improve the performance of the identified 'best' design. As a starting point, Table 9.3-4 compares ES scores, showing the percentage difference between the two design variants.

Table 9.3-4 - Scenario Scores for variant 1 and variant 2.

Evaluative scenario	Scenario Weight	Variant 1	Variant 2	% difference between Variant 1 and Variant 2
Normal Day Cruising A	1	46.14	44.33	3.9%
Normal Day Cruising B	1	50.81	46.79	7.9%
Action Stations Evacuation	1	51.45	46.70	9.2%
State 1 Preps	1.5	67.46	75.47	-11.9%
Blanket Search	1.5	78.04	84.29	-8.0%
Family Day A	1.5	48.65	47.20	3.0%
Family Day B	1.5	56.03	55.32	1.3%
Overall Performance of design		523.7	531.2	

As can be seen from Table 9.3-4, 'State 1 Preps' is variant 1's best performing ES, outperforming variant 2 by 12%. Variant 1's worst performing design was the 'Action Stations Evacuation' ES where it was 9% less efficient than variant 2. Table 9.3-4 shows how five of the seven ES perform more efficiently in the double passageway variant 2 design and only two ES perform better in the single passageway variant. This is a rather odd observation since the single passageway variant was considered the better design and yet it performs less well in the majority of the scenarios. However the two ES in which the variant 1 design performs better, it performs significantly more efficiently than variant 2 and these two ES had the higher of the ES weights, with a value of 1.5. If all of the scenario weights had been of the same value then the double passageway variant 2 design would have been the better design. This shows the importance of assigning the weights appropriately.

Having now established that the single passageway variant is the 'best' design, it would now be interesting to understand why it outperformed the double passageway variant. It has been identified that the 'Action Stations Evacuation' ES was the poorest of all the ES for the single passageway variant and therefore further examination of this ES may potentially lead to improvements to the design.

To better understand why variant 2 out performed variant 1 in the 'Action Stations Evacuation' scenario (ES_3) and to identify potential areas in which variant 1 can be improved it is necessary to further examine the sub-components of the HPM. Presented in Table 9.3-5 are the PM scores for variant 1 and 2 for ES_3. We note that variant 1 performed better than variant 2 in five of the 18 PMs (G_2, G_5, M_1, M_{14} and M_{16}). Of these five PMs, four show at least 10% better performance than the respective variant 2 PM, with M_{14} (most times a WT door was operated) and M_{16} (average number of doors used per person) returning 18% better performance. However, 12 of the PMs for variant 1 returned poorer performance. Of these PMs nine returned values which were at least 10% worse than those in variant 2. The poorest performance was achieved by G_4 (average time spent in congestion) which returned 50% worse performance.

It is interesting to note that the poor return produced by variant 2 for M_1 (number of WT doors used in the scenario) 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 watertight integrity and so is dictated by a design constraint which cannot be violated. However, even with these additional WT doors, 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 6% further (as measured by G_5) in order to complete their tasks. This additional distance is reflected in the time spent traversing the variant 2 geometry which is 20% longer than in variant 1 (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.

Table 9.3-5 - Variant 1 and variant 2 PM results for FG_1 in ES_3.

FG_1 – Entire Population		Variant 1		Variant 2	
	Weight	raw	norm	raw	norm
CONGESTION CRITERIA					
C1 – the number of locations in which the population density exceeds 4 p/m^2 for more than 10% of the overall scenario time	8	4	1	4	1
C2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	75.40	1	42.14	0.56
GENERAL CRITERIA					
G1 – average time required to complete all operations	4	256.7	1	193.54	0.75
G2 – average time spent in transition	3	36.61	0.80	45.76	1
G3 – time to reach final state	8	666.7	0.22	594.50	0.20
G4 – average time spent in congestion	3	150.6	1	74.93	0.50
G5 – average distance travelled	4	47.11	0.94	50.11	1
GEOMETRIC CRITERIA:					
M1 – the number of WTD used during the scenario	2	24	0.89	27	1
M2 – the number of hatches used during the scenario	2	31	1	25	0.81
M3 – the number of ladders used during the scenario	2	31	1	25	0.81
M5 – the number of doors used during the scenario	1	78	1	76	0.97
M8 – the number of times the FG moved between decks	2	373	1	322	0.86
M13 – average number of components used per member of FG during the scenario	2	4.47	1	4.36	0.98
M14 – most times a WT door was operated	4	9	0.82	11	1
M15 – most times a hatch was operated	3	10	1	7	0.70
M16 - average number of doors used per person	3	1.59	0.82	1.94	1
M17 - average number of WT doors per person	3	1.46	1	1.19	0.82
M18 - average number of hatches used	3	0.27	1	0.23	0.83

We note that for variant 2, the overall average time spent in congestion (as measured by G_4) was some 50% less than in variant 1. This significant reduction in congestion results in variant 2 being able to complete the scenario 11% quicker than variant 1 (as measured by G_3). Indeed, we note that while both vessels easily satisfy the international set evacuation time requirements (as measured by G_3) the levels of congestion experienced exceed the international set limits in four locations (as measured by C_1) and variant 1 experiences the most severe congestion (as measured by C_2). As the values for C_1 and C_2 are higher than the regulatory limits, neither vessel would be deemed to be acceptable. To address this issue and to improve the overall performance of variant 1, further investigation is required to uncover the causes of the severe congestion.

Further to this point, it could be suggested that improving the congestion experienced by the population in the single passageway variant 1 design could be the way forward in terms of improving the HF performance of the vessel.

After examining the graphical outputs of maritimeEXODUS, i.e. the GIF animation of the population density contour and the JPEG image of the IMO congestion regions, three areas of the severe congestion were identified, see Figure 9.3-2.

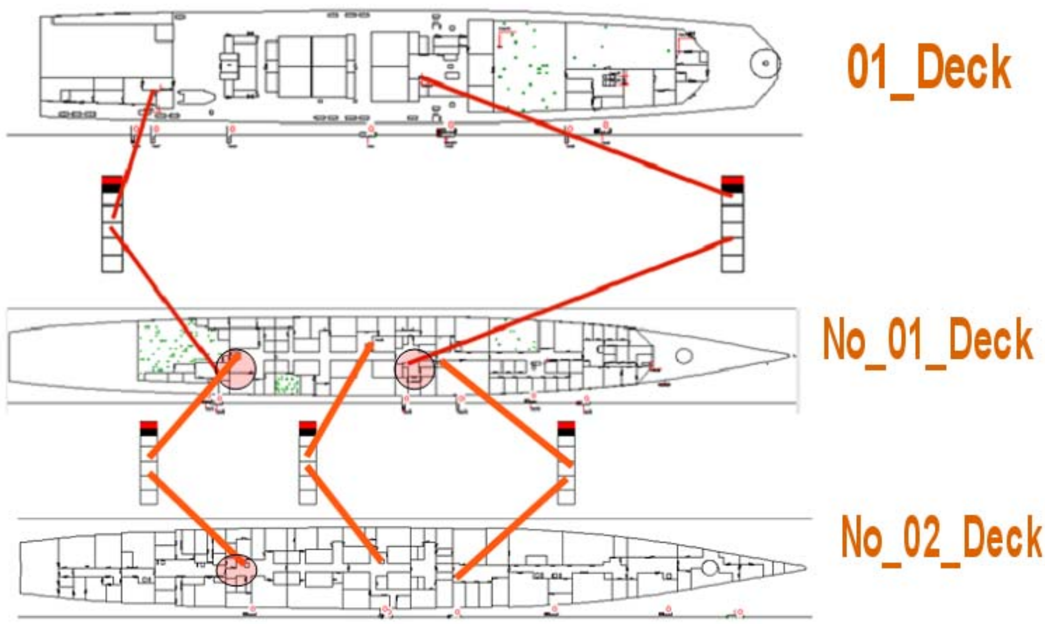


Figure 9.3-2 - Location of Severely Congested Regions

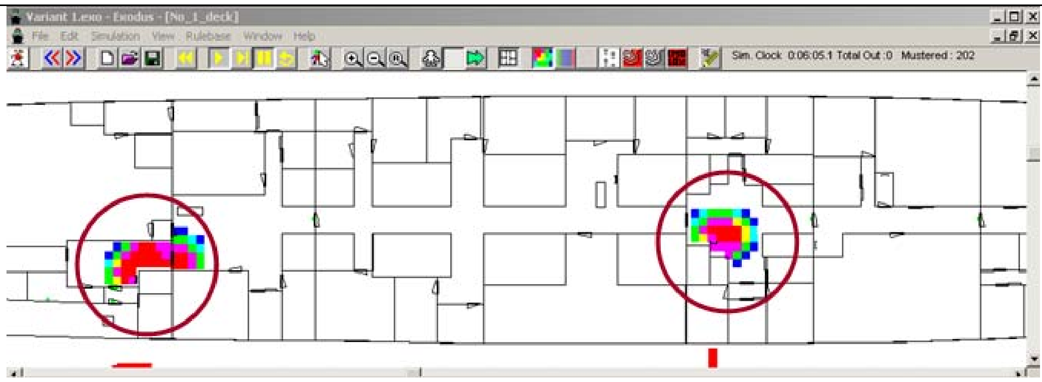


Figure 9.3-3 - IMO congestion contour as seen in maritimeEXODUS for No 1 Deck

Figure 9.3-2 shows the location of two severely congested regions on the No 1 Deck and a third severely congested region on the No 2 Deck. All three of these congestion regions are located at the base of ladders. Interestingly it can be observed from Figure 9.3-2 how there are three ladders connecting No 2 Deck to No 1 Deck but there are only two ladders connecting No 1 Deck to 01 Deck. This could explain the reason why congestion was building up on the No 1 Deck; since a large majority of the population were on the lower decks and their target location was the outer deck of 01 Deck, they would use three ladders to get from No 2 Deck to No 1 Deck but then would be forced to use only two ladders to get to their destination. This would inevitably cause a bottleneck around the deck connections, which has escalated down to the No 2 Deck.

In response to this and after some investigative work, it was suggested that an additional ladder should be inserted between the two existing ladders connecting No 1 Deck to 01 Deck. The bottom of the ladder would be located mid way between the two severe congestion regions located on the No 1 Deck. The aim of this would then be to attract crew members away from the two severely congested regions. This could actually have further implications too. The WT compartment on the No 1 Deck located between the two severely congested regions has a ladder coming up from the deck below but has no connectivity to the deck above. This is causing crew coming up from the deck below to move out of the WT compartment in order to progress to the upper deck. This causes a larger number of people to use other ladders. By inserting an extra ladder in the position described, crew would not have to move out of the WT compartment. This would also mean that they can a) take a more direct route to their destination and b) will not use as many WT doors.

9.3.5 HPM sensitivity analysis – predicting the effect of an additional ladder

Before making any changes to the selected design variant, it would be interesting, and useful, to know whether the extra effort is worthwhile or not. The aim of the ladder is to reduce the number of severely congested regions which occur during the 'Action Stations Evacuation' ES for the single passageway variant design. The sensitivity Equation (5.4.2) from Chapter 5 could be used to calculate the effect on the ES of reducing the congestion.

As such the performance measure of interest would be C_1 which has a weight of 8 and a normalised value of 1 (this is also the normalised value for the double passageway variant). The Action Stations Evacuation ES produced a scenario score of 51.45. If it was suggested that the normalised value for C_1 could be halved, which means in effect that 2 regions of severely congested regions are eliminated from the 'Action Stations Evacuation' ES, then the sensitivity equation would be:

$$\frac{SS_2 - SS_1}{SS_1} = \frac{-\frac{X}{100} \times W \times PM}{SS_1} \times 100 = \frac{-\frac{50}{100} \times 8 \times 1}{51.45} \times 100 = -7.78\%$$

From this it can be predicted that if it was possible to halve the number of severely congested regions during the Action Stations Evacuation ES then there should be at least a 7.78% improvement in the design's ability to complete the scenario.

It would also be interesting and perhaps more useful to know what possible improvement or conversely detrimental effect, the ladder may have on the overall design before going ahead and making the change. For this, Equation (5.4.6) from Chapter 5 was used. The equation required the normalised PM score and the PM's weight and in addition it also required the overall vessel performance score and the ES weight. In the case of the 'Action Stations Evacuation' ES, it had a weighting of 1 and the overall vessel performance score for the single passageway variant was 523.68. When all this information was put in to the equation, the following was produced.

$$\frac{V_2 - V_1}{V_1} = \frac{-W_{ss}\left(\frac{X}{100} \times W \times PM\right)}{V_1} \times 100 = \frac{-1\left(\frac{50}{100} \times 8 \times 1\right)}{523.68} \times 100 = -1.65\%$$

It can therefore be predicted that by halving the number of severely congested regions in the 'Action Stations Evacuation' ES the design's human factors' performance would improve by 1.65%. This may seem to be a very small number, but in fact it would not be known how the ladder would affect other PMs in the ES or indeed how the ladder would affect the other ESs.

It must be stressed that these predictions only take into account one performance measure and so do not show how one PM has an affect on other PMs in the same scenario or in other ESs.

9.4 Implementation of ladder to single passageway variant 1

After interrogating the HPMs for the single passageway variant 1 and the double passageway variant 2 design it was discovered that variant 1 had the superior human factors' performance and as such was deemed the best design in terms of its HF. When examining the HPMs in more detail, it was noticed that there was a significantly greater level of congestion being experienced in the variant 1 design during it's worst performing ES 'Action Stations Evacuation'. On a closer look it was found that congestion was building up around the base of ladders and how there were only two ladders connecting the No 1 Deck to 01 Deck whereas there were three connecting the other decks. As a result it was suggested that an additional ladder be inserted in an attempt to alleviate the congestion and improve the overall HF performance of the single passageway variant 1 design.

The ladder was placed into the geometry as indicated by Figure 9.4-1; the newly created ladder has blue lines connecting the No 1 Deck to the 01 Deck (if reading thesis in colour otherwise the extra ladder is the difference between Figure 9.3-3 and Figure 9.4-1).

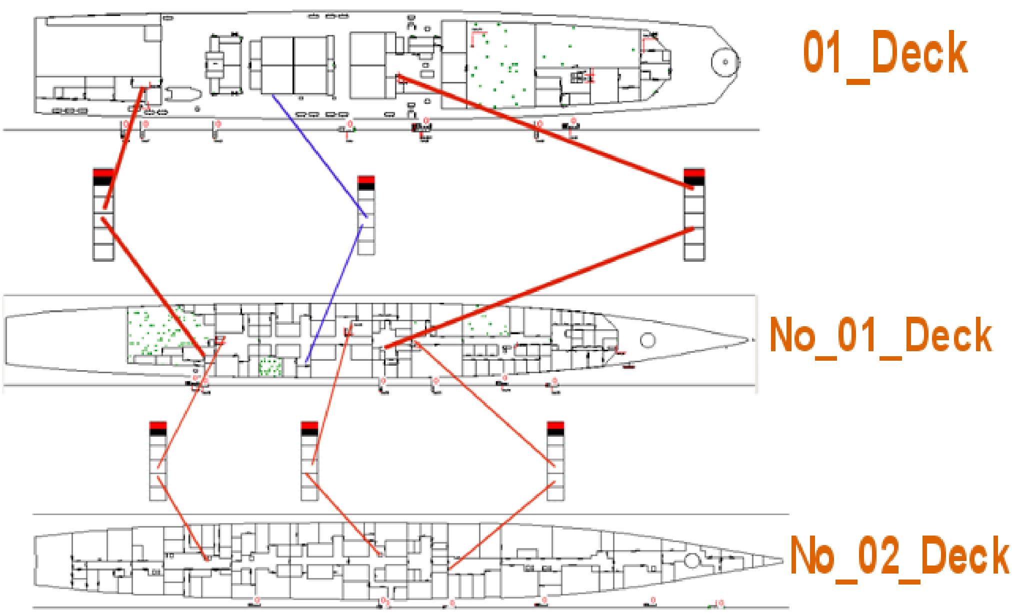


Figure 9.4-1 - Variant 1 with Additional Ladder Inserted

With the suggested ladder in place, effectively a new variant design was formed. Therefore this new design variant was labelled 'variant 3'. The simulations were performed on the variant 3 design in an identical fashion as was used to assess the variant 1 and variant 2 designs. With the simulations performed, the HPM was created using the HPM Analyser, which compared the newly created variant 3 design against its predecessor variant 1, and then compared the variant 3 design against the double passageway variant 2 design.

The following sections of this chapter report the findings of the analysis comparing variant 3 to variant 1 and variant 2.

9.5 HPMs for variant 1 and variant 3

With the seven ES having been simulated on the variant 3 design and a representative file selected for each ES, the HPMs were created for the original single passageway variant 1 design and the modified single passageway variant 3 design. These HPMs can be seen in Table 9.5-1 and Table 9.5-2.

Table 9.5-1 - HPM for variant 1

Variant 1 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG1		FG2		FG3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	47.81	0	0	0	0	47.81	1
Normal Day Cruising B	1	51.62	0	0	0	0	51.62	1
Action Stations Evacuation	1	52.78	0	0	0	0	52.78	1
State 1 Preps	0.5	74.30	0.5	77.59	0	0	75.95	1.5
Blanket Search	0	0	1	86.25	0	0	86.25	1.5
Family Day A	0.5	56.40	0	0	0.5	48.17	52.28	1.5
Family Day B	1	57.57	0	0	0	0	57.57	1.5
Overall Performance of Functional Groups	336.58		187.30		36.13			
			Overall Performance of design				560.3	

Table 9.5-2 - HPM for variant 3

Variant 3 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG1		FG2		FG3			
	weight	score	weight	score	weight	Score		
Normal Day Cruising A	1	46.59	0	0	0	0	46.59	1
Normal Day Cruising B	1	44.98	0	0	0	0	44.98	1
Action Stations Evacuation	1	44.68	0	0	0	0	44.68	1
State 1 Preps	0.5	70.10	0.5	76.76	0	0	73.43	1.5
Blanket Search	0	0	1	85.45	0	0	85.45	1.5
Family Day A	0.5	55.73	0	0	0.5	43.37	49.55	1.5
Family Day B	1	53.57	0	0	0	0	53.57	1.5
Overall Performance of Functional Groups	312.99		185.71		32.52			
			Overall Performance of design				529.2	

By introducing the single ladder in a strategic position, it has been possible to improve the single passageway design by 5.6% as seen from the comparison of the overall vessel performance score for variant 1 (560.3) and the improved variant, variant 3 (529.2). This is quite a significant difference by doing so little work (the naval architect only had to implement a ladder). The following section explores the impact that the additional ladder has made on the design.

Table 9.5-3 - Comparison of ES Score between variant 1 and variant 3

Evaluative scenario	Scenario Weight	Variant 1	Variant 3	% difference between Variant 1 and Variant 3
Normal Day Cruising A	1	47.81	46.59	-2.6%
Normal Day Cruising B	1	51.62	44.98	-12.9%
Action Stations Evacuation	1	52.78	44.68	-15.3%
State 1 Preps	1.5	75.95	73.43	-3.3%
Blanket Search	1.5	86.25	85.45	-0.9%
Family Day A	1.5	52.28	49.55	-5.2%
Family Day B	1.5	57.57	53.57	-6.9%
Overall Performance of design		560.3	529.2	

The additional ladder inserted into the single passageway variant 1 design has significantly improved its HF performance in the 'Action Stations Evacuation' ES, giving rise to a 15% improvement. In fact inserting the one ladder has improved the vessel's design across the board. The improvement is not so great in the 'Blanket Search' ES, producing a mere 1% improvement, however there are only 8 crew members moving about the vessel during this ES and of these eight, only two would use this additional ladder while searching that particular WT zone. The greatest improvement was seen in the 'Action Stations Evacuation' ES but there were also significant gains in performance for the 'Normal Day Cruising B', 'Family Day A' and 'Family Day B' ES returning 13%, 5% and 7% better performances in the design variant which included the extra ladder.

Further to this, when the 'Action Stations Evacuation' ES is further examined, in Table 9.5-4, it can be observed how the level of congestion has greatly improved.

Table 9.5-4 - PM Scores for Entire Population during the 'Action Stations Evacuation' ES

FG_1 – Entire Population		Variant 1		Variant 3	
	Weight	raw	norm	raw	norm
CONGESTION CRITERIA					
C1 – the number of locations in which the population density exceeds 4 p/m^2 for more than 10% of the overall scenario time	8	4	1	2	0.50
C2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	75.40	1	64.21	0.85
GENERAL CRITERIA					
G1 – average time required to complete all operations	4	256.7	1	217.1	0.85
G2 – average time spent in transition	3	36.61	0.80	45.79	1
G3 – time to reach final state	8	666.7	0.22	651.0	0.22
G4 – average time spent in congestion	3	150.6	1	105.5	0.70
G5 – average distance travelled	4	47.11	1	45.62	0.97
GEOMETRIC CRITERIA					
M1 – the number of WTD used during the scenario	2	24	1	23	0.96
M2 – the number of hatches used during the scenario	2	31	1	31	1
M3 – the number of ladders used during the scenario	2	31	1	31	1
M5 – the number of doors used during the scenario	1	78	1	71	0.91
M8 – the number of times the FG moved between decks	2	373	1	371	0.99
M13 – average number of components used per member of FG during the scenario	2	4.47	1	3.98	0.89
M14 – most times a WT door was operated	4	9	0.9	10	1
M15 – most times a hatch was operated	3	10	1	5	0.5
M16 - average number of doors used per person	3	1.59	1	1.42	0.89
M17 - average number of WT doors per person	3	1.46	1	1.14	0.78
M18 - average number of hatches used	3	0.27	1	0.27	0.97

The key point to observe here is that two of the severely congested regions which existed during the 'Action Stations Evacuation' ES have been eradicated as is illustrated by Figure 9.5-1 and Table 9.5-5. Figure 9.5-1 shows how the region of severe congestion on No 2 Deck has disappeared as too has the aft (left) area of congestion on the No 1 Deck. Table 9.5-5 illustrates not only how the aft (left) congestion region has been eliminated but it also shows the significant reduction in the severity of the congestion in the region which still exists on the No 1 Deck.

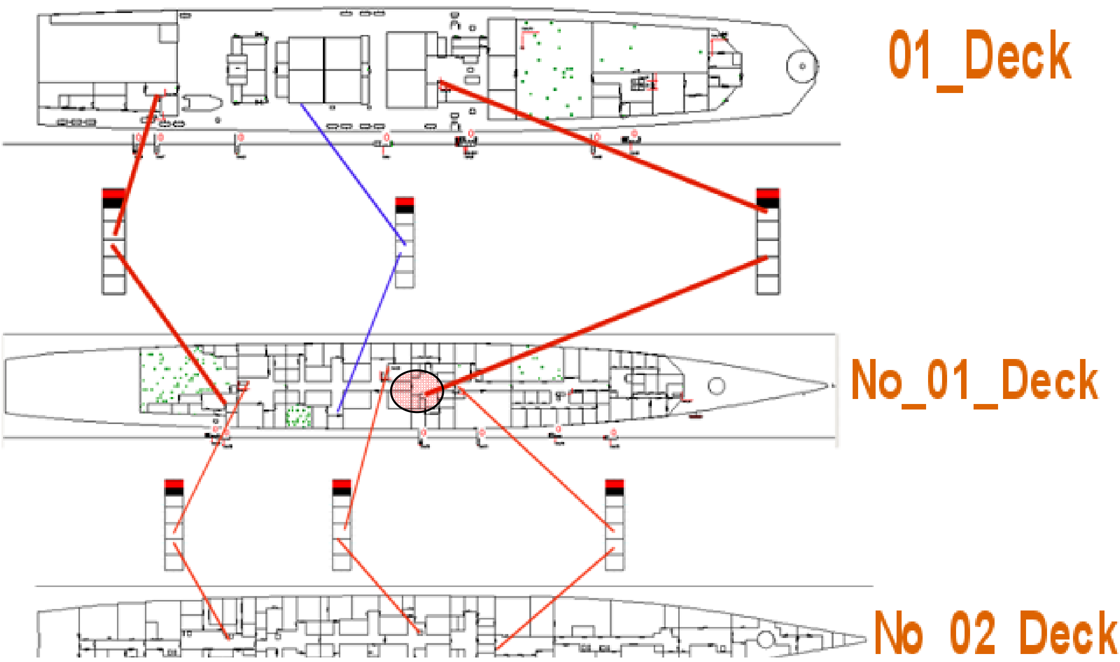
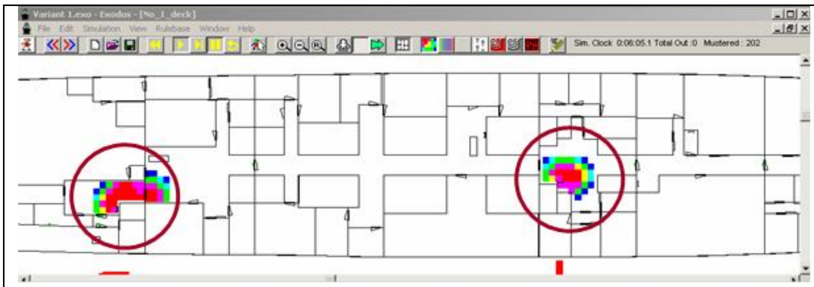
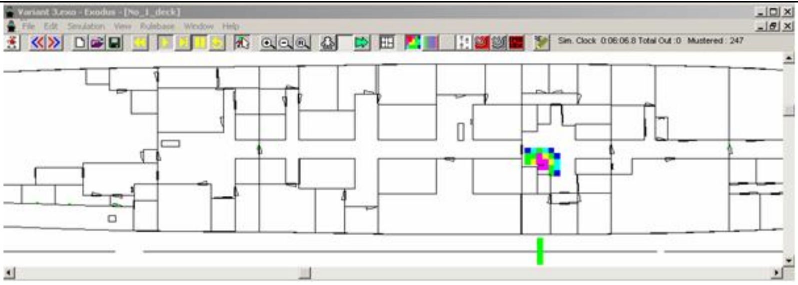


Figure 9.5-1 - Areas of severe congestion on the variant 3 design

Table 9.5-5 - Severe congestion during 'Action Stations Evacuation' ES

	Areas of severe congestion located on No 1 Deck in variant 1 during the 'Action Stations Evacuation' ES



Areas of severe congestion located on No 1 Deck in variant 3 during the 'Action Stations Evacuation' ES

9.6 Comparison between expected results and actual results caused by an additional ladder

The aim of inserting an additional ladder in to the single passageway variant was to decrease the level of congestion experienced by the population during the 'Action Stations Evacuation' scenario. The prediction had been made that if the extra ladder was able to halve the normalised value of C_1 (the number of severely congested regions) in this scenario then the design would be 7.78% more efficient in terms of its human factors' performance during the 'Action Stations Evacuation' scenario and 1.65% more efficient overall.

Once the scenarios had been performed in maritimeEXODUS and the simulation outputs analysed, it was found that the addition of the ladder between No 1 Deck and 01 Deck improved the HF performance of the vessel in the 'Action Station Evacuation' scenario by 15.3% and improved the overall HF performance of the vessel by 5.6%.

This illustrates that the extra ladder has had more of a positive result on the 'Action Stations Evacuation' scenario than had been expected. Since the targeted PM, C_1, did have its normalised value halved, then it could be suggested that the additional ladder may well have had a positive effect on one or more of the other performance measures. On closer inspection, it could be seen that not only was there a large difference in the number of severely congested regions (50% reduction), but the average level of congestion experienced by the population was also significantly reduced (by 30%). This meant that the population on average were not delayed as much and as a result were able to complete their assigned tasks more efficiently which also has the impact of the scenario being completed in less time.

The additional ladder had a very positive effect on the overall HF performance of the vessel, far surpassing the 1.65% predicted improvement; returning a 5.6% superior performance. This is because the ladder created other access routes which allowed the population to move between decks during the other six scenarios. This resulted in shorter travel distances for the population, which may only be slightly shorter but required less distance to travel, which consequently takes less time to travel, thus this means that each individual completes their tasks in a shorter amount of time and the scenario is completed in less time. The new access route would also require the crew members to use fewer WT doors and non-WT doors since they would not have to move out of the WT compartment in order to travel between decks.

9.7 HPMs for variant 3 and variant 2

Having now improved the variant 1 design by 5.6% with the introduction of a single ladder, it would be interesting to see how the modified single passageway variant compares against the double passageway variant. This would not be necessary normally, but for the purposes of demonstrating the HPM concept this analysis is performed.

No more simulations were required to compare these two designs, since they have already been performed for the purpose of other analyses. Therefore this analysis merely required using the HPM Analyser to create the HPMs. Table 9.7-1 and Table 9.7-2 show the overall HPM for the modified single passageway variant 3 design and the double passageway variant 2 design, respectively.

Table 9.7-1 - HPM for variant 3

Variant 3 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG$_1$		FG$_2$		FG$_3$			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	46.15	0	0	0	0	46.15	1
Normal Day Cruising B	1	47.74	0	0	0	0	47.74	1
Action Stations Evacuation	1	46.69	0	0	0	0	46.69	1
State 1 Preps	0.5	64.31	0.5	68.95	0	0	66.63	1.5
Blanket Search	0	0	1	80.33	0	0	80.33	1.5
Family Day A	0.5	55.71	0	0	0.5	33.88	44.80	1.5
Family Day B	1	53.04	0	0	0	0	53.04	1.5
Overall Performance of Functional Groups	310.15		172.21		25.41			
			Overall Performance of design				507.8	

Table 9.7-2 - HPM for variant 2

Variant 2 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG$_1$		FG$_2$		FG$_3$			
	weight	score	weight	score	weight	Score		
Normal Day Cruising A	1	44.94	0	0	0	0	44.94	1
Normal Day Cruising B	1	48.78	0	0	0	0	48.78	1
Action Stations Evacuation	1	49.78	0	0	0	0	49.78	1
State 1 Preps	0.5	77.11	0.5	76.08	0	0	76.60	1.5
Blanket Search	0	0	1	84.74	0	0	84.74	1.5
Family Day A	0.5	51.66	0	0	0.5	47.97	49.81	1.5
Family Day B	1	57.89	0	0	0	0	57.89	1.5
Overall Performance of Functional Groups	326.91		184.17		35.98			
			Overall Performance of design				547.1	

As can be seen from Table 9.7-1 and Table 9.7-2, the modified single passageway variant produces an overall vessel performance (VP) score of 507.8 whereas the double passageway variant produces a VP score of 547.1. This results in the modified single passageway variant having the lower overall score by 7.7% and as such it is still deemed the 'best' design.

As is illustrated in Table 9.7-3 the modified single passageway now outperforms the double passageway variant in all of the ES with the exception of the 'Normal Day Cruising A' ES. Even in this ES, the modified variant 1 design has improved its performance, just not enough to outperform variant 2.

Table 9.7-3 - Comparison of ES scores between variant 2 and variant 3

Evaluative scenario	Scenario Weight	Variant 2	Variant 3	% difference between Variant 2 and Variant 3
Normal Day Cruising A	1	44.94	46.15	2.6%
Normal Day Cruising B	1	48.78	47.74	-2.2%
Action Stations Evacuation	1	49.78	46.69	-6.6%
State 1 Preps	1.5	76.60	66.63	-15.0%
Blanket Search	1.5	84.74	80.33	-5.5%
Family Day A	1.5	49.81	44.80	-11.2%
Family Day B	1.5	57.89	53.04	-9.1%
Overall Performance of design		547.1	507.8	

It can be seen that the 'State 1 Preps' scenario remains as the best performing scenario for the single passageway variant returning a 15% better performance; the worst performing scenario is now the 'Normal Day Cruising A' scenario returning a 2.6% inferior performance.

9.8 Analysis of the effect of an additional ladder

Having compared the single passageway variant 1 to the double passageway variant 2 and the modified single passageway variant 3 to variant 2, it would be of interest to see just how much of a difference the addition of the single ladder has made to the HF performance of the designs.

Table 9.8-1 - Comparison of differences in scenario score caused by addition of a ladder

Evaluative scenario	Scenario Weight	% difference between Variant 1 and Variant 2	% difference between Modified Variant 3 and Variant 2
Normal Day Cruising A	1	3.9%	2.6%
Normal Day Cruising B	1	7.9%	-2.2%
Action Stations Evacuation	1	9.2%	-6.6%
State 1 Preps	1.5	-11.9%	-15.0%
Blanket Search	1.5	-8.0%	-5.5%
Family Day A	1.5	3.0%	-11.2%
Family Day B	1.5	1.3%	-9.1%

Table 9.8-1 further shows how the addition of the ladder to the single passageway variant has improved the design. It can be seen that the single passageway variant outperforms variant 2 in six of the seven ES assessed; even in the ES which the single passageway did not outperform the double passageway variant (Normal Day Cruising A), it still improved its performance with the addition of the ladder, just not enough to better the performance of the double passageway variant.

The extra ladder has caused a 15.8 improvement in percentage difference between the single passageway variant and the double passageway variant for the 'Action Stations Evacuation' scenario (from +9.2% to -6.6%) which is a very significant difference. This was the largest difference caused by the addition of the ladder, which was ideal since the ladder was added as result of the analysis for the 'Action Stations Evacuation' scenario. The ladder has also made a large difference to the 'Normal Day Cruising B', 'Family Day A' and 'Family Day B' scenarios returning 10.1, 14.2 and 10.4 improvements in the percentage differences seen between the single passageway and double passageway variants.

In summary, adding the extra ladder in the strategic location between the No 1 Deck and 01 Deck of the single passageway variant 1 design has made an improvement to the single passageway variant in all of the scenarios assessed, and made the largest difference in the 'Action Stations Evacuation' scenario, taking the single passageway variant from performing 9.2% poorer than the double passageway variant to performing 6.6% better.

9.9 Concluding comments

This chapter has demonstrated the general methodology for the Human Performance Metric (HPM) in evaluating HF performance of competing ship designs. The use of the methodology has been demonstrated using two example applications; one of which utilised two variant designs of a hypothetical vessel, one variant involving a single longitudinal passageway and a competing variant involving two longitudinal passageways. The other example application used a geometry loosely based upon a UK Royal Navy's Type 22 Batch III frigate. This example also consisted of two variant designs with one design having a single passageway and the other variant design having a double passageway connecting the fore section of the vessel to the aft.

It must be emphasised that these conclusions are based on the particular Evaluation Scenarios, Performance Measures and Weights that were 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.

The example applications have both distinguished between the two variant designs and suggested that the single passageway variant 1 design was marginally the better design in terms of its HF performance. However, in both examples, it was identified that being the second variant had two passageways then there should be a greater number of WT doors to uphold WT integrity and a greater number of deck connections to supply both passageways with a means of travelling from one deck to another.

During the second example application, that using the Type 22 Batch III frigate, an observation was made concerning the high level of congestion which was experienced by the crew on the single passageway variant. After investigations, it was recommended that an additional ladder should be placed in the geometry to help alleviate the congestion. After reassessing the design variant, the extra ladder had the effect of improving the HF performance by 5.6% in general, and improved the variant's worst ES by 15.3%. This demonstrated the new HPM concept's ability to not only discriminate between competing designs but also its diagnostic capabilities.

The following chapter will explore the use of the HPM concept in greater detail, demonstrating its ability to effectively assess the human factors' performance of a design and in identifying possible improvements to the designs. The HPM will also be incorporated into the design cycle of a naval vessel, demonstrating its ability to assess the HF performance of a design in an iterative process.

Chapter 10

Integration of HPM into Early Stages of the Design Cycle

10.1 Introduction

In order to incorporate human factors' (HF) analysis into the early stages of the design cycle for a new naval vessel; a study into how a naval vessel is designed was required. A literature review was conducted which identified that a key software tool used in designing naval vessels during the early stage of the design cycle was PARAMARINE (Bole & Forrest. 2005). This software tool is made up of a number of smaller modules which are used in the design cycle of a naval vessel. One of these modules, named SURFCON (SURFace ship CONcept) is used for the design of surface vessels such as frigates, destroyers and aircraft carriers. During the rest of this work, when referring to the software that designs naval vessels, PARAMARINE is used but in fact it is the SURFCON module which is being utilized. The software uses a design building block approach to creating a new prototype vessel, whereby cuboids are created and manipulated (in shape and size). These cuboids are then placed together, much like a LEGO set to form the basis of the vessel design. A variety of different analytical assessments are then performed on the design to discover its power, strength and sea keeping, to name a few. Once the design passes these assessments, it is developed further by adding more detail, after which the design is built. The aim of this work was to add HF assessment as one of the analytical assessments performed on the prototype vessel by PARAMARINE at the early stage of the design cycle.

To incorporate HF analysis into the early stages of the design cycle, it was clear that PARAMARINE and maritimeEXODUS would have to interact. An EPSRC project was undertaken between University of Greenwich (UoG) and University College London (UCL) to create a link between maritimeEXODUS (UoG software) and PARAMARINE (UCL designed software). This project was known as 'EGO'. At first it was hoped that this would be a trivial task but unfortunately this was not the case. It was hoped that either PARAMARINE could directly output maritimeEXODUS input files or maritimeEXODUS could directly import PARAMARINE output files. Unfortunately, only very limited changes could be made to PARAMARINE since access to the source code was unavailable. As will be discussed later in this chapter, development for a direct interface to allow maritimeEXODUS to read in the PARAMARINE output files was not possible. As a result, two translation tools were developed which could translate PARAMARINE's output files into maritimeEXODUS input files and then a translation tool to convert maritimeEXODUS output files into PARAMARINE's input. In addition to these translation tools, PARAMARINE was not designed to view animations, nor was it able to accurately accept and display pictures. This resulted in UCL investigating other methods for viewing the results produced from the human factors assessment and lead to the adoption of VRML as an approach to visualising the HF performance of a design.

The final system for integrating human factors' analysis into the early stages of design is illustrated in Figure 10.1-1, highlighting the responsibilities of each of the project partners in the integrated system.

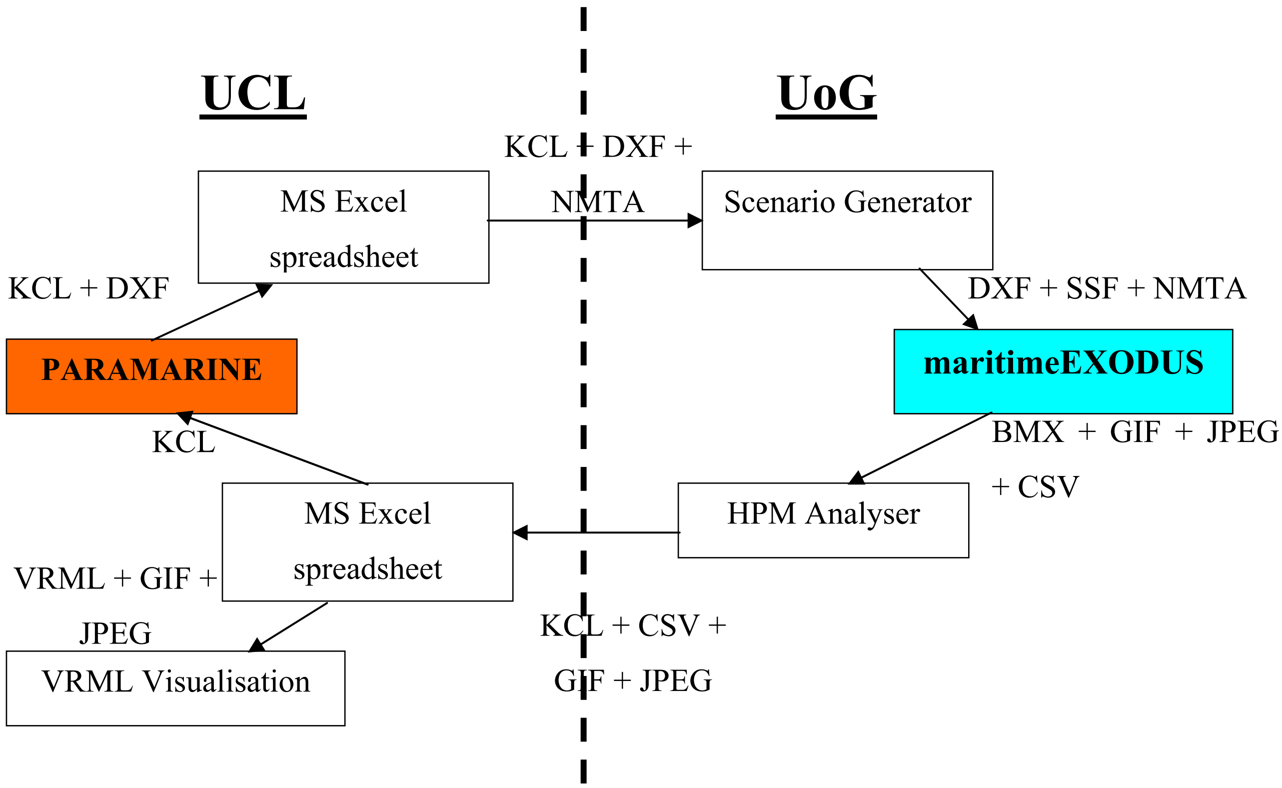


Figure 10.1-1 - Software Design Cycle

Figure 10.1-1 illustrates how the Scenario Generator and the HPM Analyser were the responsibility of University of Greenwich (UoG) and the MS Excel spreadsheet along with the VRML visualisations were the responsibility of University College London (UCL). The Scenario Generator and the HPM Analyser were the work of the author of this PhD thesis.

This proposed system for integrating human factors' analysis into the early stages of design meant that changes would have to be made to all three pieces of UoG's software; i.e. the Scenario Generator, maritimeEXODUS and the HPM Analyser.

The Scenario Generator would have to be adapted to accept UCL's output files and the HPM Analyser would have to be modified in order to produce the required output files in a format which UCL could accept.

Since the HF analysis is being incorporated into an already lengthy design process, it was very desirable that the analysis could be performed with a minimum amount of interaction. As such, it would be hoped that much of the HF analysis could be automated, especially concerning the interaction with PARAMARINE. It has been identified that setting up the geometry and the population in maritimeEXODUS can take a considerable amount of time and so these should be examined in more detail to see how these tasks can be performed more efficiently. Inserting the population with their itineraries has already been considered with the SSF file format and the Scenario Generator being produced as a result. However, creating the geometry within maritimeEXODUS had not, and therefore work would have to be done here.

The rest of this chapter discusses the changes to the UoG's software in more detail, expressing why they were required and what the solution involved.

It must be stressed that UCL did not perform any human factors' performance analysis. Their role in the EGO project was to design the naval vessel in PARAMARINE and aid in creating the link between PARAMAIRNE and maritimeEXODUS, which they did through the use of a MS Excel spreadsheet. They also assessed the best means of presenting the results of the human factors analysis to the user of PARAMARINE, this was satisfied with the use of anything MS Excel spreadsheet and the use of VRML.

10.2 Software Developments Required for the Integrated System

10.2.1 Modification to maritimeEXODUS

The starting point for integrating the human factors' analysis into a design cycle is to input the geometry of the vessel (General Arrangement - GA) into maritimeEXODUS. As stated in Chapter 3, PARAMARINE, which is used to design naval vessel's, produces two output files; KCL and DXF. As has been explained before, maritimeEXODUS can read in DXF files and therefore no work was required in order to transfer the GA from PARAMARINE into maritimeEXODUS. However, the DXF files only contain boundary lines and do not carry information regarding the location of doors, compartment names or location of equipment items. All of which are required to model the geometry within maritimeEXODUS. The idea of integrating the PARAMARINE software with maritimeEXODUS is to provide rapid assessment of HF performance with as little effort as possible. Therefore it was desired that the user would not have to insert a mesh of nodes into the GA or add necessary detail, for example doors, individually which would be time consuming and tiresome.

One approach considered for automatically generating the mesh within the model was to program maritimeEXODUS to recognise groups of lines within the DXF file as being compartments. In this way maritimeEXODUS could have the 'intelligence' to work out how to flood each compartment with nodes efficiently, filling every space. This approach would mean that maritimeEXODUS would also know whether there were compartments within compartments or objects which would need to be meshed around. maritimeEXODUS could also have been programmed in such a way as to be able to recognise the common DXF symbol for a door and for different types of doors (i.e. WT doors, double doors, hangar doors). Using this information, maritimeEXODUS could replace the DXF symbol with a door node and then connect the door to the adjacent compartments of freespace nodes. Text labels could also be recognised by maritimeEXODUS as compartment names and when cross referencing the position of the text label to freespace nodes in the model, could assign the nodes to a compartment. In addition, maritimeEXODUS could have been trained to recognise the DXF symbols for stairs and ladders. maritimeEXODUS could then have inserted the deck connection into the model. However the deck height would have been required, but a standard deck height could have been used.

This would have been the ideal approach to take and would have meant that a near perfect geometry could have been created within maritimeEXODUS with very little, if any, input from the user. However, unfortunately early investigative work showed that this would entail a significant amount of work, justifiably a PhD project in its own right, and could not be completed within the timescale of this project. Although it was possible to recognise the majority of compartments and objects, maritimeEXODUS could not do this accurately. Discarding areas within compartments, not to be meshed as part of the compartment, was also proving very difficult to overcome. Even with some of the compartments correctly recognised, it was proving difficult to efficiently mesh a space which was not square. Although all of the problems being experienced were resolvable, it was decided that it would take far too long to do.

For these reasons, an alterative method of meshing the geometry had to be adopted. After the initial investigations, it was discovered that PARAMARINE produced an output file called KCL. This was a macro file which builds up the structure of the vessel, including the shape, size and type of compartment. An attempt was made to write a program which could extract all the required information from the KCL file. However, the KCL file was too complex. Some details could be extracted such as compartment names, door names and in most cases the X, Y and Z coordinates for the doors. But extracting the shape and location of compartments proved very difficult.

Although the University of Greenwich found it difficult to translate the KCL file into something which could be used, UCL could read their software's output file. Unfortunately UCL do not own the source code to PARAMARINE and therefore could not make any changes to the software but they could, and did, create a Microsoft Excel spreadsheet which utilized VB macros. These macros were programmed to read in the KCL file, translate them and produce an output which maritimeEXODUS could import and use. Their Excel translation software could not be used to generate the entire mesh, but it could extract all the information required by maritimeEXODUS to complete the geometry.

The UCL spreadsheet would be used to extract the required information about doors (including X, Y and Z coordinates and door type) and the deck connections (such as ladders and stairs) as well as information about the compartments. Their spreadsheet would then create a MTA file which maritimeEXODUS could import. The MTA file when imported into maritimeEXODUS would place a door node (with its correct characteristics) in the correct location above a DXF symbol for a door. The MTA would then place a Free Space node either side of the door node, to indicate the direction of the door. One of the freespace nodes would also have a title which would represent the name of the compartment. The other freespace node would have the title 'delete' and acted as a dummy node. A dummy node would be inserted so that maritimeEXODUS knew where to connect the door. The dummy node was used, as opposed to another node with the title of the compartment, since the door component in PARAMARINE is only associated with one compartment and not both. The MTA file would also contain all the equipment items (such as valves, machinery, weaponry etc), these would be represented as door nodes which had the specific characteristics of being closed and inactive. The MTA file would also contain links to the DXF files required for the geometry.

When this MTA file was read into maritimeEXODUS, the software would first load all the DXF files and then place all the nodes from the MTA file into the geometry. At this stage all the doors would have been inserted and the names of the compartments would be known and deck connections inserted.

The geometry would then need to be prepared so that simulations could be carried out. To do this the mesh would have to be created. The names of all the compartments would be known; therefore the user would have to flood every room with nodes and then created compartment zones for each compartment. This is required so that individuals can be sent to a zone. Although part of this task has been done using the MTA file, there is still a considerable amount of time consuming work required to complete this task. As a result a feature was created within maritimeEXODUS to automate the creation of the geometry. An automated node flood operation was developed. This operation would remove all of the freespace nodes and carry out a node flood task from the X, Y and Z coordinates of the freespace node which it had just deleted. maritimeEXODUS would name every node in the node flood operation with that of the compartment (extracted from the freespace node just deleted) and once the software completed the node flooding of a compartment, it would create a compartment zone with the name of the deleted freespace node and add all of the newly created nodes to it. All the previously inserted doors and deck connections would then have to be connected to the newly created meshes. Once this was done, the geometry would then be ready for a population to be inserted and simulation to be run. What would have taken about a week's worth of work can now be carried out in as little as 10 minutes (approximately, based on the Type 22 Frigate used in the demonstration see Chapter 11)

This automated node flood operation is not flawless and still needs the user to examine the geometry. The main problem with this method is that the node flood operation is performed from the first door in the compartment, but this may not necessarily be the optimal position to start the node flood from, especially if the compartment space is not square. The automatic node flood operation may not flood round corners efficiently, leaving a large gap between the last row / column of nodes and the boundary line. An example of this can be seen in Figure 10.2-1 where the node flooding starts from the red square (first column on left, third node down from top). It can be seen that the space has not been efficiently filled at the top. The upper vertical corridor has a large gap between the nodes and the boundary lines and as such maritimeEXODUS will see that space as only 1 metre wide when in fact it is 1.5 metres wide. This is not a huge difference, but then this is just a simple geometry. In a more complex geometry, such as a warship, this difference could be quite significant.

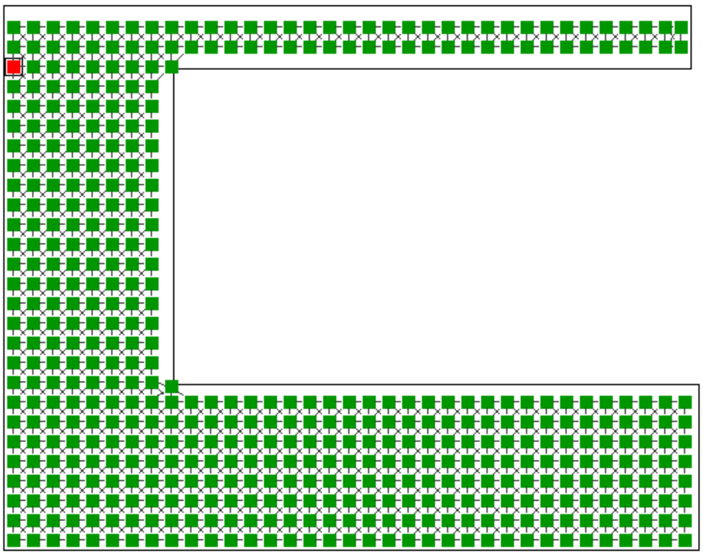


Figure 10.2-1 - problem with node flooding

In the example above (Figure 10.2-1), the user would have to shift the top two rows of nodes up and insert an additional row of nodes below in order to make better use of the space available.

In addition to setting up the geometry within maritimeEXODUS, modifications were requested by UCL to enable maritimeEXODUS to produce an additional output file which could be read by Microsoft Excel in the format of a CSV (Comma Separate Value). This output file would contain WT door usage; specifically, information about when each WT door was operated (i.e. opened or closed) and how many people went through each door both in total and between each door operation. This CSV output file also contains the overall time and the longest time that each WT door was open for. This CSV output file was then imported into UCL's Microsoft Excel spreadsheet where macros would translate the information into a VRML file along with the GIFs and JPEGs produced by maritimeEXODUS.

10.2.2 Modifications to the Scenario Generator

In addition to inputting the geometry into maritimeEXODUS, the population along with their itineraries also needed to be inserted into the model. Developments already discussed in this work explored the SSF file format as the method of choice for inserting a population with a complex itinerary. Work has also been reported on the Scenario Generator and its use in creating a SSF file. However, in the integrated system, it was decided the user / ship designer / naval architect would predominantly use PARAMARINE with very little interaction with maritimeEXODUS. With this in mind, it was decided that the population and their itineraries would be defined in PARAMARINE using its spreadsheet capabilities.

With this decision made, the task then became how to import the population from PARAMARINE into maritimeEXODUS. It has already been stated that the output files from PARAMARINE could not be changed, and therefore the Scenario Generator would have to be adapted to become a translation tool.

The plan was for the population and their itinerary to be defined within PARAMARINE using simple and coherent language which should make the implementation by the user as simple and effortless as possible. The spreadsheet would be exported in a KCL file which would then be read by the Scenario Generator. The Scenario Generator would then be able to extract all the information about the population and their itineraries from the KCL file. This is possible since (unlike the information regarding the vessel structure) the spreadsheet table in the KCL file is always the same and quite simple to read.

When defining the population in PARAMARINE, the designer would define the watch and station bill (W & SB) in a single spreadsheet table. The W&SB defined by UCL contains the location of every crew member on board the naval vessel during six different ship states. These states are; state 1, state 2, state 3, emergency stations, evacuation and cabin. With this information it is possible to know the start and end location of every crew member on board the vessel during the majority of scenarios (if not all scenarios). The W&SB also contains the rank and department of each crew member and their functional group which the Scenario Generator would use as the crew member's name.

The designer, after defining the population, can then create additional spreadsheet tables within PARAMARINE for each scenario they want to simulate. In these tables, which are labelled with the name of the scenario, each row will define an itinerary for an individual or a group of people (much like in the Scenario Generator when creating itineraries). The itineraries will be written using high level commands such as ‘DRESS_4_FIRE’ which will then be interpreted by the Scenario Generator and translated into the SSF commands which maritimeEXODUS will be able to understand. There are set commands which the designer can use within PARAMARINE for defining the itineraries. These commands have been coded into the Scenario Generator. Therefore, new commands could be used by the designer but the Scenario Generator would have to be told what these commands mean and how to deal with them. The range of commands which the designer can use in PARAMARINE are listed in Table 10.2-1, along with what the Scenario Generator recognises them as.

Table 10.2-1 - PARAMARINE commands and their maritimeEXODUS translation

PARAMARINE Command	maritimeEXODUS command
DRESS_4_FIRE	Delay with specified range
UN_DRESS_4_FIRE	Delay with specified range
GOTO_ST_1	Go to state 1 location
GOTO_ST_2	Go to state 2 location
GOTO_ST_3	Go to state 3 location
GOTO_MUST_ST	Go to muster station
GOTO_EM_ST	Go to emergency station
GOTO_EVACUATE	Go to evacuation station
CIV_NUMBER_X	Insert X number of civilians
CIV_GROUPS_X	Split civilians into X groups
CIV_LOWEST_DECK_No_2_deck	Lowest deck civilians can be located on
SEARCH_SWIC_#Zone_1#Zone_2#	Blanket search WT zones 1 and 2
CHECK_SWIC_#Zone_3#Zone_4#	Close all WT doors in WT zones 3 and 4

In the case of the 'Go to …' commands in Table 10.2-1, the Scenario Generator would extract each person's location from the W&SB and create a SSF command which would consist of a delay command at the specified location with a time delay of 0 seconds. The commands 'CIV_NUMBER_', 'CIV_GROUPS_' and 'CIV_LOWEST_DECK_' are all used specifically for the Family Day scenarios and define the civilian population. The 'SEARCH_SWIC_' and

'CHECK_SWIC_' commands use a hash ('#') to separate WT zone names which are to be searched / checked by the crew.

The designer can configure some of these commands by inserting an extra spreadsheet table labelled 'Actions'. This table allows the user to list the commands they have used along with any parameters required for the task. For example, the 'DRESS_4_FIRE' command will need a time delay associated with it so that maritimeEXODUS knows how long it takes a crew member to get dressed for fire.

As a default, if the Scenario Generator does not recognise a command then it will assume it to be a standard delay and as such will look for it in the 'Actions' table. If the command is not there then it will flag up an error.

In addition to the 'Actions' table, there is a table labelled 'WHOS_WHO' which identifies particular groups of people. These are different to the functional groups since this table defines groups within the functional groups. For instance, only 8 members of the damage control and fire fighting group close all the WT doors in the 'State 1 Preps' scenario, therefore the whole group does not need this command. The Scenario Generator will use this as a look up table for when a group of crew members are assigned an itinerary in the scenario definition tables.

Within the KCL file sent to the Scenario Generator is a table labelled 'Waypoints'. This is an important table in setting up the population's itineraries. When assigning a location to a person or itinerary, the designer could use a shorter, possibly abbreviated name for a compartment. These 'Waypoints' will then link the designers name for the compartment to the name of the compartment which will be implemented in maritimeEXODUS. In some cases there may be no difference in the names.

The final spreadsheet table in the KCL file exported to the Scenario Generator is entitled 'Setup'. This contains a list of all the scenarios to be simulated along with the conditions to be set within the simulations. The initial and final state that the vessel will be in (i.e. state 1, state 2 or state 3 etc) during the scenario will be listed here along with the initial and final WT integrity condition (i.e. X, Y or Z). This information allows the Scenario Generator to set the initial open / close status of all the WT doors in the geometry as well as stating how the population will interact with them, i.e. leave them open or close the door behind them The 'Setup' table will also state what time of day the scenario will be carried out (i.e. day or night) and which watch teams will be on duty during the scenario. This is important since not everyone will be involved in the scenario, some crew may be allowed to sleep in their cabins for instance.

When the spreadsheet tables are exported in the KCL file and the Scenario Generator loaded, the user has to first load the geometry, i.e. the NMTA file created by UCL's MS Excel spreadsheet translation tool, and the KCL file. This is done by clicking on the 'Load Nmta File' button on the program's main menu screen, Figure 10.2-2. This will prompt the user with a common open dialog box where they can navigate to the directory where the NMTA file is located and open the required file. The user must then click on the 'Load KCL File' button on the program's main menu screen. This will also prompt the user with an open dialog box where they can navigate to the desired directory and select the required KCL file.

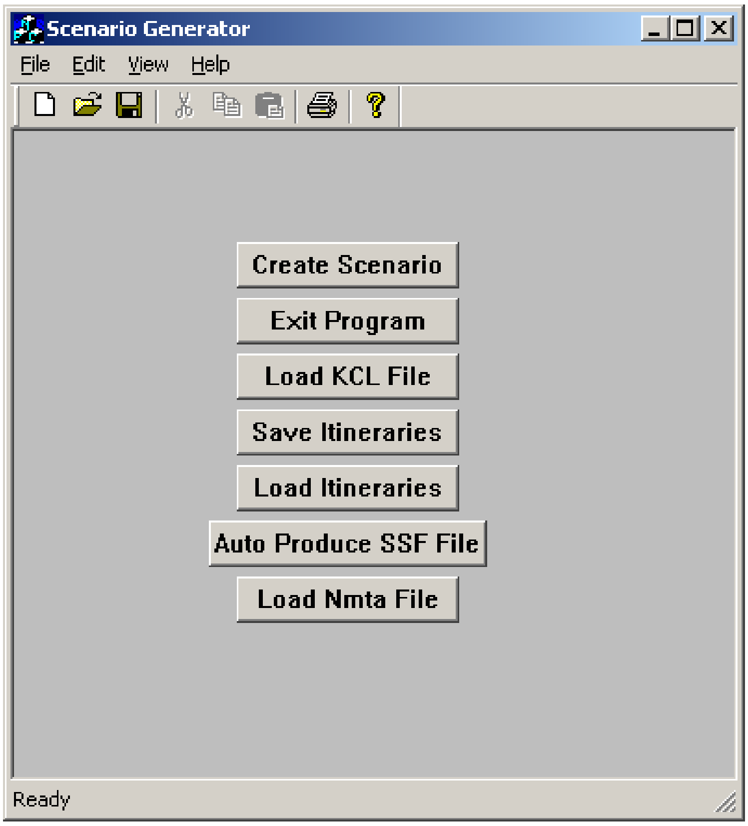


Figure 10.2-2 - Scenario Generator Main Menu

Once the geometry and the KCL file have been loaded into the Scenario Generator, the user can click on the 'Auto Produce SSF File' button where they will be presented with the window shown in Figure 10.2-3. There may be a delay between pressing the button and the next window being displayed, since the Scenario Generator is reading in and interpreting the KCL and NMTA files. This delay will very much depend on the complexity of the vessel – since this will affect the size of the KCL and the NMTA file. This window allows the user to select which of the define scenarios they wish to produce a SSF file for. The list of scenarios will have been extracted from the KCL file.

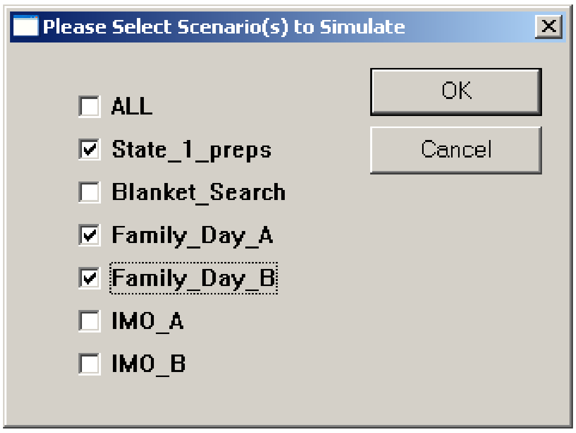


Figure 10.2-3 - Scenario Selection Screen

The list of scenarios will always start with the choice to select 'ALL'. The user can select any combination of scenarios to be simulated. If this check box is selected then all the other check boxes will be overridden.

Once the user has made their selection, the Scenario Generator will then prompt the user with a 'Save As' dialog box (Figure 10.2-4) which will ask them what they want to save the SSF file as and where the file should be saved to. As a default, the 'Save As' dialog box will provide the SSF file with the name of the scenario, as can be seen in Figure 10.2-4. This will help the user identify which scenario is being produced.

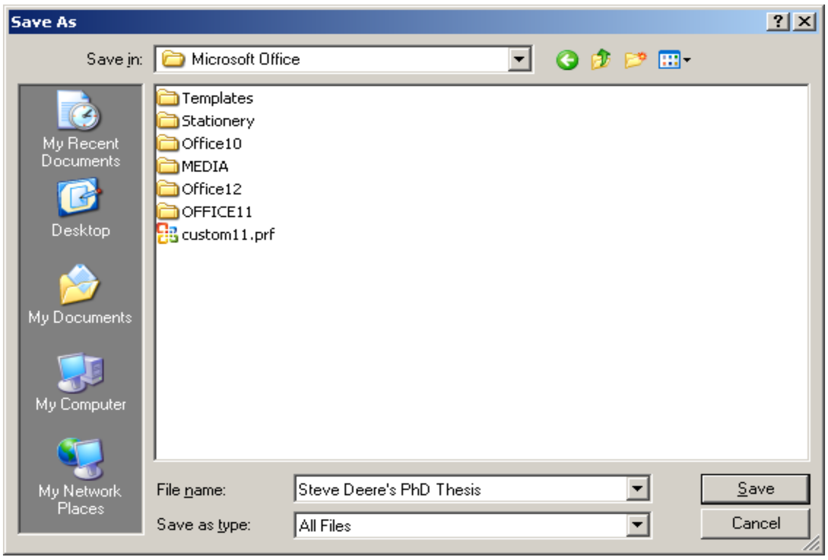


Figure 10.2-4 -'Save As' dialog box

After the user clicks 'Save', the Scenario Generator will produce the SSF file with the provided name in the selected directory. Once created a 'Successfully Created SSF file' message will be displayed. The Scenario Generator will then carry out this process again for any other scenarios selected. i.e. it will prompt the user with the 'Save As' dialog box.

10.2.3 Modifications to the Human Performance Metric Analyser

As has been discussed, the ideal solution for incorporating human factors' analysis into the early stages of design would be to make maritimeEXODUS and PARAMAINE interact with each other. In addition it would be desired that the designer would predominantly carry out their work within PARAMARINE with little interaction with maritimeEXODUS, since the designers would be familiar with PARAMARINE. With this in mind and in order to complete the design cycle it was decided that the results of the HPM should be imported into PARAMARINE where it could be interrogated by the designer.

The HPM Analyser had been designed to produce the results for the HPM in file formats which could be read into Microsoft Excel for interrogation or be opened in any text editor. However PARAMARINE could not read these files, and nor could it be modified to import any of these files. Consequently, it was decided the HPM Analyser would be extended in order to produce the HPM results in the format of a KCL file which could be displayed within PARAMARINE.

As was the case for the Scenario Generator, reading the spreadsheet tables from the KCL file and writing the tables in KCL was not difficult since the spreadsheet tables all have the same structure in KCL files.

This was the only amendment required to the HPM Analyser tool in order to integrate human factors' analysis into the early stages of the design cycle for a naval vessel.

10.3 Summary

This chapter has outlined the software modifications which were required in order to integrate the human factors' analysis into the early stages of the design cycle for a naval vessel.

The next chapter will take these newly implemented modifications and apply them to an example application of the Type 22 Batch III frigate from the UK's Royal Navy. In this example application, the frigate will be designed within PARAMARINE and exported to maritimeEXODUS via UCL's translation spreadsheet and UoG's Scenario Generator. The frigate will then be assessed for its human factors' performance before the results of which will be sent back to PARAMARINE via the HPM Analyser.

Chapter 11

Demonstration Application of the Human Performance Metric Implemented into the Early Stages of the Design Cycle for a New Naval Vessel

11.1 Introduction

This chapter will make use of the HPM concept to evaluate the relative performance of two designs of a hypothetical naval vessel, based on the UK Royal Navy's Type 22 Batch III frigate. Chapter 6 suggested seven evaluative scenarios which should be used to assess the Human Factors' (HF) performance of the design. These seven scenarios will be made up of three evacuation scenarios and four normal operational scenarios (NOP). The analysis will attempt to discriminate between the two design variants and determine which is the most efficient in terms of its HF performance. The HPM concept will be used to identify possible weaknesses in the winning design which could be addressed, improving the design's HF performance in the process.

11.2 The Geometry

As mentioned earlier, this demonstration analysis will make use of two fictitious variant designs of the UK Royal Navy's Type 22 Batch III frigate. The difference between the two design variants can be seen on deck No 1 and No 2 with variant 1 having a single passageway leading centrally from the fore of the vessel to the aft and the second design variant having two passageways running in parallel from the fore of the vessel to the aft. For ease of reference, the first variant will be referred to as the single passageway variant and the second design will be referred to as the double passageway variant.

The single passageway variant design consists of 453 compartments spread over eight decks. The double passageway variant design consists of 445 compartments spread over eight decks as in variant 1. The difference in the design variants can be seen in Figure 11.2-1.

In both design variants, the lowest deck is No 4 Deck whilst 03 Deck is the highest. No 1 Deck is the first level above the waterline which has an outer deck to it. The 01 Deck is the main outer deck where most exterior equipment, such as lifeboats and machine guns, are located. The majority of cabins are located in the lower decks although the officers' cabins of note can be found on No 1 Deck. Other compartments of note are the operations room which is located on the 01 Deck, the bridge which is located on the 02 Deck, the hangar located over No 1 Deck and 01 Deck, and the forward and aft FRPP (fire repair party post) which are both located on No 1 Deck.

Both design variants consist of four watertight zones, of which there are three vertical zones stretching the breadth of the vessel under the waterline and a single WT zone consisting of all the compartments above the waterline, i.e. the 01 Deck and above.

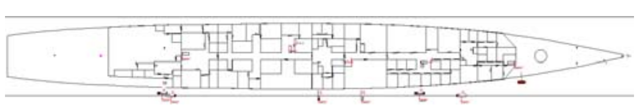
	
(a) No 1 Deck of variant 1	(c) No 1 Deck of variant 2
	
(b) No 2 Deck of variant 1	(d) No 2 Deck of variant 2

Figure 11.2-1 - Layout of variant 1 (a, b) and variant 2 (c, d).

The vessel as designed by UCL can be seen in PARAMARINE in Figure 11.2-2. As part of the integrated design cycle, both vessel designs were built within PARAMARINE and sent to maritimeEXODUS via UCL's spreadsheet translation program and UoG's Scenario Generator. The resulting geometry of the Type 22 Batch III frigate can be seen in maritimeEXODUS as illustrated in Figure 11.2-1.

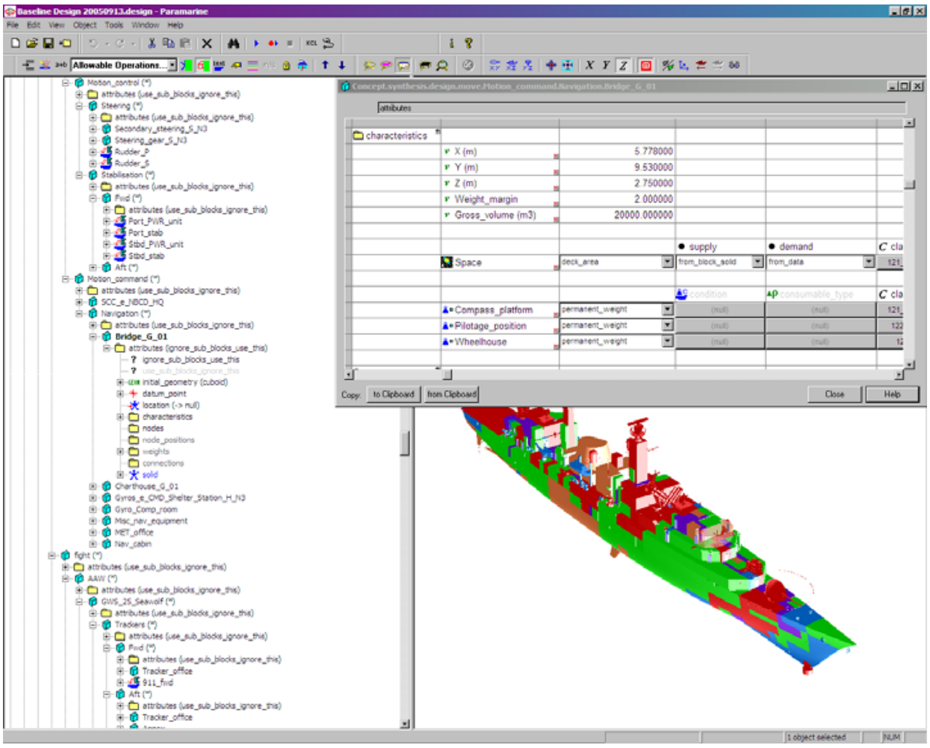


Figure 11.2-2 - The Type 22 Batch III frigate as seen in PARAMARINE

11.3 The Scenarios

As discussed in the introduction to this chapter, the two variant designs will be assessed by seven scenarios, three of which are evacuation scenarios and four normal operational scenarios. Each of the scenarios will have a full complement of 262 crew members who will initially be located depending on the initial state of the vessel. This was discussed in Chapter 6.

As a summary, these scenarios are ‘Normal Day Cruising A’ (ES_1), ‘Normal Day Cruising B’ (ES_2), ‘Action Station Evacuation’ (ES_3), ‘State 1 Preps’ (ES_4), ‘Blanket Search’ (ES_5), ‘Family Day A’ (ES_6) and ‘Family Day B’ (ES_7). These scenarios have all been described in some detail in Chapter 6, so a short description of each will now be provided.

The NOP scenario ‘State 1 Preps’ (ES_4) involves the entire complement moving to designated locations across the vessel and changing into appropriate clothing. In addition, two teams of five fire fighters in the damage control and fire fighting party 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, four crew members from FG_2 close all WTD on the vessel. The 'Blanket Search' scenario involves the crew searching the entire vessel for damage. Each crew member searches the compartment they currently occupy while eight crew members search all the unoccupied compartments. 'Family Day A' involves a number of untrained civilians on board the vessel when an incident occurs. The civilians are ushered to the muster stations while the crew move to their emergency stations in preparation to tackle the incident. In 'Family Day B', the incident engulfs the entire vessel and the command is given to evacuate, at which point the crew move to join the civilians at the muster stations. In both designs, the same procedures are employed so the results produced from the HPM will be a direct result of the differences in vessel layout. The evacuation scenario ES_1 involves the complement moving from their cruising locations towards their designated emergency stations ready for the call to abandon ship. The evacuation scenario ES_2 then involves the complement moving from their emergency stations to the muster stations where they will collect vital life saving equipment prior to evacuating. The evacuation scenario ES_3 involves the ship's complement moving from their action stations to the muster stations.

In all the scenarios, crew were given response times as stipulated in the draft Naval Ship code (NATO, 2006). 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.

11.4 The weights

The weights were discussed with the UK MoD project partners on the EGO project (EPSRC, 2004) and presented in Table 11.4-1 are the results of those discussions. The table presents the weights for every performance measure in each functional group of each scenario. In addition to Table 11.4-1, each of the NOP scenarios were given an ES weight of 1.5 while the evacuation scenarios given a weight of 1.

Table 11.4-1 - Weightings assignment for the PMs associated with each ES

Performance Measure	Normal Day Cruising A (ES_1)	Normal Day Cruising B (ES_2)	Action Stations Evacuation (ES_3)	State 1 Preps (ES_4)		Blanket Search (ES_5)	Family Day A (ES_6)		Family Day B (ES_7)
	FG_1	FG_1	FG_1	FG_1	FG_2	FG_1	FG_1	FG_3	FG_1
C_1	8	8	8	3	0	0	8	0	8
C_2	3	3	3	3	0	0	3	0	3
G_1	4	4	4	6	6	6	4	4	4
G_2	3	3	3	5	5	5	3	3	3
G_3	8	8	8	8	8	8	8	8	8
G_4	3	3	3	6	6	6	3	3	3
G_5	4	4	4	2	2	2	4	4	4
P_1	0	0	0	3	3	3	0	0	0
P_2	0	0	0	4	4	4	0	0	0
U1	0	0	0	0	0	7	0	0	0
U2	0	0	0	0	0	7	0	0	0
M_1	2	2	2	4	4	4	2	2	2
M_2	2	2	2	4	4	4	2	2	2
M_3	2	2	2	2	2	2	2	2	2
M_5	1	1	1	1	2	2	1	1	1
M_6	0	0	0	4	0	0	0	0	0
M_7	0	0	0	4	0	0	0	0	0
M_8	2	2	2	4	4	4	2	2	2
M_{10}	2	2	2	3	3	3	2	2	2
M_{11}	4	4	4	3	3	3	4	4	4
M_{12}	3	3	3	3	3	3	3	3	3
M_{13}	3	3	3	3	3	3	3	3	3
M_{14}	3	3	3	3	3	3	3	3	3
M_{15}	3	3	3	3	2	2	3	3	3
M_{16}	0	0	0	0	6	0	0	0	0
M_{17}	0	0	0	0	6	0	0	0	0
M_{18}	0	0	0	0	0	6	0	0	0

Since there was just a single point of contact from the UK MoD project partner, the need to use the Delphi method was not required. To aid the project partner in selecting appropriate weights for the HPM, the author of this thesis presented the project partner with a first attempt at assigning weights. The project partner then agreed and disagreed with the weights and changed them to suit.

In formulating the first set of weights and then discussing them with our MoD partner, it became clear how two different people could assign weights differently. Although the initial set of weights was not too distant apart, there was a difference. This highlights the need for the client to set the weights, since they will have their own view as to what is important. If anyone other than the client sets the weights then factors may become highlighted as problems even if the client is not worried about them. This can lead to modifications to the structure and / or the procedures which are not required or could even be detrimental to the running of the scenarios within the structure.

Examining the weights assignment in Table 11.4-1, there is very little change between the sets of weights for each scenario.

The ‘Normal Day Cruising B’ scenario was considered an extension of the ‘Normal Day Cruising A’ scenario and as such they both had the same weights. On the same note, the ‘Family Day B’ scenario was considered an extension of the ‘Family Day A’ scenario and as such both scenarios had the same weights. In addition to this, although the two scenarios had different populations and slightly different procedures, in essence the ‘Normal Day Cruising’ and the ‘Family Day’ scenarios were very similar and as such had the same set of weights.

The ‘Blanket Search’ scenario, as defined by our MoD partner, was intended to be an extension of the ‘State 1 Preps’ scenario and as such the ship would be in the same conditions in both scenarios. For this reason the weights were set very similarly for both ES.

During the evacuation ES, i.e. ‘Normal Day Cruising A’ and B and ‘Action Stations Evacuation’, the number of severely congested regions and the time to complete the scenario were considered the measures of greatest interest. These were viewed as the most important since these are required for regulatory compliance. Thus these PM, C_1 and G_3, were given the higher weights of 8. Other than the regulatory requirements, the MoD's priorities were relating to completing the scenario as quickly as possible. The UK MoD wanted the population to travel the shortest possible distance which should therefore reduce the time for each person to reach their destination. As such the performance measures G_5 (measuring the distance travelled) and G_1 (measuring the average time for each individual to complete the scenario) were given a slightly higher weight of 4. The MoD were not too interested in the number of components within the geometry used but were slightly more interested in the number of components which each person on average had to navigate through. In response to this PMs M_1, M_2 and M_3 were all given weights of 2 (relating to the number of WT doors, hatches, and ladders respectively used), then the average number of WT doors, hatches and ladders (M_{13}, M_{14}, M_{15}) were given a fractionally higher weighting of 3.

Moving on to the normal operational scenarios and starting with the 'State 1 Preps'. In this scenario, the emphasis is on upholding the watertight integrity. The aim of this scenario, apart from preparing the vessel for combat, is to close all the WT doors as quickly as possible. Since one of the specific tasks of the damage control and fire fighting group is to close all the WT doors then this group needed to be analysed in greater detail. Two specific performance measures were developed to assess FG_2 ability to close all the WT doors efficiently, M_{16} (time to close all WT doors) and M_{17} (time to report back that vessel has upheld WT integrity). Both of these measures would be seen as rather interesting to the MoD and as a result were given higher weights at a value of 6 each. It was only given a 6 since these measures, although essential to the ES, were not considered as important as the overall time to complete the scenario (G_3); G_3 was given a high value of 8. Even though this PM was considered the most important measure for this scenario, it was not given the highest possible weighting of 10 since this was reserved for the number of fatalities and the next highest weighting of 9 was reserved for the level of exposure to narcotic gas, elevated temperatures and to the amount of time spent in smoke. These were each given the highest possible weightings since they are a direct threat to life. However, there was no need to model these PMs since there was no fire simulated and as such the value of the PMs would have been zero and would not have made any impact on the HF performance of the design.

With the 'Blanket Search' scenario, although the entire population of the vessel are on board and at their action stations, there are just a few people from the damage control and fire fighting party who are of interest in this scenario. Everyone on board the vessel will search the compartment which they occupy but they will not move out of the compartment, in fact they will not move much at all as part of the scenario. As such the entire population is not assessed for their HF performance. Instead just the few members of the damage control and fire fighting group (FG_2) will be assessed.

The 'Blanket Search' scenario entails the selected few crew members from FG_2 searching all unoccupied compartments on board the vessel as quickly as possible. In response to this, it was decided that the overall time to complete the scenario (G_3) would be considered the most important performance measure and therefore was given a weight of 8. The average time for each individual of FG_2 to complete their assigned tasks (G_1) was also considered important and accordingly was given a weight of 6, as too was the average level of congestion experienced by the FG (G_4) which was considered to be of particular interest since congestion would slow the time required to complete the scenario. However, since there were only a small number of crew moving about the vessel, it was unlikely that the level of congestion would have been considered significant. Due to the points outlined here, the population size and more importantly the percentage of inactive population, was considered a rather useful PM for the 'Blanket Search' scenario, since the higher the number of inactive population then the more crew members that could help perform the blanket search.

11.5 The software and the scenario technique

The example application using the Type 22 Batch III frigate is designed to demonstrate the HPM's capabilities to assess the human factors' performance of a vessel which is still at the very early stages of the design cycle, where changes to the structure of the design can be implemented relatively easily. Since this example application is demonstrating the integration of HF assessment into the early stages of design of a naval vessel, the software tools developed and demonstrated in the previous chapter will be applied such that they actively accept and produce the inputs and outputs of PARAMARINE.

Both variants of the Type 22 Batch III frigate were designed within PARAMARINE, see Figure 11.2-2. Whilst being designed, both variants underwent several rigorous assessments including weight analysis, power analysis and stability analysis as documented earlier in this thesis.

Once the designs reached a satisfactory standard (i.e. passed the analysis mentioned), PARAMARINE then produced a KCL output file along with a number of DXF files defining the variant designs. The KCL file was passed through UCL's Microsoft Excel spreadsheet translation tool which created an NMTA file.

The NMTA file and KCL file were then passed onto the Scenario Generator which then read in the files and extracted all the information it required in order to create the scenarios as defined within PARAMARINE. The Scenario Generator then asked the user which scenarios they wished to be created. The Scenario Generator was told to create all seven ES which it then did. The utility tool then produced seven SSF files relating to the seven ES.

The NMTA file and DXF files were then passed onto maritimeEXODUS which then imported the design. maritimeEXODUS then developed the geometry using its newly constructed 'automatic node flood' operation. Once the mesh had been created, the user checked the geometry, making sure that the stairs and ladders were correctly connected to the decks. Following this, the user ran the simulations. The geometry was saved so that it could be reused.

Within maritimeEXODUS, batch mode was employed to carry out the simulations for each scenario. Batch mode was configured to read in the geometry and then the SSF file. It would then run the simulations 5 times before deleting the population and reloading the SSF file and running the simulations again. A total of 50 simulations were performed for each scenario for each design. This enabled a representative distribution of results to be produced.

Once all the simulation runs were performed for every scenario for each design, the HPM Analyser was used to select the representative output file for each scenario. The HPM structure for each design was defined and the representative output files for each scenario read in. The HPM Analyser then normalised the HPM and produce all the output files to be sent back to the naval architect and PARAMARINE. An example is shown in Figure 11.6-1. This includes the KCL file required to recreate the HPM tables within PARAMARINE and the

CSV files required for UCL to create a 3D visualisation in VRML of all the results produced by maritimeEXODUS and the HPM Analyser.

maritimeEXODUS then replayed the representative simulation run and the graphical GIF and JPEG output files were generated which illustrated the common footfall contour map produced by maritimeEXODUS as a JPEG picture as well as the population density as a GIF animation.

11.6 The Results and Analysis

The seven evaluation scenarios (i.e. ES_1 - ES_7) were each run 50 times and representative simulation result files were selected for each scenario to construct the HPM for each variant. The PMs for each variant were then determined and the final HPM constructed for each variant as shown in Table 11.6-1 and Table 11.6-2.

Table 11.6-1- HPM for Single Passageway variant 1

Variant 1 Design								
Evaluative scenario	**Functional Groups**						**Scenario Score**	**Scenario Weight**
	FG₁		**FG₂**		**FG₃**			
	weight	**score**	**weight**	**score**	**weight**	**score**		
Normal Day Cruising A	1	44.90	0	0	0	0	44.90	1
Normal Day Cruising B	1	49.86	0	0	0	0	49.86	1
Action Stations Evacuation	1	49.43	0	0	0	0	49.43	1
State 1 Preps	0.5	60.79	0.5	62.05	0	0	61.42	1.5
Blanket Search	0	0	1	78.59	0	0	78.59	1.5
Family Day A	0.5	50.37	0	0	0.5	40.52	45.44	1.5
Family Day B	1	56.63	0	0	0	0	56.63	1.5
Overall Performance of Functionality Groups	312.50		164.42		30.39			
			Overall Performance of design				507.3	

Table 11.6-2 - HPM for Double Passageway variant 2

Variant 2 Design								
Evaluative scenario	**Functional Groups**						**Scenario Score**	**Scenario Weight**
	FG₁		**FG₂**		**FG₃**			
	weight	**score**	**weight**	**score**	**weight**	**score**		
Normal Day Cruising A	1	47.76	0	0	0	0	47.76	1
Normal Day Cruising B	1	46.05	0	0	0	0	46.05	1
Action Stations Evacuation	1	48.42	0	0	0	0	48.42	1
State 1 Preps	0.5	78.28	0.5	76.54	0	0	77.41	1.5
Blanket Search	0	0	1	85.96	0	0	85.96	1.5
Family Day A	0.5	54.40	0	0	0.5	40.98	47.69	1.5
Family Day B	1	53.40	0	0	0	0	53.40	1.5
Overall Performance of Functionality Groups	321.84		186.34		30.74			
			Overall Performance of design				538.9	

From Table 11.6-1 and Table 11.6-2, it can be seen that the single passageway variant 1 design has the lower overall vessel performance score of 507.2, compared to 538.9 for variant 2, and therefore can be considered the better design. This equates to variant 1 being considered 5.9% more efficient out of the two designs in terms of their HF performance.

Table 11.6-3 - Scenario scores for variant 1 and variant 2

Evaluative scenario	Scenario Weight	Variant 1	Variant 2	% difference between Variant 1 and Variant 2
Normal Day Cruising A	1	44.90	47.76	-6.4%
Normal Day Cruising B	1	49.86	46.05	7.6%
Action Stations Evacuation	1	49.43	48.42	2.0%
State 1 Preps	1.5	61.42	77.41	-26.0%
Blanket Search	1.5	78.59	85.96	-9.4%
Family Day A	1.5	45.44	47.69	-5.0%
Family Day B	1.5	56.63	53.40	5.7%
Overall Performance of design		507.3	538.9	

Table 11.6-3 shows how the variant 1 design out performed variant 2 in 5 of the seven ES; with its best performing scenario being the 'State 1 Preps' ES, returning a 26% better score. The variant 1 design's worst performing ES was the 'Normal Day B' scenario, returning a 7.6% inferior performance.

Having identified the worst performing scenario for variant 1, we can now examine the HPM in more detail and interrogate the PM for the ES. The aim of this is to see why variant 1 did not perform as well as variant 2 in this ES and to hopefully identify any scope for improvement to the design.

Table 11.6-4 - PM for FG_1 during 'Normal Day Cruising B'

FG_1 – Entire Population		Variant 1		Variant 2	
	Weight	raw	Norm	raw	norm
CONGESTION CRITERIA					
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'	8	5	1	2	0.40
C_2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	55.15	0.83	66.77	1
GENERAL CRITERIA					
G_1 – average time required to complete all operations;	4	211.4	1	208.0	0.98
G_2 – average time spent in transition	3	40.18	0.97	41.22	1
G_3 – time to reach final state	8	563.0	0.19	611.3	0.20
G_4 – Average time spent in congestion	3	102.4	1	93.86	0.92
G_5 – average distance travelled	4	42.91	0.92	46.73	1
GEOMETRIC CRITERIA:					
M_1 – the number of WTD used during the scenario.	2	14	0.61	23	1
M_2 – the number of Hatches used during the scenario.	2	23	1	17	0.74
M_3 – the number of ladders used during the scenario.	2	22	1	17	0.77
M_5 – the number of doors used during the scenario.	1	47	0.90	52	1
M_8 – the number of times the FG moved between decks	2	362	1	343	0.95
M_{13} – Average number of components used per member of FG during the scenario	2	3.90	0.97	4.02	1
M_{14} – Most times a WT door was operated	4	9	0.90	10	1
M_{15} – Most times a hatch was operated	3	6	0.86	7	1
M_{16} - Average number of doors used per person	3	1.47	1	1.16	0.79
M_{17} - Average number of WT doors per person	3	1.05	0.68	1.55	1
M_{18} - Average number of hatches used	3	0.24	1	0.18	0.75

The analysis of the PM for the 'Normal Day Cruising' scenario highlighted that there is a high level of congestion. From C_1, both designs would fail to comply with the IMO regulations (IMO, 2007), since variant 1 showed 5 severely congested regions and variant 1 has 2 regions of severe congestion. Both designs do however comply with the IMO regulations in terms of the final evacuation time, G_3, with both variants completing the scenario at least 80% inside the regulatory specified limit.

It can be seen from Table 11.6-4, that there are less ladders (M_3) used during the 'Normal Day Cruising' scenario in the variant 2 design. This is rather strange since the variant 2 design has an additional passageway running from the forward section of the vessel to the aft; to make best possible use of this extra passageway, it would be expected that each passageway would have their own set of deck connections. This would lead to the variant 2 design having more ladders which the population could utilise and more access routes to other decks.

The population in the single passageway variant 1 design do however use 40% less WT doors than the population in the double passageway variant 2 design, as measured by M_1. This is to be expected since variant 1 has fewer passageways which stretch across WT zones.

The results of the HPM were sent to PARAMARINE from the HPM Analyser, where they were displayed to the designer. Figure 11.6-1 illustrates the HPM results as presented to the designer. Figure 11.6-1 shows two of the seven graphs sent to PARAMARINE relating to the times when each individual completed their part of the scenario. Both graphs plot the number of people to have completed the scenario (X-axis) against the time in seconds (Y- axis).

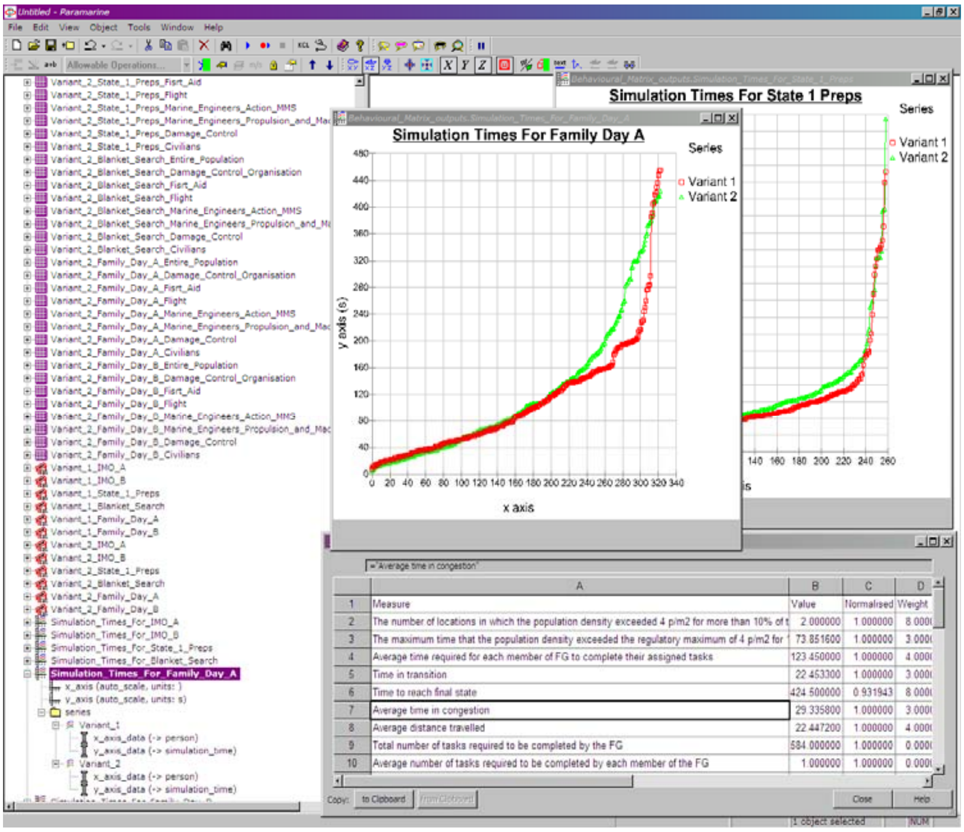


Figure 11.6-1 - HPM results as seen in PARAMARINE

11.7 Discussion of results

This example application has demonstrated the general methodology for the Human Performance Metric (HPM) in evaluating HF performance of competing ship designs. The use of the methodology has been 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 single passageway variant was identified as the superior design on the basis of seven evaluation scenarios, three evacuation scenarios and four NOP scenarios.

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 used to challenge the vessel (i.e. the evaluation scenarios) are changed, it is possible that a different result would be obtained.

The example has distinguished between the two variant designs and suggested the single passageway variant 1 design was marginally the better design in terms of its human factors' performance. However, it was identified how the second variant had two passageways therefore should have a greater number of WT doors to uphold WT integrity and a greater number of deck connections to supply both passageways with a means of travelling from one deck to another. As was seen, both from the designs and the HPM, there were indeed a greater number of WT doors in the design but there were fewer number of deck connections. This leads to the conclusion that if there had been the correct number of deck connections or even if there had been at least two deck connections within each WT zone, where each deck connection supplies a vertical access for each passageway, then the population would not have to travel so far in order to move between decks.

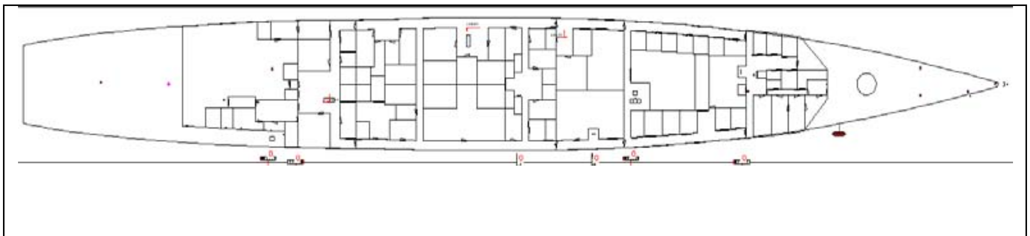
11.8 Modifications to the double passageway variant design – implementing the correct number of deck connections

11.8.1 The vessel designs

After consultations between the university project partners, the HPM results and work from the first section of this chapter were presented to the UCL team along with the conclusions drawn and the suggestion to add additional deck connections. Suggestions as to where these deck connections should be were also provided. The project partners agreed to these extra deck connections and stated that all these deck connections should be ladders rather than 60 degree stairs.

With this agreed, the second variant was modified with decks No 1 and No 2 having the additional ladders installed connecting them to the other decks. The final design can be seen in Table 11.8-1, the three newly installed ladders have been highlighted.

With the new variant 2 design modified, the simulations for each of the seven defined ES were repeated. There was no need to perform the simulations for the variant 1 design since this did not change and therefore the raw data values for the PMs would not change. Once the simulations had been carried out on the modified variant 2 design, the HPM was constructed, using the HPM Analyser, as before and the results interrogated. Even though the raw data values for the variant 1 design did not change, the design's normalised values would be different since it is being compared against a different design.



(a) No 1 Deck of variant 2

(b) No 2 Deck of variant 2

Table 11.8-1 - Layout of the modified variant 2 design.

11.8.2 The Results

The results presented here are the same as those presented in Chapter 9. Although the analysis performed here was part of the integrated design cycle rather than using the HPM concept as a stand alone system.

With the simulations performed for the modified variant 2 design, the HPM was created by the HPM Analyser the results of which are shown in Table 11.8-2 and Table 11.8-3. By inserting the additional ladders into the double passageway variant 2 design, the gap between the HF performance results had narrowed. Without the extra ladders, there was a 5.86% difference between the two design variants, with variant 1 producing an overall score of 507.3

and variant 2 producing an overall score of 538.9. Now with the extra ladders, there was just a 1.41% difference between the two designs in terms of their human factors' performance. This is a direct result of adding the three extra ladders.

It is interesting to note that although the overall vessel performance score for the double passageway variant 2 design decreased with the addition of ladders as expected, the score for the single passageway variant 1 design actually increased. This is due to some of the PM in the variant 2 design which were poorer than their respective PM in the variant 1 design improving significantly enough to outperform those in the variant 1 design.

Table 11.8-2 - HPM for variant 1

Variant 1 Design								
Evaluative scenario	**Functional Groups**						**Scenario Score**	**Scenario Weight**
	FG_1		**FG_2**		**FG_3**			
	weight	**score**	**weight**	**score**	**weight**	**score**		
Normal Day Cruising A	1	46.14	0	0	0	0	46.14	1
Normal Day Cruising B	1	50.81	0	0	0	0	50.81	1
Action Stations Evacuation	1	51.45	0	0	0	0	51.45	1
State 1 Preps	0.5	67.01	0.5	67.91	0	0	67.46	1.5
Blanket Search	0	0	1	78.04	0	0	78.04	1.5
Family Day A	0.5	55.88	0	0	0.5	41.43	48.65	1.5
Family Day B	1	56.03	0	0	0	0	56.03	1.5
Overall Performance of Functionality Groups	324.61		167.99		31.07			
			Overall Performance of design				523.7	

Table 11.8-3 - HPM for modified variant 2

Variant 2 Design								
Evaluative scenario	**Functional Groups**						**Scenario Score**	**Scenario Weight**
	FG_1		**FG_2**		**FG_3**			
	weight	**score**	**weight**	**score**	**weight**	**score**		
Normal Day Cruising A	1	44.33	0	0	0	0	44.33	1
Normal Day Cruising B	1	46.79	0	0	0	0	46.79	1
Action Stations Evacuation	1	46.70	0	0	0	0	46.70	1
State 1 Preps	0.5	75.20	0.5	75.74	0	0	75.47	1.5
Blanket Search	0	0	1	84.29	0	0	84.29	1.5
Family Day A	0.5	51.05	0	0	0.5	43.35	47.20	1.5
Family Day B	1	55.32	0	0	0	0	55.32	1.5
Overall Performance of Functionality Groups	315.49		183.24		32.51			
			Overall Performance of design				531.2	

Having seen the final HPMs for both design variants and having identified variant 1 as being marginally the better design, it would be useful to examine the matrices in more detail to see if there were any interesting results from the HPM sub components which could be used to improve the performance of the identified 'best' design. As a starting point Table 11.8-4 compares ES scores, showing the percentage difference between the two design variants. The table also displays the percentage between the ES when the original variant 2 (i.e. less ladders) was compared against the variant 1 design.

Table 11.8-4 - Scenario Scores for variant 1 and modified variant 2.

Evaluative scenario	Scenario Weight	Variant 1	Modified Variant 2	% difference between Variant 1 and Modified Variant 2	% difference between Variant 1 and Variant 2
Normal Day Cruising A	1	46.14	44.33	3.9%	-6.4%
Normal Day Cruising B	1	50.81	46.79	7.9%	7.6%
Action Stations Evacuation	1	51.45	46.70	9.2%	2.0%
State 1 Preps	1.5	67.46	75.47	-11.9%	-26.0%
Blanket Search	1.5	78.04	84.29	-8.0%	-9.4%
Family Day A	1.5	48.65	47.20	3.0%	-5.0%
Family Day B	1.5	56.03	55.32	1.3%	5.7%
Overall Performance of design		523.7	531.2		

As can be seen from Table 11.8-4, 'State 1 Preps' is variant 1's best performing ES, outperforming variant 2 by 12%. However, although this was the best ES when the original variant 2 design was utilised the difference is not so great. The difference between the two designs was 26% but has now been more than halved to 12%. This is directly due to the additional ladders inserted into the double passageway variant 2 design.

Variant 1's worst performing design was the 'Action Stations Evacuation' ES where it was 9% less efficient than variant 2. This is interesting since the worst performing ES using the original variant 2 was 'Normal Day Cruising B'.

Table 11.8-4 shows how six of the seven ES in the double passageway variant 2 design have improved their performance with the addition of the extra deck connections. This consequently means that six of the seven ES in variant 1 now achieves a worse performance than they did when compared to the original variant 2 design (i.e. less the additional ladders). This is a result of the newly modified variant 2 design having the extra deck connections providing more access routes. However, as a result of the additional ladders, the gap between the HF performance of the two design variants has narrowed but the single passageway variant is still marginally considered the better design.

Having now established that the single passageway variant is the 'best' design, it would now be interesting to understand why it outperformed the double passageway variant. It has been identified that the 'Action Stations Evacuation' ES was the poorest of all the ES for the single passageway variant and therefore further examination of this ES may potentially lead to improvements to the design.

To better understand why variant 2 out performed variant 1 in the 'Action Stations Evacuation' scenario (ES_3) and to identify potential areas in which variant 1 can be further improved it is necessary to examine the sub-components of the HPM in more detail. Presented in Table 11.8-5 are the PM scores for variant 1 and 2 for ES_3. We note that variant 1 performed better than variant 2 in five of the 18 PMs (G_2, G_5, M_1, M_{14} and M_{16}). Of these five PMs, four show at least 10% better performance than the respective variant 2 PM, with M_{14} (most times a WT door was operated) and M_{16} (average number of doors used per person) returning 18% better performance. However, 12 of the PMs for variant 1 returned poorer performance. Of these PMs nine returned values which were at least 10% worse than those in variant 2. The poorest performance was achieved by G_4 (average time spent in congestion) which returned 50% worse performance.

It is interesting to note that the poor return produced by variant 2 for M_1 (number of WT doors used in the scenario) 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 watertight integrity and so is dictated by a design constraint which cannot be violated. However, even with these additional WT doors, 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 6% further (as measured by G_5) in order to complete their tasks. This additional distance is reflected in the time spent traversing the variant 2 geometry which is 20% longer than in variant 1 (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.

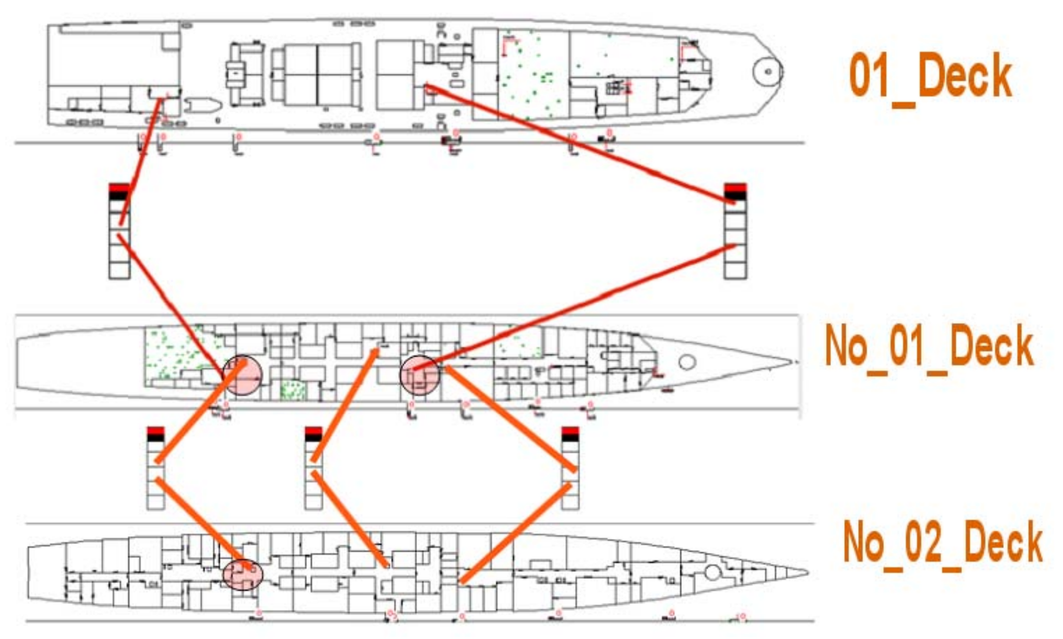
Table 11.8-5 - variant 1 and variant 2 PM results for FG_1 in ES_3.

FG_1 – Entire Population		Variant 1		Variant 2	
	Weight	raw	norm	raw	norm
CONGESTION CRITERIA					
C1 – the number of locations in which the population density exceeds 4 p/m^2 for more than 10% of the overall scenario time'	8	4	1	4	1
C2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	75.40	1	42.14	0.56
GENERAL CRITERIA					
G1 – average time required to complete all operations;	4	256.7	1	193.54	0.75
G2 – average time spent in transition	3	36.61	0.80	45.76	1
G3 – time to reach final state	8	666.7	0.22	594.50	0.20
G4 – Average time spent in congestion	3	150.6	1	74.93	0.50
G5 – average distance travelled	4	47.11	0.94	50.11	1
GEOMETRIC CRITERIA:					
M1 – the number of WTD used during the scenario.	2	24	0.89	27	1
M2 – the number of Hatches used during the scenario.	2	31	1	25	0.81
M3 – the number of ladders used during the scenario.	2	31	1	25	0.81
M5 – the number of doors used during the scenario.	1	78	1	76	0.97
M8 – the number of times the FG moved between decks	2	373	1	322	0.86
M13 – Average number of components used per member of FG during the scenario	2	4.47	1	4.36	0.98
M14 – Most times a WT door was operated	4	9	0.82	11	1
M15 – Most times a hatch was operated	3	10	1	7	0.70
M16 - Average number of doors used per person	3	1.59	0.82	1.94	1
M17 - Average number of WT doors per person	3	1.46	1	1.19	0.82
M18 - Average number of hatches used	3	0.27	1	0.23	0.83

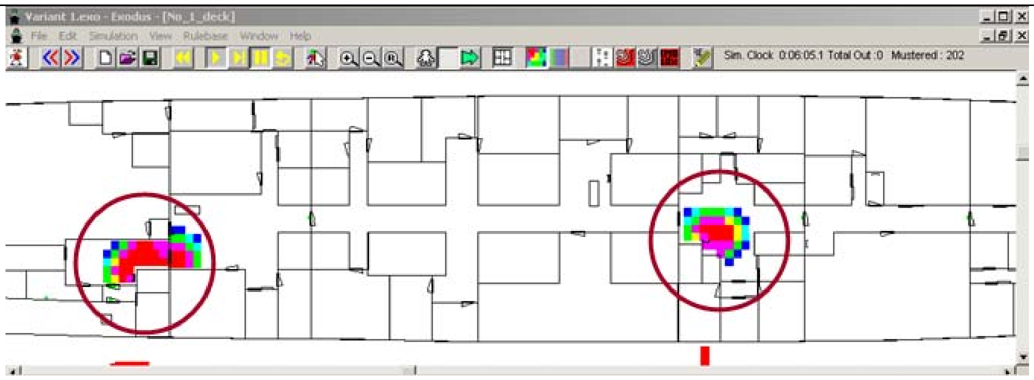
We note that for variant 2, the overall average time spent in congestion (as measured by G_4) was some 50% less than in variant 1. This significant reduction in congestion results in variant 2 being able to complete the scenario 11% quicker than variant 1 (as measured by G_3). Indeed, we note that while both vessels easily satisfy the international set evacuation time requirements (as measured by G_3) the levels of congestion experienced exceed the international set limits in four locations (as measured by C_1) and variant 1 experiences the most severe congestion (as measured by C_2). As the values for C_1 and C_2 are higher than the regulatory limits, neither vessel would be deemed to be acceptable. To address this issue and to improve the overall performance of variant 1, further investigation is required to uncover the causes of the severe congestion.

Further to this point, it could be suggested that improving the congestion experienced by the population in the single passageway variant 1 design could be the way forward in terms of improving the HF performance of the vessel.

After examining the graphical outputs of maritimeEXODUS, i.e. the GIF animation of the population density contour and the JPEG image of the IMO congestion regions, three areas of severe congestion were identified, see Figure 11.8-1.



(a) Location of Severely Congested Regions



(b) IMO congestion contour as seen in maritimeEXODUS for No 1 Deck

Figure 11.8-1 - Location of Severely Congested Regions

Figure 11.8-1 shows the location of two severely congested regions on the No 1 Deck and a third severely congested region on the No 2 Deck. All three of these congestion regions are located at the base of ladders. Interestingly it can be observed from Figure 11.8-1(a) how there are three ladders connecting No 2 Deck to No 1 Deck but there are only two ladders connecting No 1 Deck to 01 Deck. This could explain the reason why congestion was building on the No 1 Deck. As the majority of the population were on the lower decks and their target location was the outer deck of 01 Deck, they would be able to use three ladders to get from No 2 Deck to No 1 Deck but then would be forced to use only two ladders to get to their destination. This would inevitably cause a bottleneck around the deck connections, which has escalated down to the No 2 Deck.

In response to this, it was suggested that an additional ladder should be inserted between the two existing ladders connecting No 1 Deck to No 2 Deck. The bottom of the ladder would be located mid way between the two severe congestion regions located on the No 1 Deck with the aim of attracting crew members away from the two severely congested regions. The addition of this ladder could also have further implications to the scenario. The WT compartment on the No 1 Deck located between the two severely congested regions has a ladder coming up from the deck below but has no connectivity to the deck above. This caused crew coming up from the deck below to move out of the WT compartment in order to progress to the upper deck. By inserting an extra ladder in the position described, crew would not have to move out of the WT compartment. This would also mean that they could a) take a more direct route to their destination and b) would not use as many WT doors.

11.8.3 Predicting the affect of an additional ladder – A HPM sensitivity study

Before making any changes to the selected design variant, it would be interesting, and useful, to know whether the extra effort is worthwhile or not. The aim of the ladder is to reduce the number of severely congested regions which occur during the ‘Action Stations Evacuation’ ES for the single passageway variant design.

As such the performance measure of interest would be 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) which has a weight of 8 and a normalised value of 1 (this is also the normalised value for the double passageway variant). The ‘Action Stations Evacuation’ ES produced a scenario score of 51.45. If it was suggested that the normalised value for C_1 could be halved, which means in effect that 2 regions of severely congested regions (C_1 raw data value = 4) are eliminated from the ‘Action Stations Evacuation’ ES, then the equation would be:

$$\frac{SS_2 - SS_1}{SS_1} = \frac{-\frac{X}{100}\times W \times PM}{SS_1}\times 100 = \frac{-\frac{50}{100}\times 8\times 1}{51.45}\times 100 = -7.78\%$$

Equation 11.8.1

From this it can be predicted that if it was possible to halve the number of severely congested regions during the ‘Action Stations’ Evacuation ES then there should be at the very least a 7.78% improvement in the design’s abilities to complete the scenario.

It would also be interesting and perhaps more useful to know what possible improvement or hindrance the ladder may have on the overall design before going ahead and making the change. For this, Equation (5.4.6) from Chapter 5 was used. The equation required the normalised PM score and the PM’s weight and in addition it also required the overall vessel performance score and the ES weight. In the case of the ‘Action Stations Evacuation’ ES, it had a weighting of 1 and the overall vessel performance score for the single passageway variant was 523.68. When all this information was put in to the equation, the following was produced

$$\frac{V_2 - V_1}{V_1} = \frac{-W_{ss}\left(\frac{X}{100}\times W \times PM\right)}{V_1}\times 100 = \frac{-1\left(\frac{50}{100}\times 8\times 1\right)}{523.68}\times 100 = -1.65\%$$

Equation 11.8.2

It can therefore be predicted that by halving the number of severely congested regions in the ‘Action Stations Evacuation’ ES would improve the design’s HF performance by 1.65%. This may seem to be a very small number, but in fact it would not be known how the ladder would affect other PMs in the ES or indeed how the ladder would affect the other ES.

It must be stressed that these predictions only take into account one performance measure and so do not show how one PM has an effect on other PMs in the same scenario or in other ESs. The following section (Section 11.9) assesses the impact the ladder has on the HPM and whether halving the number of severely congested regions (C_1) can have a significant impact on the human factors' performance of the design.

11.9 Modifications to the single passageway variant 1 design – Implementing an additional ladder

11.9.1 Introduction

After interrogating the HPMs for the single passageway variant 1 and the double passageway variant 2 design it was discovered that variant 1 had the superior human factors' performance and as such was deemed the best design in terms of its HF. When examining the HPMs in more detail, it was noticed that there was a significantly greater level of congestion being experienced in the variant 1 design during its worst performing ES 'Action Stations Evacuation'. On closer inspection, it was found that congestion was building up around the base of the ladders. It was also identified that there were only two ladders connecting the No 1 Deck to 01 Deck whereas there were three connecting the No 1 Deck to No 2 Deck. As a result it was suggested that an additional ladder should be inserted in an attempt to alleviate the congestion and improve the overall HF performance of the single passageway variant 1 design.

The ladder was placed into the geometry as indicated by Figure 11.9-1; the newly created ladder has blue lines connecting the No 1 Deck to the 01 Deck and is the middle of the three ladders in Figure 11.9-1 connecting these two decks. The "No" in the naming of the decks specifies that the deck is below the outer deck, as such in Figure 11.9-1 "01 Deck" is the first outer deck above the waterline and "No 01 Deck" is the first deck below the waterline.

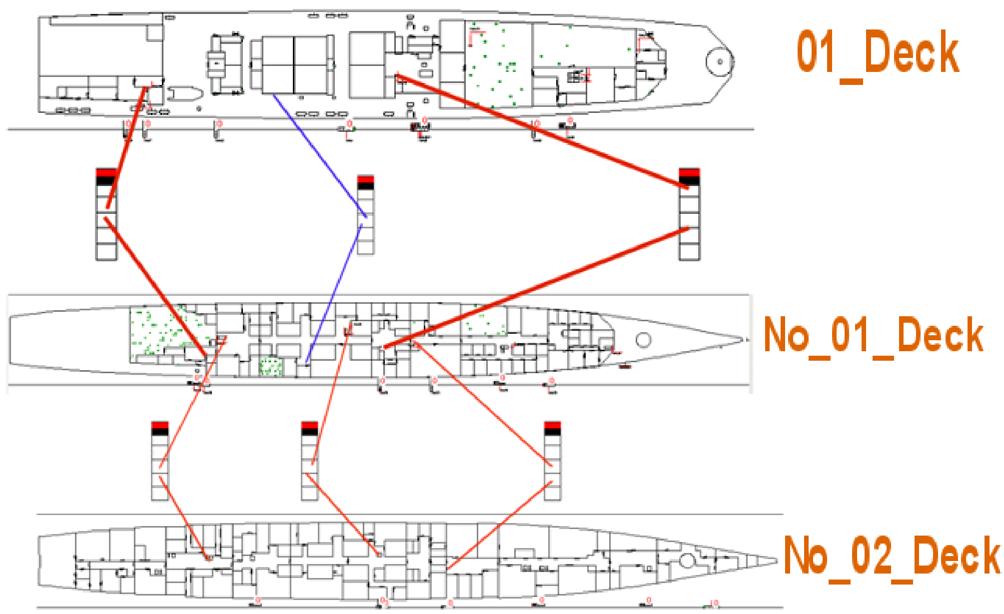


Figure 11.9-1 - Variant 1 with Additional Ladder Inserted

With the suggested ladder in place, effectively a new variant design was formed. This new design variant was labelled ‘variant 3’. The simulations were performed on the variant 3 design in an identical fashion as was used to assess the variant 1 and variant 2 designs. With the simulations performed, the HPM was created using the HPM Analyser, which compared the newly created variant 3 design against its predecessor variant 1, and then compared the variant 3 design against the double passageway variant 2 design.

The following sections report the findings of the analysis comparing variant 3 to variant 1 and variant 2.

11.9.2 The HPMs for variant 1 and variant 3

With the seven ES having been simulated on the variant 3 design and a representative file selected for each ES, the HPMs were created for the original single passageway variant 1 design and the modified single passageway variant 3 design. These HPMs can be seen in Table 11.9-1 and Table 11.9-2.

Table 11.9-1 - HPM for variant 1

Variant 1 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	47.81	0	0	0	0	47.81	1
Normal Day Cruising B	1	51.62	0	0	0	0	51.62	1
Action Stations Evacuation	1	52.78	0	0	0	0	52.78	1
State 1 Preps	0.5	74.30	0.5	77.59	0	0	75.95	1.5
Blanket Search	0	0	1	86.25	0	0	86.25	1.5
Family Day A	0.5	56.40	0	0	0.5	48.17	52.28	1.5
Family Day B	1	57.57	0	0	0	0	57.57	1.5
Overall Performance of Functionality Groups	336.58		187.30		36.13			
			Overall Performance of design				560.3	

Table 11.9-2 - HPM for variant 3

Variant 3 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	Score		
Normal Day Cruising A	1	46.59	0	0	0	0	46.59	1
Normal Day Cruising B	1	44.98	0	0	0	0	44.98	1
Action Stations Evacuation	1	44.68	0	0	0	0	44.68	1
State 1 Preps	0.5	70.10	0.5	76.76	0	0	73.43	1.5
Blanket Search	0	0	1	85.45	0	0	85.45	1.5
Family Day A	0.5	55.73	0	0	0.5	43.37	49.55	1.5
Family Day B	1	53.57	0	0	0	0	53.57	1.5
Overall Performance of Functionality Groups	312.99		185.71		32.52			
			Overall Performance of design				529.2	

By introducing the single ladder in a strategic position, it has been possible to improve the single passageway design by 5.6% as seen from the comparison of the overall vessel performance score for variant 1 (560.3) and the improved variant, variant 3 (529.2). This is quite a significant difference by doing only a small amount of work.

Table 11.9-3 - Comparison of ES Score between variant 1 and variant 3

Evaluative scenario	Scenario Weight	Variant 1	Variant 3	% difference between Variant 1 and Modified Variant 2
Normal Day Cruising A	1	47.81	46.59	-2.6%
Normal Day Cruising B	1	51.62	44.98	-12.9%
Action Stations Evacuation	1	52.78	44.68	-15.3%
State 1 Preps	1.5	75.95	73.43	-3.3%
Blanket Search	1.5	86.25	85.45	-0.9%
Family Day A	1.5	52.28	49.55	-5.2%
Family Day B	1.5	57.57	53.57	-6.9%
Overall Performance of design		560.3	529.2	

The additional ladder inserted into the single passageway variant 1 design has significantly improved its HF performance in the ‘Action Stations Evacuation’ ES, giving arise to a 15% improvement. In fact inserting the one ladder has improved the vessel’s design across the board. The improvement is not so great in the ‘Blanket Search’ ES, producing a mere 1% improvement, however there are only 8 crew members moving about the vessel during this ES and of these eight, only two would use this additional ladder while searching that particular WT zone. The greatest improvement was seen in the ‘Action Stations Evacuation’ ES but there were also significant gains in performance for the ‘Normal Day Cruising B’, ‘Family Day A’ and ‘Family Day B’ ES returning 13%, 5% and 7% better performances in the design variant which included the extra ladder.

Further to this, when the ‘Action Stations Evacuation’ ES is further examined, in Table 11.9-4, it can be observed how the level of congestion has greatly improved.

Table 11.9-4 - PM Scores for Entire Population during the 'Action Stations Evacuation' ES

FG_1 – Entire Population		Variant 1		Variant 3	
	Weight	raw	norm	raw	norm
CONGESTION CRITERIA					
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'	8	4	1	2	0.50
C_2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	75.40	1	64.21	0.85
GENERAL CRITERIA					
G_1 – average time required to complete all operations;	4	256.7	1	217.1	0.85
G_2 – average time spent in transition	3	36.61	0.80	45.79	1
G_3 – time to reach final state	8	666.7	0.22	651.0	0.22
G_4 – Average time spent in congestion	3	150.6	1	105.5	0.70
G_5 – average distance travelled	4	47.11	1	45.62	0.97
GEOMETRIC CRITERIA:					
M_1 – the number of WTD used during the scenario.	2	24	1	23	0.96
M_2 – the number of Hatches used during the scenario.	2	31	1	31	1
M_3 – the number of ladders used during the scenario.	2	31	1	31	1
M_5 – the number of doors used during the scenario.	1	78	1	71	0.91
M_8 – the number of times the FG moved between decks	2	373	1	371	0.99
M_{13} – Average number of components used per member of FG during the scenario	2	4.47	1	3.98	0.89
M_{14} – Most times a WT door was operated	4	9	0.9	10	1
M_{15} – Most times a hatch was operated	3	10	1	5	0.5
M_{16} - Average number of doors used per person	3	1.59	1	1.42	0.89
M_{17} - Average number of WT doors per person	3	1.46	1	1.14	0.78
M_{18} - Average number of hatches used	3	0.27	1	0.27	0.97

The key point to observe here is that two of the severely congested regions which existed during the 'Action Stations Evacuation' ES have been eradicated as is illustrated by Figure 11.9-2 and Table 11.9-5. Figure 11.9-2 shows how the region of severe congestion on No 2

Deck has disappeared as too has the left area of congestion on the No 1 Deck. Table 9.5-5 illustrates not only how the left congestion region has been eliminated but it also shows the significant reduction in the severity of the congestion in the region which still exists on the No 1 Deck.

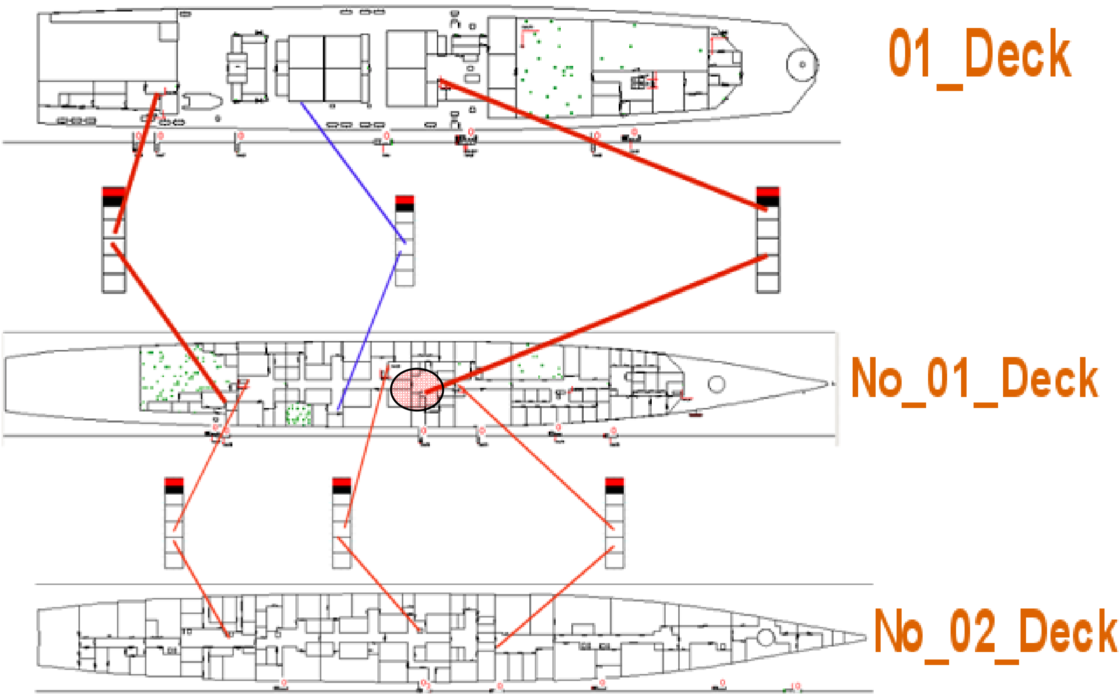
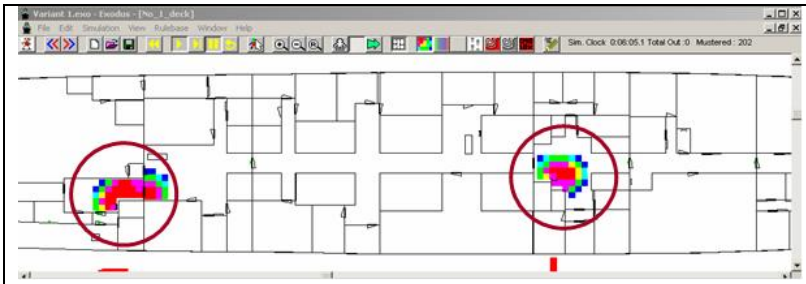
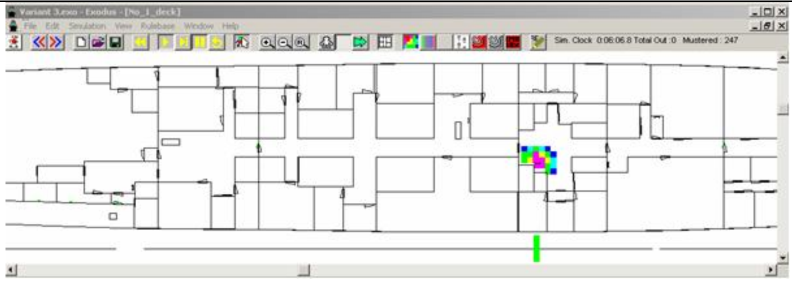


Figure 11.9-2 - Areas of severe congestion on the variant 3 design

Table 11.9-5 - Severe congestion during Action Stations Evacuation ES

	Areas of severe congestion located on No 1 Deck in variant 1 during the 'Action Stations Evacuation' ES
	Areas of severe congestion located on No 1 Deck in variant 3 during the 'Action Stations Evacuation' ES

11.9.3 A comparison between expected results and actual results following the addition of an extra ladder

The aim of inserting an additional ladder in to the single passageway variant was to decrease the level of congestion experienced by the population during the 'Action Stations Evacuation' scenario. The prediction had been made that if the extra ladder was able to halve the number of severely congested regions in this scenario, then the design would be 7.78% more efficient in terms of its human factors' performance during the 'Action Stations Evacuation' scenario and 1.65% more efficient overall.

Once the scenarios had been performed in maritimeEXODUS and the simulation outputs analysed, it was found that the addition of the ladder between No 1 Deck and 01 Deck improved the HF performance of the vessel in the 'Action Station Evacuation' scenario by 15.3% and improved the overall HF performance of the vessel by 5.6%.

This illustrates that the extra ladder has had more of a positive result on the 'Action Stations Evacuation' scenario than had been expected. Since the targeted PM, C_1, did have its normalised value halved then it could be suggested that the additional ladder may well have had a positive effect on one or more of the other performance measures. On closer inspection, it could be seen that not only was there a large difference in the number of severely congested regions (50% reduction), but the average level of congestion experienced by the population was also significantly reduced (by 30%). This meant that the population on average were not slowed down so much and as a result were able to complete their assigned tasks more efficiently which also has the impact of the scenario being completed in less time.

The additional ladder had a very positive effect on the overall HF performance of the vessel, far surpassing the 1.65% predicted improvement; returning a 5.6% superior performance. This is because the ladder created other access routes for the population to use to move between decks during the other six scenarios. This resulted in shorter travel distances for the population, which may only be slightly shorter but required less distance to travel which consequently took less time to travel, thus each individual completed their tasks in a shorter amount of time and the scenario as a whole was completed in less time. The new access route would also require the crew members to use less WT doors and non-WT doors since they would not have to move out of the WT compartment in order to travel between decks.

11.9.4 The HPMs for variant 3 and variant 2

Having now improved the variant 1 design by 5.6% with the introduction of a single ladder, it was felt that it would be of interest to make a comparison between the modified single passageway variant and the double passageway variant. This would not be necessary normally but for the purposes of demonstrating the HPM concept this analysis is performed.

No more simulations were required to compare these two designs, since they have all been performed for the purpose of other analyses. Therefore this analysis merely required using the HPM Analyser to create the HPMs. Table 11.9-6 and Table 11.9-7 show the overall HPM for the modified single passageway variant 3 design and the double passageway variant 2 design, respectively.

Table 11.9-6 - HPM for variant 3

Variant 3 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	46.15	0	0	0	0	46.15	1
Normal Day Cruising B	1	47.74	0	0	0	0	47.74	1
Action Stations Evacuation	1	46.69	0	0	0	0	46.69	1
State 1 Preps	0.5	64.31	0.5	68.95	0	0	66.63	1.5
Blanket Search	0	0	1	80.33	0	0	80.33	1.5
Family Day A	0.5	55.71	0	0	0.5	33.88	44.80	1.5
Family Day B	1	53.04	0	0	0	0	53.04	1.5
Overall Performance of Functionality Groups	310.15		172.21		25.41			
			Overall Performance of design				507.8	

Table 11.9-7 -HPM for variant 2

Variant 2 Design	Functional Groups						Scenario Score	Scenario Weight
Evaluative scenario	FG$_1$		FG$_2$		FG$_3$			
	weight	score	weight	score	weight	Score		
Normal Day Cruising A	1	44.94	0	0	0	0	44.94	1
Normal Day Cruising B	1	48.78	0	0	0	0	48.78	1
Action Stations Evacuation	1	49.78	0	0	0	0	49.78	1
State 1 Preps	0.5	77.11	0.5	76.08	0	0	76.60	1.5
Blanket Search	0	0	1	84.74	0	0	84.74	1.5
Family Day A	0.5	51.66	0	0	0.5	47.97	49.81	1.5
Family Day B	1	57.89	0	0	0	0	57.89	1.5
Overall Performance of Functionality Groups	326.91		184.17		35.98			
			Overall Performance of design				547.1	

As can be seen from Table 11.9-6 and Table 11.9-7, the modified single passageway variant produces an overall vessel performance (VP) score of 507.8 whereas the double passageway variant produces a VP score of 547.1. This results in the modified single passageway variant having the lower overall score by 7.7% and as such it is still deemed the 'best' design.

As is illustrated in Table 11.9-8 the modified single passageway now outperforms the double passageway variant in all of the ES with the exception of the 'Normal Day Cruising A' ES. Even in this ES, the modified variant 1 design has improved its performance, just not enough to outperform variant 2.

Table 11.9-8 - Comparison of ES scores between variant 2 and variant 3

Evaluative scenario	Scenario Weight	Variant 2	Variant 3	% difference between variant 2 and Modified variant 3
Normal Day Cruising A	1	44.94	46.15	2.6%
Normal Day Cruising B	1	48.78	47.74	-2.2%
Action Stations Evacuation	1	49.78	46.69	-6.6%
State 1 Preps	1.5	76.60	66.63	-15.0%
Blanket Search	1.5	84.74	80.33	-5.5%
Family Day A	1.5	49.81	44.80	-11.2%
Family Day B	1.5	57.89	53.04	-9.1%
Overall Performance of design		547.1	507.8	

It can be seen that the 'State 1 Preps' scenario remains as the best performing scenario for the single passageway variant returning a 15% better performance; the worst performing scenario is now the 'Normal Day Cruising A' scenario returning a 2.6% inferior performance.

11.9.5 Analysis of the affect of implementing an additional ladder

Having compared the single passageway variant 1 to the double passageway variant 2 and the modified single passageway variant 3 to variant 2, it was felt that an examination of the difference the addition of the single ladder made to the human factors' performance of the designs would be of interest.

Table 11.9-9 - comparison of differences in scenario score caused by addition of ladder

Evaluative scenario	Scenario Weight	% difference between Variant 1 and Variant 2	% difference between Modified Variant 3 and Variant 2
Normal Day Cruising A	1	3.9%	2.6%
Normal Day Cruising B	1	7.9%	-2.2%
Action Stations Evacuation	1	9.2%	-6.6%
State 1 Preps	1.5	-11.9%	-15.0%
Blanket Search	1.5	-8.0%	-5.5%
Family Day A	1.5	3.0%	-11.2%
Family Day B	1.5	1.3%	-9.1%

Table 11.9-9 demonstrates how the addition of the ladder to the single passageway variant has improved the design. It can be seen that the single passageway variant outperforms variant 2 in six of the seven ES assessed; even in the ES which the single passageway did not outperform the double passageway variant (Normal Day Cruising A), it still improved its performance with the addition of the ladder, just not enough to better the performance of the double passageway variant.

The extra ladder has caused a 15.8 improvement in percentage difference between the single passageway variant and the double passageway variant for the 'Action Stations Evacuation' scenario (from +9.2% to -6.6%) which is a very significant difference. This was the largest difference caused by the addition of the ladder, which was ideal since the addition of the ladder was a result of the analysis for the 'Action Stations Evacuation' scenario. The ladder has also made a large difference to the 'Normal Day Cruising B', 'Family Day A' and 'Family Day B' scenarios returning 10.1, 14.2 and 10.4 improvements in the percentage differences seen between the single passageway and double passageway variants.

In summary, adding the extra ladder in the strategic location between the No 1 Deck and 01 Deck of the single passageway variant 1 design made an improvement to the single passageway variant in all of the scenarios assessed, and made its largest impression on the 'Action Stations Evacuation' scenario taking the single passageway variant from performing 9.2% poorer than the double passageway variant to performing 6.6% better.

11.10 Vessel designs with a lower level of detail

After having performed the evaluation of the single passageway and the double passageway variant designs, it was suggested by our university project partner that the level of detail inserted in the variant designs in order to run the analysis within maritimeEXODUS was much greater than would normally be seen at the early stages of the design cycle. This detail was required in order to provide the vessel's population with the most accurate itinerary possible, and as such objects such as lockers had been included in the design but such objects take time to implement. In response to this, a set of lower level resolution design variants were produced in PARAMARINE and sent via the project partner's spreadsheet translation program and the Scenario Generator program (as developed for this PhD thesis) to maritimeEXODUS where the same seven ES were performed. The itineraries were altered to suit the lower level of detail in the model, in many cases this simply meant that a person moved to the centre of a compartment rather than to a specific location within that compartment.

Table 11.10-1 - Comparison of level of detail required for model

	JOINT EPSRC Type 22 Batch III	UCL LCS Trimaran Design	UCL Dock Mothership Design
Design Building Blocks	461	343	226
Equipment Items	119	105	67
Connectivity Items	366	0	0

The problem that the designer has with creating a new vessel design in PARAMARINE is that during the early stages of design, the vessel would merely be made up of cuboids representing the shell of the vessel. In order for the human factors' analysis to be performed on the design, there must be connectivity between these cuboids, which means that doors, ladders and stairs need to be introduced. The data presented in Table 11.10-1 is courtesy of our UCL project partners. As can be seen from Table 11.10-1, the Type 22 Batch III frigate used in this example application requires 366 connectivity items to be inserted. The high resolution variant designs used in this example application also involved above average number of design building blocks.

As a result much of the higher detail was stripped out of the design variants, which included removing compartments. This involved merging similar spaces such as cabins into a single large compartment. This reduces the number of connectivity items and the number of building blocks, both of which would save the designer time and effort.

Having less detail in the model will affect simulating the evaluative scenarios, in some cases it may not be possible to model certain ES without appropriate detail. The ‘State 1 Preps’ ES requires crew members to circulate around the vessel and close all the WT doors, however with a number of these WT doors having been removed then the dynamics within this ES will be different between the high resolution and the lower resolution designs. In addition, it was decided that it was not worth simulating the ‘Blanket Search’ ES since there were fewer compartments to search. The difference in the detail would cause a completely different dynamic within the ES and perhaps would not be representative of the final design. Therefore this ES was removed from the human factors’ analysis for these design variants of a lesser resolution.

The lower resolution designs can be seen in Table 11.10-2 and Table 11.10-3; these illustrate the difference between the high resolution (HR) design and the lower resolution (LR) design. The large change in the resolution of the models can quite clearly be seen at the forward section (right hand side of image) of the No 1 Deck in Table 11.10-2. The difference is not so clear cut in the other decks such as the No 2 Deck in Table 11.10-3, however there are still differences.

Table 11.10-2 - Illustrated difference on No 1 Deck between HR and LR variant 1

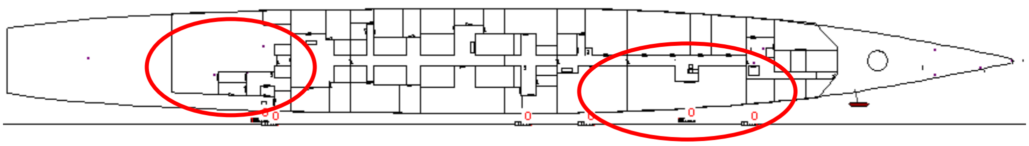
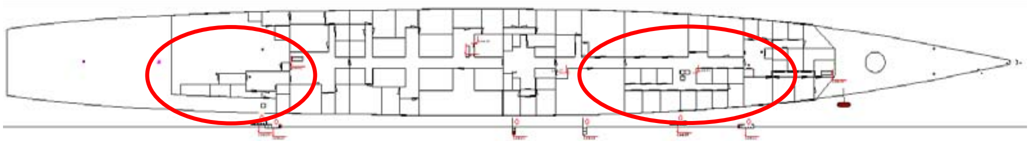
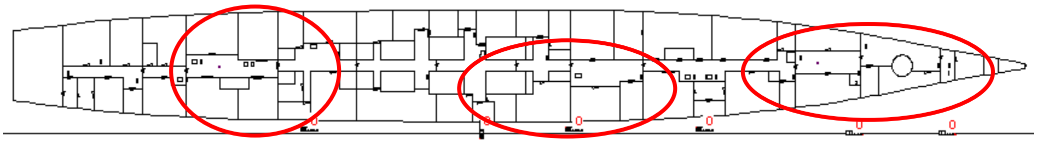
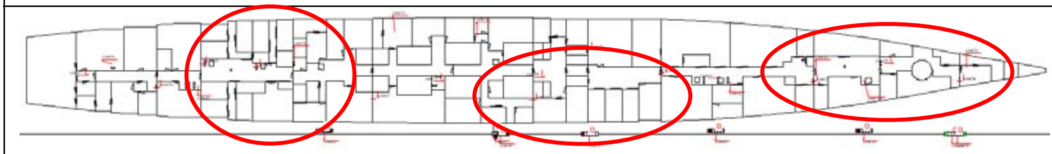
	No 1 Deck on LR variant 1
	No 1 Deck on HR variant 1

Table 11.10-3 - Illustrated difference on No 2 Deck between HR and LR variant 1

	No 2 Deck on LR variant 1
	No 2 Deck on HR variant 1

11.10.1 HPM analysis of the lower resolution variant designs

Once the LR design variants were produced, the six ES were simulated ('Normal Day Cruising A' & B, 'Action Stations Evacuation', 'State 1 Preps' and 'Family Day A' & B) using maritimeEXODUS. Once all the simulations were performed, the HPM Analyser was used to produce the HPM for each design variant. The results of this can be seen in Table 11.10-4 and Table 11.10-5. As can be seen from these tables, variant 1 produces an overall vessel performance score of 361.4 and variant 2 produces a score of 394.2. This results in variant 1 outperforming variant 2 by 9% and being deemed the best design.

Table 11.10-4 -HPM for LR variant 1

Variant 1 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG$_1$		FG$_2$		FG$_3$			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	36.12	0	0	0	0	36.12	1
Normal Day Cruising B	1	47.54	0	0	0	0	47.54	1
Action Stations Evacuation	1	46.74	0	0	0	0	46.74	1.5
State 1 Preps	0.5	56.94	0.5	63.18	0	0	60.06	1.5
Family Day A	0.5	49.52	0	0	0.5	36.61	43.06	1.5
Family Day B	1	50.90	0	0	0	0	50.90	1.5
Overall Performance of Functionality Groups	307.51		159.80		29.94			
			Overall Performance of design				361.4	

Table 11.10-5 -HPM for LR variant 2

Variant 2 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG$_1$		FG$_2$		FG$_3$			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	42.17	0	0	0	0	42.17	1
Normal Day Cruising B	1	44.70	0	0	0	0	44.70	1
Action Stations Evacuation	1	43.73	0	0	0	0	43.73	1.5
State 1 Preps	0.5	75.97	0.5	73.21	0	0	74.59	1.5
Family Day A	0.5	54.78	0	0	0.5	44.35	49.57	1.5
Family Day B	1	51.54	0	0	0	0	51.54	1.5
Overall Performance of Functionality Groups	328.28		185.37		36.26			
			Overall Performance of design				394.2	

If we now have a closer look at the HPMs and compare the ES scores for the two variant designs, we can deduce the results illustrated in Table 11.10-6. This table shows how the majority of the ES perform better in the single passageway variant 1 design. This was the case with the high resolution designs. As was the case in the higher resolution models, 'State 1 Preps' ES is the best performing scenario for variant 1 and its worst performing ES was 'Action Stations Evacuation' ES. Therefore in these general conclusions, the lower level of detail has not changed the conclusions drawn about the human factors' performance of the design variants for the Type 22 Batch III frigate.

Table 11.10-6 - Comparison of ES scores between LR variant 1 and variant 2

Evaluative scenario	Scenario Weight	variant 1	variant 2	% difference between variant 1 and Modified variant 2
Normal Day Cruising A	1	36.12	42.17	-16.7%
Normal Day Cruising B	1	47.54	44.70	6.0%
Action Stations Evacuation	1	46.74	43.73	6.4%
State 1 Preps	1.5	60.06	74.59	-24.2%
Blanket Search	1.5	43.06	49.57	-15.1%
Family Day A	1.5	50.90	51.54	-1.3%
Family Day B	1.5	36.12	42.17	-16.7%
Overall Performance of design		361.4	394.2	

From these HPM results it would be suggested that if further improvements to the 'best' design were desired then a closer look should be taken at the 'Action Stations Evacuation' ES, which was the 'best' design's (variant 1) worst performing ES. This ES may provide the greater scope for improvements since variant 2 outperformed the 'best' design and therefore the exercise is to find out why. Table 11.10-7 shows the PM scores for the Entire Population (the only FG assessed during this ES) during the 'Action Stations Evacuation' ES.

Table 11.10-7 - HPM for Entire Population during 'Action Stations Evacuation' ES

FG_1 – Entire Population		Variant 1		Variant 2	
	Weight	raw	norm	raw	norm
CONGESTION CRITERIA					
C1 – the number of locations in which the population density exceeds 4 p/m^2 for more than 10% of the overall scenario time'	8	5	1	5	1
C2 – the maximum time that the population density exceeded the regulatory maximum of 4 p/m^2 for 10% of the simulation time	3	63.52	1	50.77	0.80
GENERAL CRITERIA					
G1 – average time required to complete all operations;	4	268.3	1	179.8	0.67
G2 – average time spent in transition	3	50.99	1	49.40	0.97
G3 – time to reach final state	8	683.5	0.23	539.7	0.18
G4 – Average time spent in congestion	3	149.1	1	64.45	0.43
G5 – average distance travelled	4	50.31	0.96	52.29	1
GEOMETRIC CRITERIA:					
M1 – the number of WTD used during the scenario.	2	18	0.62	29	1
M2 – the number of Hatches used during the scenario.	2	26	0.90	29	1
M3 – the number of ladders used during the scenario.	2	26	0.90	29	1
M8 – the number of times the FG moved between decks	2	429	1	325	0.76
M13 – Average number of components used per member of FG during the scenario	2	4.88	1	4.47	0.92
M14 – Most times a WT door was operated	4	12	1	8	0.67
M15 – Most times a hatch was operated	3	5	0.83	6	1
M17 - Average number of WT doors per person	3	1.34	0.96	1.40	1
M18 - Average number of hatches used	3	0.18	0.62	0.28	1

Looking at Table 11.10-7, eight of the sixteen performance measures perform better in the variant 2 design with six of the PMs returning significantly better performances (i.e. greater than 10%). Of these 6 PMs, G_4 returns a 57% better performance while G_1 and M_{14} both return a 33% superior score.

The first observation to take note of in the above table is that both designs contain five areas of severe congestion, and since this ES is one defined by the IMO (2007) and Naval Ship Code (NATO, 2006) both of which suggest that there should not be any areas of severe congestion, then both of these variant designs would fail to comply with the regulations. This instantly provides scope for improvement and would require addressing if these designs were to be developed further.

Following this observation, it should also be noted that the population in variant 2 experience on average 57% less congestion (as measured by G_4) en-route to completing their part in the ES than the population on the variant 1 design. This illustrates a huge difference in the level of congestion experienced and goes some way towards explaining why variant 2 outperformed variant 1 in this ES.

In addition to the reduced congestion experienced by the population, the average time taken for each crew member to evacuate (as measured by G_1) is 33% and the total time for the entire population to evacuate (as measured by G_3) was 21% less in variant 2. This significant difference in the efficiency of the two performance measures can largely be accredited to the large difference in the level of congestion experienced by the population (G_4).

As a result of the much higher levels of congestion seen in the variant 1 design, if improvements were desired to the human factors' performance of the 'best' design then it would be suggested that an effort should be made to reduce the congestion, with particular attention made to the areas of severe congestion.

After some investigations, it was shown that three of the five severe congestion regions experienced in the LR variant 1 design were identical to those seen in the higher resolution variant 1 design. This could suggest that the addition of a ladder in a similar location as was carried out to create the HR variant 3 design may have the same effect in the LR variant 1 design.

In summary, it has been shown that although the low resolution design variants have quite a lot less detail in them compared to their higher resolution design variants, the same overall conclusions can be drawn as to which design variant has the better human factors' performance. Both sets of analysis (high resolution and low resolution models) showed that the single passageway variant was considered the 'best' design. However the double passageway variant did outperform the single passageway variant in the evacuation scenarios. In addition, the same ES, 'Action Stations Evacuation', was selected as the worst performing ES. As well as this, the same conclusion as to how to improve the 'best' design was identified. This analysis would suggest that the concept for assessing human factors' performance can be used at any stage of the design cycle, whether that be at an early stage of design or in a finalised state. Though, caution should be taken here, since this is just a single case. If the analysis was run again a different conclusion may be obtained. The correct walls / doors may have been removed which have not impacted the simulations greatly. If the same low resolution analysis was performed again but with a different level of detail it cannot be guaranteed that the same results would be obtained.

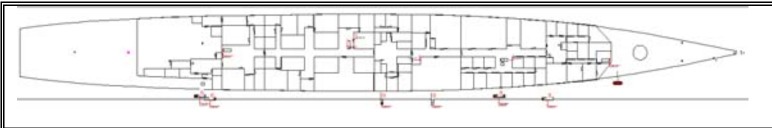
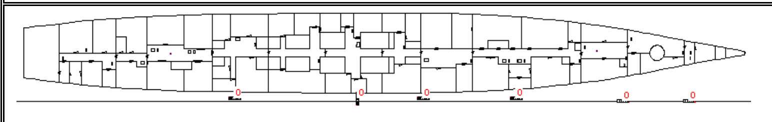
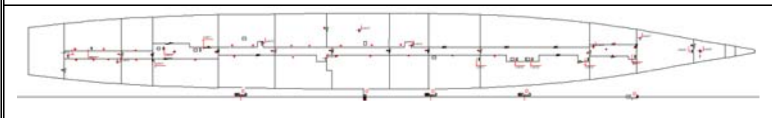
11.11 Vessel designs with a very low level of detail

Having assessed variant designs of the very highest level of resolution accomplishable in the early stages of design, it was felt of interest to see how little detail would be necessary in the design while still being able to simulate all the required scenarios. In addition, since some detail had been removed to create the low resolution models (from the high resolution models), there came about the argument as to what detail should be removed and what detail was essential.

The overall aim of this example application was to see whether the single passageway variant was more efficient in terms of human factors' than the double passageway variant. As such, both variant designs were stripped down to the very barest resolution, which consisted of the passageways and WT compartments. The compartments where the crew were placed were governed by the location, shape and size of the WT compartment and passageways encompassing them. Therefore the space formed between each WT compartment and passageway represents a block of compartments. At this very early stage of the design cycle, the designer would have a vague idea as to how many compartments there were in each block but would not be concerned with their shape or size. The designer could then add non WT doors to each compartment block, connecting them to the passageway. These doors should be evenly distanced between each other.

The very low resolution (VLR) design variants which were created for this work can be seen in Table 11.11-1.

Table 11.11-1 - comparison of LR and VLR variant 1 design

	Low Resolution variant 1, No 1 Deck
	Very Low Resolution variant 1, No 1 Deck
	Low Resolution variant 1, No 2 Deck
	Very Low Resolution variant 1, No 2 Deck

11.11.1 The HPM analysis results of the very low resolution design variants

After 50 simulations had been performed for all six ES for each design variant, representative files were selected for each ES and the HPM for each design variant formed. Table 11.11-2 and Table 11.11-3 present the summary of the HPMs for each variant design. From these tables, it can be seen that the single passageway variant 1 design is marginally the better design, outperforming the double passageway variant by a mere 0.7%, with variant 1 returning a overall vessel performance score of 370.3 and variant 2 returning a score of 373.0. This is comparable to the 1.4% difference seen between the high resolution design variants.

Table 11.11-2 -HPM for VLR variant 1

Variant 1 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	38.75	0	0	0	0	38.75	1
Normal Day Cruising B	1	46.19	0	0	0	0	46.19	1
Action Stations Evacuation	1	45.93	0	0	0	0	45.93	1.5
State 1 Preps	0.5	69.87	0.5	63.72	0	0	66.79	1.5
Family Day A	0.5	41.23	0	0	0.5	43.32	42.28	1.5
Family Day B	1	50.57	0	0	0	0	50.57	1.5
Overall Performance of Functionality Groups	290.04		47.79		32.49			
			Overall Performance of design				370.3	

Table 11.11-3 -HPM for VLR variant 2

Variant 2 Design								
Evaluative scenario	Functional Groups						Scenario Score	Scenario Weight
	FG_1		FG_2		FG_3			
	weight	score	weight	score	weight	score		
Normal Day Cruising A	1	43.55	0	0	0	0	43.55	1
Normal Day Cruising B	1	45.61	0	0	0	0	45.61	1
Action Stations Evacuation	1	40.80	0	0	0	0	40.80	1.5
State 1 Preps	0.5	68.13	0.5	74.22	0	0	71.18	1.5
Family Day A	0.5	40.60	0	0	0.5	31.55	36.07	1.5
Family Day B	1	54.80	0	0	0	0	54.80	1.5
Overall Performance of Functionality Groups	293.71		55.66		23.66			
			Overall Performance of design				373.0	

Having selected the ‘best’ as being the single passageway variant 1 design, it would then be of interest to see why it was marginally the better design, and ultimately see if there is any scope for improvement to the ‘best’ design.

Table 11.11-4 makes the comparison of the seven scenario scores between the two design variants. As can be seen from the table, the worst performing scenario is the ‘Family Day A’ ES; returning a 14.7% inferior performance for variant 1. This is in contrast to the other resolution models where the ‘Action Stations Evacuation’ ES was the worst performing scenario. Another contrast in this analysis when compared to the higher resolution models is the ‘best’ design’s greatest performing ES. In this analysis, the ‘Normal Day Cruising A’ scenario is variant 1’s best performing ES (outperforming variant 2 by 12.4%), however in the higher resolution models, the ‘State 1 Preps’ ES was the outperforming scenario. These contrasts are most likely due to the great lack of detail in the designs, making the population behave very differently in terms of their human factors’ performance. There are far fewer doors to operate, although the same number of WT doors exists, and fewer walls to walk around. Both of which affect the population’s route to their destinations and the speed at which they progress to them.

Table 11.11-4 - Comparison of ES scores between VLR variant 1 and variant 2

Evaluative scenario	Scenario Weight	Variant 1	Variant 2	% difference between Variant 1 and Modified Variant 2
Normal Day Cruising A	1	38.75	43.55	-12.39%
Normal Day Cruising B	1	46.19	45.61	1.24%
Action Stations Evacuation	1	45.93	40.80	11.16%
State 1 Preps	1.5	66.79	71.18	-6.56%
Family Day A	1.5	42.28	36.07	14.67%
Family Day B	1.5	50.57	54.80	-8.36%
Overall Performance of design		370.3	373.0	

As with the high and the low resolution models, the next step in the analysis is to look into the HPM and see why the single passageway variant 1 design outperformed the double passageway variant and whether there is any scope for improvements.

It was noted from Table 11.11-4 that the 'Family Day A' ES was variant 1's worst performing scenario and as such it would be worth examining this ES in greater detail to see why variant 1 did not perform as well as variant 2. On further examination it was observed that the civilians were the functional group which let down variant 1's human factors' performance.

Table 11.11-5 – 'Family Day A' Scenario for the Civilians

FG_3 – Civilians		**Variant 1**		**Variant 2**	
	Weight	raw	norm	raw	norm
GENERAL CRITERIA					
G1 – average time required to complete all operations;	4	199.3	1	199.3	1
G2 – average time spent in transition	3	37.97	0.50	76.09	1
G3 – time to reach final state	8	425.9	0.98	435.3	1
G4 – average time spent in congestion	3	49.86	1	41.13	0.82
G5 – average distance travelled	4	40.99	1	39.26	0.96
GEOMETRIC CRITERIA:					
M1 – the number of WTD used during the scenario.	2	11	1	6	0.55
M2 – the number of Hatches used during the scenario.	2	14	1	9	0.64
M3 – the number of ladders used during the scenario.	2	44	1	30	0.68
M8 – the number of times the FG moved between decks	2	76	1	50	0.66
M13 – Average number of components used per member of FG during the scenario	2	6.73	1	2.33	0.35
M14 – Most times a WT door was operated	4	19	1	2	0.11
M15 – Most times a hatch was operated	3	3	1	1	0.33
M17 - Average number of WT doors per person	3	1.91	1	1.05	0.55
M18 - Average number of hatches used	3	0.32	1	0.15	0.48

Table 11.11-5 shows how the single passageway variant 1 design only outperforms the double passageway variant in two PMs, G_2 and G_3. While G_3 has a high weight of 8, it is 2% better in variant 1 and G_2 is a whopping 50% better in the single passageway variant but only carries a weight of 3. These two PMs therefore do not have much of an impact on the HPM which

means that since all the other PMs (with the exception of G_1) perform better in the double passageway variant design, the impact of these other PMs cause the variant 2 design to perform better for this functional group in this scenario.

With the exception of G_3 all the other PMs have a low weight of 2, 3 or 4 assigned to them, therefore these do not have much impact on the overall HPM. Having said that, there are 11 performance measures which perform more efficiently in the double passageway and although individually they do not have much impact on the HPM, collectively they do.

Of those 11 PMs, 10 perform greater than 18% more efficiently in the double passageway variant. Further to this 9 of the 11 performance measures were at least 32% better in the double passageway variant design. Therefore although all of these PMs may have a low weight assigned to them, there is such a difference between the two design variants that the collective difference between the two designs has a rather large impact on the HPM.

It must be remembered at this point that there was a certain amount of randomness in this scenario. Although it was known exactly where every crew member was at the start and end of the scenario, the civilians, in their groups, were randomly placed in the geometry. Even with the restrictions imposed regarding where these groups could be located, the comparison of the two design variants is not as dependable as with the other scenarios.

The biggest difference between any of the performance measures can be found in M_{14} which represents the most number of times a single WT door is operated. A WT door was operated 19 times in the single passageway variant; this is compared to just 2 in the double passageway variant. This is a staggering 89% difference between the two designs. The main reason for this is due to the two passageways in the variant 2 design providing additional access routes for the population to use in their quest to reach their destinations; thus each WT door is used less since the population is more distributed. In addition, it is possible that due to the random positioning of the civilian groups in the double passageway variant, they did not need to use as many WT doors as the civilians in the variant 1 design.

The main difference between the two design variants with regards to the most times a WT door was operated is further explained by the average number of WT doors used per person (M_{17}). The population in the double passageway variant used on average 45% less WT doors than their counterparts in the single passageway variant. In addition, the population in variant 2 used 65% less components as measured by PM M_{13}.

11.12 Concluding remarks and a summary of varying the resolution of the designs

After performing the same analysis on varying levels of detail for the same design variants, it would be interesting to see if the HPM concept of analysing human factors' performance can be used at any stage in the design cycle and still produce the same conclusions.

Table 11.12-1 compares the percentage differences between scenario scores produced by the High Resolution (HR), Lower Resolution (LR) and Very Low Resolution (VLR) models. It is quite interesting to see how each scenario performs very differently in each of the differing resolution models, with the exception of the 'Action Stations Evacuation' ES which performs relatively consistently throughout all the levels of resolution. In the majority of ES (four out of seven), there is at least one instance where the double passageway variant outperforms the single passageway design. This alone suggests that the concept of assessing human factors' performance cannot accurately be measured at all stages of the design cycle. Nevertheless all three sets of analysis identified the single passageway as being the 'best' design.

Table 11.12-1 - Comparison of ES scores for different resolutions of variant 1 and variant 2

Evaluative scenario	Scenario Weight	% difference between HR V1 and V2	% difference between LR V1 and V2	% difference between VLR V1 and V2
Normal Day Cruising A	1	3.9%	-16.7%	-12.4%
Normal Day Cruising B	1	7.9%	6.0%	1.2%
Action Stations Evacuation	1	9.2%	6.4%	11.2%
State 1 Preps	1.5	-11.9%	-24.2%	-6.6%
Blanket Search	1.5	-8.0%	-15.1%	14.7%
Family Day A	1.5	3.0%	-1.3%	-8.4%
Family Day B	1.5	1.3%	-16.7%	-12.4%
% difference in Overall Vessel Performance Score		1.4%	9.1%	0.7%

It is interesting to note from the analysis that the 'Action Stations Evacuation' scenario performed particularly badly for the single passageway variant, although it was not the worst ES during the very low resolution model analysis. In the two instances where this ES was the worst performing scenario, the same problem was highlighted; that of the level of congestion. In addition, in both cases where the 'Action Stations Evacuation' ES was the worst performing scenario, the same possible solution of an additional ladder linking the 01 Deck with the No 1 Deck was identified. This suggests a possible use of the HPM concept in various stages of the design cycle; however it could also be an anomaly. Just because it has happened here, does not mean that it will happen every time or even ever again.

As has been demonstrated in this chapter, removing any level of detail, or indeed adding any detail, results in the production of a completely new design which will behave quite differently in terms of the design's human factors. As such this comparison has shown that the HPM concept can be employed to measure the human factors' performance of a design at any stage of the design cycle, but the results of each assessment should be taken as individual. The results will not be the same for variations of the same design variant.

This was demonstrated with the addition of a single ladder; this made quite a large impact on the human factors' performance of the single passageway variant. Other items which create access routes, such as WT doors and non WT doors, can also have a large effect on the HF performance of a design. Creating and removing compartments can also have a large HF impact, especially for scenarios such as the 'Blanket Search' ES where these compartments need to be checked / searched.

Chapter 12

Conclusions

12.1 Introduction

This thesis has addressed two main research objectives: the first to improve the reliability of passenger ship evacuation analysis from modelling, and the second to introduce human factor analysis into the early stages of naval ship design for normal operations.

Based on the work in this thesis a more realistic passenger response time distribution has been established by the introduction of more realistic passenger response time distribution, and the international maritime regulations governing the modelling of evacuation scenarios updated in IMO MSC 1238. A methodology has also been developed for the assessment of evacuation and normal operational scenarios of a naval vessel, in terms of human factor performance, for the early stages of a design cycle.

As a result of this work, the maritimeEXODUS evacuation model can now model non-emergency normal operational scenarios, and a new concept, the Human Performance Metric (HPM), was devised which will efficiently and effectively analyse the vast amount of simulation results from an evacuation / human factors modelling software tool. This innovative concept is both discriminating and diagnostic in nature and can be used to select the best design from a set of designs, in terms of their human factors' performance. This concept is systematic and transparent in nature and the results are reproducible. maritimeEXODUS coupled with the HPM concept can be used as a stand alone system, as demonstrated in Chapter 9, or as intended, in the early stage of the design cycle for a naval vessel. This was achieved through the software link between the ship evacuation tool maritimeEXODUS and the ship design tool PARAMARINE and has been successfully demonstrated in Chapter 11.

This chapter presents a number of conclusions which have been produced in answer to the questions posed in Chapter 1 (Introduction).

12.2 A mark of success?

In this section of the thesis, the questions posed in the Introduction chapter (Chapter 1) are answered, presenting any findings, problems and developments made during the work of this thesis.

1) How realistic is the IMO 1033 passenger response time distribution?

The response time distribution (RTD) specified in the IMO MSC Circ 1033 guidelines takes the form of a random uniform distribution. This means that at every time step in a model there are the same number of passengers responding to the sound of the alarm. This was highlighted as a potential problem in the literature review in Chapter 2, and was considered unrealistic, since more people will respond to an alarm at an earlier stage of an evacuation and over time there will be less people responding.

1 a) What is the IMO specified response time distribution based on?

As discussed in the literature review in Chapter 2, the response time distribution which was specified in the IMO MSC Circ. 1033 guidelines followed the form of a random uniform distribution. This distribution was not based on any real life data but instead was devised by a panel of experts in the field. In the original IMO meeting where this random uniform response time distribution was posed, it was stated that further examination of the response time distribution would be required.

1 b) Does the IMO specified response time distribution represent reality?

Chapter 4 performed a range of simulations which applied the IMO MSC Circ 1033 specified random uniform distribution to a hypothetical vessel and presented the results of these. Chapter 4 then compared the results produced using the random uniform curve with more realistic response time curves obtained from the built environment. The results of this comparison proved that the IMO MSC Circ 1033 specified response time distribution was not realistic of passengers during an evacuation scenario and as such was not suitable for use in modelling an evacuation scenario on board a passenger vessel.

1 c) Can knowledge of response time distributions derived from the building industry be of use in passenger ship applications?

Experiments have been performed in the built environment aimed at collecting the response times of occupants in a building when the fire alarm is sounded and the call to evacuate is given. Chapter 4 discussed two such experiments, one of which was performed in a university library building and the other was captured on CCTV cameras during the evacuation of a retail premises. The experience gained from these examples demonstrated how the response times of a population followed a lognormal distribution. Unless the behaviour of people in buildings is completely different to that found on passenger ships, this strongly suggested that the uniform random distribution representation used in the IMO MSC 1033 was completely inappropriate.

1 d) Can we develop a more realistic response time distribution for passenger ships?

A more realistic passenger response time distribution was extracted from evacuation trials undertaken at sea. This RTD, presented and demonstrated in Chapter 4, took the form of a lognormal distribution. This distribution had the limits of 0 seconds to 300 seconds, which was quite different to the RTD presented in the IMO MSC Circ 1033 guidelines (210 – 390 seconds). The shape of this response time distribution was identical to that observed in the building industry which supports the validity of the proposed response time distribution.

1 e) What impact would this have on predicted evacuation times?

The lognormal response time distribution was demonstrated as being more challenging to a design during the evacuation scenarios. During the demonstrations presented in Chapter 4, the lognormal response time distribution unearthed more regions of severe congestion compared to when the IMO MSC Circ 1033 specified random uniform distribution was used. The log normal response time distribution proposed in this thesis has been adopted by IMO in 2007 and now forms part of the modified version of Circ 1033, IMO MSC Circ 1238.

2) How is the evacuation analysis of a naval vessel governed?

In 2006, the NATO navies recognised that there were no guidelines governing the evacuation analysis of naval vessels and in light of this they set up a specialist team on naval ship safety and classification. This specialist team created the Naval Ship Code. Chapter 7 of the Naval Ship Code is attributed to governing the safety of the crew during an evacuation. The code requires an evacuation analysis to be performed in the early stages of the design cycle for a new naval vessel and that the design should undergo the assessment through a number of scenarios. Chapter 2 of this thesis discussed the Naval Ship Code in detail, presenting the required scenarios and the criteria which a vessel must satisfy.

2 a) What problems are there with the Naval Ship Code with regard to evacuation analysis of a naval vessel?

Chapter 2 highlighted a number of shortfalls in the Naval Ship Code. The code fails to specify the travel speeds and response times of individual crew members or a typical population demographic, for example, the spread of ages and the proportion of male and female crew members. All of which are essential to the modelling of an evacuation scenario. A recommendation from this thesis is that research should be conducted to establish an appropriate parameter set to use in naval ship evacuation analysis (see Chapter 13).

2 b) Can work carried out in the passenger shipping industry fulfil the requirements of the Naval Ship Code in terms of the evacuation analysis of naval vessels?

With insufficient data available for the modelling of a naval vessel, this PhD thesis applied the validated data available from evacuations performed on passenger vessels to provide the missing information in the Naval Ship Code. This data was obtained from the IMO MSC Circ. 1033 guidelines, see Chapter 9). This data also included the new passenger response time distribution which was recommended for use in Chapter 4 of this thesis (and later adopted by IMO). Although we can hypothesise that naval personnel will in general respond to orders much faster than untrained civilians, the exact data required for this is not available. Therefore using validated passenger response times and travel speed data to represent that of trained service personnel is considered more representative than a hypothetical data set and provides an upper limit on expected performance parameters.

3) How can we assess human factors associated with Normal OPerations (NOP) of a naval vessel?

Prior to the work carried out in this thesis, there was no methodology for assessing the human factors' performance of a naval vessel during normal operational scenarios. This was discussed in Chapter 2. However, the work carried out in Chapter 7 demonstrated that by identifying and then simulating key crew functions using an adapted evacuation model it was possible to assess and quantify the human factors' performance of a design during the normal operational scenarios.

3 a) What types of NOP scenarios are relevant to a naval vessel?

As discussed in Chapter 5, different classes of naval vessel may perform different types of normal operational (NOP) scenarios, and each NOP scenario will be ship specific. Thus, the NOP scenarios considered for a surface combatant are likely to be different to those for an aircraft carrier or a submarine and one type of surface combatant may be different from another type of surface combatant. Three NOP scenarios were identified for use in demonstrating the work developed in this thesis and were selected with guidance from the UK MoD partners working on the 'EGO' project (see Chapter 10). These scenarios were: 'State 1 Preps', 'Family Day' and 'Blanket Search'. These scenarios were identified to represent a broad range of the normal operational scenarios on board a surface combatant, in particular a variant of the Royal Navy Type 22 Batch III frigate. More NOP scenarios are likely to be undertaken on this type of vessel, but these three were considered sufficient to demonstrate the concept developed in this thesis.

3 b) What specific human factors aspects of these scenarios are relevant?

Some 32 criteria were developed which uniquely assessed the human factors' aspects of the defined scenarios. These criteria were categorised into five different groups namely; Congestion, General, Procedural, Population, and Geometric. These criteria assessed such aspects as the average time spent in congestion by the functional group (G_4), the average distance travelled by the population during the scenario (G_5), the average number of watertight doors (M_1) and hatches (M_2) operated and the overall time to complete a scenario (G_3). Chapter 5 defines these criteria in greater detail.

3 c) How can the end-user (customer) exercise their requirements on the relative importance of these scenarios and human factors' criteria?

In Chapter 5, weights were developed which when applied (multiplied) to the components of the Human Performance Metric (scenarios, functional groups and performance measures) would increase the importance of that component in the overall assessment of the human factors' performance. By increasing its importance (value), the performance measures would have a greater effect on functional group score and thus on the scenario score. Therefore by using higher values of weights for each component of the metric, that component has a greater impact on the subsequent component. Thus the end-user could identify which components of the HPM were of greater significance and hence which should carry greater weight in the overall assessment. In this way the end-users interests and requirements could be specifically addressed.

3 d) Are these scenarios and criteria applicable to all types of naval vessel?

While the scenarios and criteria described in Chapter 6 were specific to the Type 22 Batch III frigate, they may also be applicable to other types of naval vessel. However, there will undoubtedly be additional scenarios and criteria that could be developed for other types of naval vessel. Different ship types, such as aircraft carriers or submarines, will have specialist procedures and practices that will require the definition of additional scenarios and criteria. Furthermore, even the same type of vessel operated by different navies may employ different procedures requiring additional scenarios and criteria to be specified. This was discussed in Chapter 5.

3 d) i) Can the technique be easily adapted to address these differences?

Yes, the technique can easily be expanded and adjusted to suit any type of vessel. The type and specifics of each scenario is irrelevant to the metric, as too is the type and size of each functional group. New scenarios may, however, require new performance measures to be identified. These performance measures need to be defined, such that the higher their value, the worst the performance of the design. Provided this can be done, the technique can be easily adapted to suit any design. In addition, the modelling tool may need to be modified to include the behaviours required by the new scenarios.

3 e) Can ship evacuation models be used to assess NOP scenarios?

Yes, as discussed in Chapter 2, in principle the same tool used to evaluate evacuation scenarios can be used to assess NOP scenarios. However, the evacuation tool must have the capability to represent the NOP scenarios. For example, it will be necessary to evaluate a Blanket Search scenario, which requires the ability to represent agents searching a number of unoccupied compartments in a particular order and reporting any findings to HQ. However, it should be possible to modify an agent based evacuation modelling tool to address these requirements.

3 e) i) What changes to the human factors capabilities of these software tools are required?

Since evacuation models are primarily designed to model the evacuation of people from a structure and normal operational scenarios involve the population moving around the structure, the model would need to be extended in order to have the capability to do this. Chapter 7 analysed each of the identified NOP and identified what new human factors capabilities would be required in order to satisfactory model these NOP. These new capabilities included the ‘Close WT Door’, ‘Search’, ‘Repeat’, ‘Blanket Search’, ‘Give’ and ‘Receive’ commands, each of which instructs an agent to perform a particular task required to complete the NOP scenario. For example, it is a requirement of the ‘State 1 Preps’ scenario that all WT doors are closed, therefore the ‘Close WT Door’ command was created to instruct an agent to do this. In addition, Chapter 5 discussed a number of human factors criteria which would need to be modelled by an evacuation model in order to satisfactorily assess the human factor’s performance of a vessel design. These factors include the time required for a functional group to complete all of their assigned tasks and the number of watertight doors operated.

3 e) ii) What changes to the modelling capabilities of these software tools are required?

The main modification required to the software was the implementation of the ‘Terminate’ command. This command tells an agent that they have come to the end of their involvement in the simulation and instructs them to remain where they are, while all their attributes, such as personal simulation time or cumulative wait time, cease to change. This command allows the evacuation software to model non-evacuation scenarios. In addition, six new human factors capabilities (see 3e i) were required in order to model the specific NOP scenarios identified in Chapter 6; this resulted in new agent behaviours being implemented within the software. Furthermore, two existing behaviours within the software were significantly modified; these were the delay and the wait tasks. In addition to these new behaviours, to improve the efficiency of creating a maritimeEXODUS model, a new input file was developed, the SSF file. This file allows the population and scenario settings to be imported into the software and negates the need to use the complex maritimeEXODUS user interface. Finally, the evacuation model, maritimeEXODUS, now produces a new output file which directly populates the HPM. This greatly improves the efficiency in building the HPM structure and carrying out the HF analysis.

4) Can we establish a combined assessment methodology that simultaneously takes into consideration human factors associated with evacuation and normal operations?

Yes, this thesis created the Human Performance Metric (HPM) which does just that. The HPM is described in Chapter 5 and combines the analysis of many scenarios irrespective of what type of scenario it is. To the HPM, a scenario is just a collection of performance measures.

The HPM methodology uses a weighted sum approach to simultaneously assess the human factors performance of all the scenarios and produce a score for each design variant. Normalising each performance measure (PM) against the equivalent PM in another design variant, and summing up the weighted scores of the PM produces a scenario score. This score can then be compared to other scenarios within the design or in other design variants. The performance measures are defined such that the lower their score, the better the design performed in that aspect of the scenario. This is the same with the scenario score and the design score i.e. the best design is that with the lowest overall score

4 a) How sensitive is the technique to small changes in user requirements or vessel design?

Chapter 5 explored the sensitivity of the HPM methodology and in doing so created a series of equations which will show how much of an effect changing a normalised performance measure score, functional group score, scenario score or their relative weights has on the overall metric. These equations can also show how much of a change is required in any of the HPM components in order to obtain a required performance from the HPM.

4 b) Can the methodology be used to not only assess human factors performance but to suggest improvements in ship design and operational procedures, making the approach both discriminating and diagnostic?

Yes, as described in Chapter 5 and demonstrated in Chapter 9 and Chapter 11, the HPM methodology is both discriminating and diagnostic. Since each performance measure is defined such that the lower its score the better the design performed, then when all the performance scores are summed up, the design with the lowest overall score is deemed the best in terms of its human factors' performance. Hence the technique is discriminating. Continuing on from this, if it is desired to improve the best design, then a closer examination of the scenario scores and the performance measure scores can be made. Where a scenario or performance measure has a higher score than its equivalent in another design variant, a closer inspection at that component can help identify areas where the design performed less well. In Chapter 11 (Section 8), it was identified how there was a high level of congestion in the best design, and on further analysis it was noted that adding a ladder created an additional access route which significantly reduced this congestion and improved the human factors' performance of the design by over 5%.

4 c) Can the approach be designed so that the assessment is both transparent and reproducible?

Yes, the HPM methodology is both transparent and reproducible in nature. The methodology is transparent, as it can be seen where the values of the HPM have come from in each layer and the methodology is easy to follow from the ground up. The structure of the HPM (collection of scenarios, functional groups and performance measures) and the set of weights can be given to a different person to calculate and they will be able to produce the same results every time, therefore the methodology is reproducible, provided the structure of the HPM or weights are not changed.

5) How can we introduce human factors associated with normal operations into naval ship design assessment?

Chapter 10 explored the link between the ship design tool PARAMARINE and the ship evacuation tool maritimeEXODUS. The work carried out in this thesis successfully created the link between the two tools. A demonstration of the new design cycle was presented in Chapter 11 using a variation of the Royal Navy Type 22 Batch III frigate. This entailed two variations of the design undergoing the human factors assessment at differing levels of detail. The main assessment of the design was performed with the highest level of detail present in the design. The demonstration showed how the Human Performance Metric could be used to identify the best variant from a set of designs and then be further used to improve it. In Chapter 11, the human performance metric was first used to identify missing ladders in the best design, and then it identify a strategically positioned ladder which improved the design by 5.6% and as a by product also improved some scenarios by over 12%.

12.3 Key achievements

This thesis has produced five main achievements, these were:

1. The recommendation of a more realistic passenger response time distributions were presented for use in the evacuation analysis of a passenger RO-RO vessel. These response time distributions were adopted by the IMO in their revised guidelines governing the evacuation analysis of a passenger vessel (IMO MSC Circ 1238). A link to this work has also been included in the regulations as reference to how the response time distribution should be implemented.
2. The capabilities of the ship evacuation tool, maritimeEXODUS, were extended in order to model normal operational scenarios.
3. The development of a novel methodology for the assessment of human factors' performance of a design during both evacuation and normal operational scenarios.

This methodology, called the ‘Human Performance Matrix’, is discriminating, diagnostic, systematic and transparent in nature.

4. The integration of the human factors’ performance analysis into the early stages of the design cycle for a new naval vessel.
5. 10 published papers, 5 of which were in refereed journals

12.4 Final comments

The work reported in this thesis was very interesting and an enjoyable experience. A significant amount of work was carried out and has been well documented in publications and reports. Some important and useful results came from the work, for example how much detail is required in a design to be able to perform human factor’s analysis.

With the benefit of hindsight and if more time were available to continue the research, it would be useful to create a design from scratch rather than basing it on a real vessel. During the example application in Chapter 11, the design was built with a lot of detail in it. After performing a human factors’ performance analysis on the design, detail was then stripped out. In reality the HF analysis would be performed on the shell of the vessel, and then help assess the effect of adding extra detail.

The most difficult problem that had to be overcome within this work was transferring the ship design from PARAMARINE to maritimeEXODUS, since neither software could read or write each other’s input or output files. This created the need for the utility tools to do the conversions.

With additional time and resources the software developed during the project could be refined with the potential for a final commercial product which would be more user friendly and automate more of the process of integration into the design cycle.
Potential improvements could include the development of maritimeEXODUS to enable KCL files to be read directly and thus create the geometry within maritimeEXODUS automatically. In addition, the utility tools, the scenario generator and the HPM Analyser, could be

integrated into the maritimeEXODUS software, thus removing the need for the user to be trained in the use of more tools than necessary.

As a result of the work reported in this thesis, new research questions can be posed, these include:

- Do the passenger response time distributions presented in Chapter 4 apply to all types of passenger vessel, for example cruise ships?
- How much detail is required in a design to perform a valid human factors' analysis?
- What affect can placing a vertical or horizontal access point have on a design' human factors performance? Can there be too many access points?
- Can the methodology presented in this thesis be used to calculate the optimal location for an access point? (such as a door or a staircase)
- Are there other methods of assigning weights that could be used which remove its subjective nature?
- Can the methodology be used to help build passenger vessels such as cruise ships and Ro-Ro vessels?
- Can the methodology be used to help construct buildings and other types of structures? (such as planes or trains)

Chapter 13

Recommendations for Further Work

This Chapter attempts to identify some areas of this thesis where more work could be carried out. Some of these relate to the use of the new integrated ship design cycle, some related to the use the HPM concept and other suggest further software development.

A major issue which was identified during the literature review, but not addressed in this thesis, was the insufficient availability of data required to perform both evacuation and normal operational scenarios on board a naval vessel. During the course of this thesis, a limited amount of naval personnel performance data, collected through small scale trials, was available. The remaining required data was obtained from the International Maritime Organization's (IMO) guidelines governing the evacuation analysis of passenger vessels. As was discussed during the thesis, trained naval personnel will generally respond to instructions much faster and efficiently than untrained civilian passengers. Therefore, the use of civilian data from the IMO guidelines to model naval personnel is likely to be misrepresentative. As further work, trials could be performed involving naval personnel with the aim of collecting the required data for a true and meaningful evacuation scenario and normal operational scenarios to be carried out. This will involve the collection of response times (during day and night time conditions) and travels speeds obtained under a number of different sea states. A typical naval vessel population demographic should also be defined which will more appropriately represent that found onboard a naval vessel.

In addition to this, it has been assumed that the passenger response time distribution recommended in Chapter 4 is representative of all passenger vessels. However, further work could explore the realism of the passenger response time distribution for use on other class of vessels, such as cruise ships.

Following on from this, Chapter 2 identified an unavailability of validation datasets with which to assess the performance of evacuation models against. Further studies could be explored into the development of realistic validation datasets which can be used to assess the performance of an evacuation model. There is a project on going called SAFEGUARD, which is an EU funded research project aimed at collecting the required data to produce three validation datasets. The project is collecting response times, initial locations and paths taken by passengers during an evacuation drill on board three class of vessel. These vessels represent a cruise ship, a Ro-Pax vessel with cabins and a Ro-Pax vessel without cabins. However, is one dataset sufficient to truly represent all vessel of that class? For example would the evacuation of another cruise ship produce the same data that is in the validation data set? If more than one validation dataset is required to obtain a satisfactory performance from evacuation, how many datasets would be required?

The HPM concept can be extended to not only assess the designs of naval vessels, but also for civilian passenger vessels such as high speed ferries. In addition, the HPM concept does not need to be restricted to maritime structures. With the addition of appropriate performance measures the concept can be extended to assess the human factors performance of building designs, aircrafts or trains or any other type of structure. Indeed, the HPM concept does not need to be restricted to enclosures either, for example the methodology could be used to help design an outdoor music festival such as Glastonbury (in the UK) or help form strategies for police kettling protestors in riots. The possibilities are endless, whenever there is a design to be used with humans, the HPM concept could be used to help select and improve a design.

Further developments could be made to the integrated system such that a common file could be used to transfer data from the ship design software to the ship evacuation software in a more efficient manner. It was suggested during this thesis that the KCL file was difficult to interpret. If a simpler data file could be created then both software tools would be able to represent the results from the other software tool better. For example, if PARAMARINE could export a design's structure in XML, maritimeEXODUS could read in, interpret and build up the structure of the design with out the need of the DXF's. This would enable maritimeEXODUS to more accurately and intelligently fill each space with nodes. It would allow maritimeEXODUS to fill around objects more effectively and this would allow the geometry to be set up far more efficiently with hardly any human involvement.

As a follow up to the work performed as part of this thesis, the Scenario Generator and the HPM Analyser could be integrated into the maritimeEXODUS software. This would reduce the need to use external utility programs. In both cases, the utility tools could make use of features within maritimeEXODUS. For example the Scenario Generator would not need to read in an MTA file in order to know the structure of the geometry. maritimeEXODUS could supply this information directly. In addition, if new behaviours were developed within maritimeEXODUS, these could automatically be included in the Scenario Generator and the HPM Analyser.

More work could be carried out to improve an agents' ability to carry out wayfinding. At present, the people within maritimeEXODUS move to their targets via the shortest possible path. However in real life the shortest path may not be the quickest. For example the shortest path may be heavily congested or the shortest path may contain very narrow spaces to navigate through. Both of which will slow down the progress of the people in achieving their goals. The shortest path may also lead the individuals through hazardous areas. For example on a naval vessel, it maybe dangerous to walk across the outer deck where you may get shot, in this case although neither the shortest nor the quickest route, the individuals may want to move to a lower deck in order to reach their target safely..

Further development of the behaviours implemented as part of this PhD thesis will be required. The search compartment behaviour will need further options to be made available to better represent an agent performing this task. For example does the agent walk to the centre of the compartment (zone) and experience a delay, or does the agent walk around the perimeter of the compartment (zone) or does the agent simply step into the compartment (zone) and experience a time delay. This final suggestion was implemented as part of the thesis and demonstrated in Chapter 8. The algorithm for assigning compartments to agents as past of the blanket search command will need further investigation in the future in order to better represent the procedures implemented on the vessel being assessed.

The work of this thesis could be furthered by exploring other scenarios on board a naval vessel. One such scenario suggested during the course of this work was the scenario 'Replenishment at sea". This involves a naval vessel receiving supplies while it is at sea and requires the crew to move these supplies from one location to another for example from open deck to the stores.

More work could be carried out in order to identify a more robust method of assigning the weights. The selected method in this thesis was considered very subjective. Although the HPM concept devised was systematic, transparent and reproducible, thus the weights could be changed and a new result from the HPM obtained.

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Appendix A

This section of the thesis will present the first page of each of the published papers. The author of this thesis was either the 1st author or co-authored these papers. The papers presented in this section are:

Deere, S., Galea, E.R., Lawrence, P., Filippidis, L. and Gwynne, S., 2006, The impact of the passenger response time distribution on ship evacuation performance, International Journal of Maritime Engineering

Deere, S. J., Galea, E. R. Lawrence, P., 2008a, Optimising Vessel Layout using human factors simulation', Pedestrian and Evacuation Dynamics 2008

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International Journal of Maritime Engineering

THE IMPACT OF THE PASSENGER RESPONSE TIME DISTRIBUTION ON SHIP EVACUATION PERFORMANCE

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SUMMARY

The International Maritime Organisation (IMO) has adopted the use of computer simulation to assist in the assessment of the assembly time for passenger ships. A key parameter required for this analysis and specified as part of the IMO guidelines is the passenger response time distribution. It is demonstrated in this paper that the IMO specified response time distribution assumes an unrealistic mathematical form. This unrealistic mathematical form can lead to serious congestion issues being overlooked in the evacuation analysis and lead to incorrect conclusions concerning the suitability of vessel design. In light of these results, it is vital that IMO undertake research to generate passenger response time data suitable for use in evacuation analysis of passenger ships. Until this type of data becomes readily available, it is strongly recommended that rather than continuing to use the artificial and unrepresentative form of the response time distribution, IMO should adopt plausible and more realistic response time data derived from land based applications.

1. INTRODUCTION

However remote the possibility or difficult the task, ship evacuations do occur and they are usually the result of fire (e.g. ECSTASY [1]), collision (e.g. European Gateway), equipment failure (Estonia [2]), grounding (e.g. Saint Malo Ferry [3]), or mal-operation (Herald of Free Enterprise [4]). In the wake of these prominent maritime disasters, as well as several offshore oil rig disasters (e.g. Piper Alpha), and in light of the growth in the numbers of high density, high-speed ferries and large capacity cruise ships, there is a growing interest in the marine industry in issues of evacuation of passengers and crew at sea. The High Speed Craft Code (MSC. 36 (63), May 1994) introduced the concept of performing critical path analysis of the evacuation arrangements, SOLAS regulation II-2/28 1.3 required Ro-Ro passenger ships built after 1 July 1999 to have an early design stage evacuation analysis performed and the International Maritime Organisation (IMO) developed and issued Guidelines for a Simplified Evacuation Analysis of Ro-Ro passenger vessels [5].

In recognition of the development of sophisticated evacuation simulation techniques [6,7] IMO - through a Correspondence Group (CG) of the Fire Prevention Sub-Committee FP46 - developed and adopted a set of Interim Guidelines that set out the standards on how evacuation simulation should be undertaken for certification applications [8]. These guidelines define two benchmark scenarios (along with two variants) that must be simulated as part of the certification process. These are defined as the "night" and "day" scenarios. While arbitrarily defined, they establish a baseline performance for the vessel and crew allowing comparison with both the set target time and alternative designs. The scenarios only address the mustering or assembly phase of the evacuation and involve conditions of dead calm (i.e. zero list, heel and roll) and do not explicitly take into consideration the impact of fire. To allow for these omissions a safety factor is added to the predicted muster time.

In particular, the resulting analysis should allow identification of areas of congestion that develop during an evacuation and to demonstrate that escape arrangements are sufficiently flexible to account for the loss of particular parts of the evacuation system. The difference between the "night" and "day" scenarios consists of the starting locations of passengers and the simulated passenger response time distribution exhibited by the passengers. During an emergency, passengers will not respond immediately to the call to assemble. The time between the instruction being issued and the passengers moving off to the assembly station – which can take several minutes - is known as the response time. Even when an individual decides to react to the call to evacuate, their situation often prohibits immediate flight. Individuals may decide to perform a number of tasks prior to actually evacuating such as collecting belongings, reuniting family members, complete a financial transaction, finish a meal etc. Thus not everyone will react at the same time, some will react sooner and some later than others. As each passenger will have a unique response time it is necessary to define a response time distribution to represent this inherent variation.

If the response time distribution is set to zero or near zero, then all the passengers will react (almost) immediately and so considerable unrealistic congestion is likely to develop in many locations. If the response time distribution is too wide then there will be a considerable gap between the starting times of passengers and so potential choke points in the geometry will not be detected. Furthermore, as the process is inherently non-

Optimising Vessel Layout Using Human Factors Simulation

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Summary. 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. In this paper we present a systematic and transparent methodology for assessing the HF performance of ship design which is both discriminating and diagnostic.

1 Introduction

When modifying the internal configuration of a ship, it is important to determine what, if any, 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 overall HF performance of ship design.

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. 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.

Advanced ship evacuation models such as maritimeEXODUS can be used to determine the performance of personnel under emergency conditions for both passenger and naval vessels as well as the normal circulation of personnel for both passenger and naval vessels [1, 2]. These models produce a

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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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Assessing the Suitability of Ship Design for Human Factors Issues Associated with Evacuation and Normal Operations

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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. 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.

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 overall HF performance of ship design.

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 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.

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 ships, *Deere et al. (2006), Galea et al. (2004),* and naval vessels, *Boxall et al. (2005),* as well as the normal circulation of personnel for both passenger and naval vessels, *Boxall et al. (2005), Caldeira-Saraiva et al. (2004).* These models produce a wide variety of simulation outputs, such as time to assemble and the levels of congestion experienced. As the number of different scenarios investigated increases, so does the

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INTEGRATING PERSONNEL MOVEMENT SIMULATION INTO PRELIMINARY SHIP DESIGN

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SUMMARY

Traditionally, when designing a ship the driving issues are seen to be powering, stability, strength and seakeeping. Issues related to ship operations and evolutions are investigated later in the design process, within the constraint of a fixed layout. This can result in operational inefficiencies and limitations, excessive crew numbers and potentially hazardous situations.

This paper summarises work by University College London and the University of Greenwich prior to the completion of a three year EPSRC funded research project to integrate the simulation of personnel movement into early stage ship design. This integration is intended to facilitate the assessment of onboard operations while the design is still highly amenable to change.

The project brings together the University of Greenwich developed maritimeEXODUS personnel movement simulation software and the SURFCON implementation of the Design Building Block approach to early stage ship design, which originated with the UCL Ship Design Research team and has been implemented within the PARAMARINE ship design system produced by Graphics Research Corporation. Central to the success of this project is the definition of a suitable series of Performance Measures (PM) which can be used to assess the human performance of the design in different operational scenarios.

The paper outlines the progress made on deriving the PM from human dynamics criteria measured in simulations and their incorporation into a Human Performance Metric (HPM) for analysis. It describes the production of a series of SURFCON ship designs, based on the Royal Navy's Type 22 Batch 3 frigate, and their analysis using the PARAMARINE and maritimeEXODUS software. Conclusions on the work to date and for the remainder of the project are presented addressing the integration of personnel movement simulation into the preliminary ship design process.

1. INTRODUCTION

1.1 PERSONNEL MOVEMENT ISSUES IN SHIP DESIGN

Human Factors (HF) have a significant impact on the design of ships and can be considered at two levels: that of micro-ergonomics and of macro-ergonomics. Micro-ergonomics applies at the detailed level of design, to achieve effective person-machine interfaces and to conduct specific maintenance and repair operations to the ship and its equipment. Historically, macro-ergonomics has been adopted as systems-based term, encompassing HF related organisational and management aspects of the design, including designing the watch-keeping organisation and assessing the trade off between automation and overall manning [1].

Apart from these two levels of HF application there is the important aspect of addressing personnel movement on board ship as a major influence on the operability and usability of the whole ship. This is strongly related to the overall physical arrangements or architecture of the vessel [2]. In order to assess the aspects related to personnel movement in the ship, the configuration at an early stage of the design process has to be accurately yet flexibly modelled. That is to say the model must provide a broad definition of the main configurational features. Up to the present only after the broad form of the ship's layout has been finalised and the traditional naval architectural issues (e.g. powering, stability, strength and seakeeping) have been addressed, are issues related to crewing, ship operations and evolutions then investigated, and only then within those overall design constraints. It can be seen that this relatively late consideration of personnel movement aspects could then result in significant operational inefficiencies and potentially hazardous environments, in particular on a combatant vessel.

Once the ship design is into the detailed development stage then detailed CAD models can be used by specialist experts to assess the relevant Human Factors aspects, as part of evaluating the usability of a given design. A typical example of micro-ergonomics features appraisal is the use of computer generated models in conjunction with virtual reality and simulation software packages to perform real-time 3-D assessment of the practicality of both the operation and maintenance of onboard systems. An example of this was the simulation using, the simulation tool VSTEP, of the operator position and associated sightlines on a dredger [3].

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RECOMMENDATIONS ON THE NATURE OF THE PASSENGER RESPONSE TIME DISTRIBUTION TO BE USED IN THE MSC 1033 ASSEMBLY TIME ANALYSIS BASED ON DATA DERIVED FROM SEA TRIALS

E R Galea, S Deere, G Sharp, L Filippidis, P Lawrence and **S Gwynne**, University of Greenwich, UK.

SUMMARY

The passenger response time distributions adopted by the International Maritime Organisation (IMO) in their assessment of the assembly time for passenger ships involves two key assumptions. The first is that the response time distribution assumes the form of a uniform random distribution and the second concerns the actual range of response times. These two assumptions are core to the validity of the IMO analysis but are not based on real data, being the recommendations of an IMO committee. In this paper, response time data collected from assembly trials conducted at sea on a real passenger vessel using actual passengers are presented and discussed. Unlike the IMO specified response time distributions, the data collected from these trials displays a log-normal distribution, similar to that found in land based environments. Based on this data, response time distributions for use in the IMO assembly analysis for the day and night scenarios are suggested.

1. INTRODUCTION

Understanding how people behaviour in emergency situations within maritime settings is vital if we are to; design and develop evacuation efficient vessels and crew evacuation procedures, train crew in the management of evacuation situations and regulate the design and operation of vessels. An essential component of this understanding is the collection and characterisation of human performance data.

The EU project Fire-Exit [1] has made an important contribution to the development of our understanding of human behaviour within the maritime environment through the collection of human performance data in laboratory-scale trials relating to movement rates of passengers under a variety of conditions, including; static adverse angles of orientation, dynamic ship motion, a combination of dynamic motion and reduced visibility due to smoke and the time required to board a variety of Life Safety Appliances (LSA). In addition to these laboratory scale experiments two full-scale trials at sea using an operational passenger vessel and actual passengers were conducted as part of the Fire-Exit project. The primary purpose of this work was to collect data relating to the response time of passengers involved in assembly trials.

During an emergency, passengers will not respond immediately to the call to assemble. The time between the instruction being issued and the passenger moving off to the assembly station is known as the response time (also referred to as pre-movement time). The response time is a key component of the entire evacuation process and so if we are to reliably simulate evacuation at sea [2,3] using models such as maritime EXODUS [4-6], it is essential that we fully understand and quantify the passenger response time [7]. The concept of occupant response time is not unique to maritime evacuation applications but is a standard feature of all evacuation situations [4]. In building applications, occupant response time can in fact be longer than the actual evacuation travel time. As a result considerable effort has been expended in the building industry in attempts to quantify and understand occupant response time for particular situations [4].

Unfortunately, little or no data relating to passenger response time in maritime environments exists [8,9]. Nevertheless, the passenger response time distribution in MSC 1033 [10] – the IMO document which sets the guidelines for ship based computer evacuation analysis - has been set to a distribution of 210 – 390 seconds with a mean of 300 seconds for "day" case scenarios and 420 – 780 seconds with a mean of 600 seconds for "night" case scenarios. The shape of these distributions is described by a uniform random probability function.

The response time distributions adopted in MSC 1033 [10] involve two key assumptions. The first is that the response time distribution assumes the form of a uniform random distribution. Evidence from studies in the building industry suggests that this is not the case with response time distributions typically following a positively skewed distribution, with large numbers of people displaying relatively short response times and fewer people displaying progressively longer response times. In appearance, these response time distributions resemble log-normal distributions [4]. The second key assumption concerns the actual range of response times. This range is not based on real measurements but consists of values derived by committee.

New model for ship evacuation

IN the second part of their in depth analysis of passenger response times during ship evacuation, E R Galea, S Deere, G Sharp, L Filippidis, P Lawrence and S Gwynne, of the Fire Safety Engineering Group, University of Greenwich, UK, recommend a fundamental rethink of International Maritime Organization methodology.

UNDERSTANDING how people behave in emergency situations within maritime settings is vital if we are to design and develop evacuation efficient vessels and crew evacuation procedures, train crew in the management of evacuation situations and regulate the design and operation of vessels. An essential component of this understanding is the collection and characterisation of human performance data.

The EU project Fire-Exit, which included the University of Greenwich, BMT, BMT Fleet Technology, Marine Institute of Memorial University of Newfoundland, Mettle Groupe and Gruppo Grimaldi has made an important contribution to the development of our understanding of human behaviour within the maritime environment.

Grimaldi made one of its ro-ro ferries available for use in trials in April 2005. Two trials were conducted over two days on the Port of Rome to Barcelona route. Both crew and passengers were aware that they were participating in experimental assembly trials. Both trials were conducted in the morning with passengers distributed throughout the vessel according to their normal shipboard activities. On both days, passengers were instructed to assemble and don lifejackets.

The vessel consisted of 11 decks of which three could be utilised by passengers. The total passenger capacity of the vessel is 1400, with 208 passengers in aircraft style seating, 626 accommodated in cabins and 566 deck passengers. The vessel has a crew complement of 100. The vessel has 200 cabins of single, double, triple or quadruple berth. Onboard the vessel are two restaurants, two bars and a casino area. The ship has also a reception area, shop and outdoor pool.

In order to capture most of the behaviour and data for timed analyses, video cameras were positioned in key locations within the vessel.

The first trial took place on the outward leg of the voyage. On this leg of the trip, there were some 508 passengers onboard, the majority of which were unaccompanied teenage school students. The weather conditions were quite poor and a large number of passengers experienced sea sickness. The conditions were so poor that the Master decided not to allow passengers to assemble in the uncovered areas of the vessel.

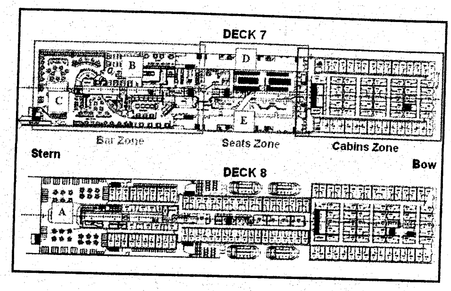


Figure 1: Location of assembly areas, *Roma*.

The second trial took place on the return leg of the voyage on the following day. On this leg of the trip, there were some 236 passengers onboard. There was a mixture of adult and unaccompanied school aged children. In this trial a large number of passengers were located in cabins and the public spaces. The weather conditions were fine and calm. In this trial the Master allowed the passengers to assemble in the uncovered areas of the vessel.

According to the trial protocols, once passengers boarded they were to be informed that an assembly drill would take place and that their performance would be recorded as part of a research study. It was considered important that the exact time at which the drill would take place was not passed onto the passengers until the last possible moment. Furthermore, while it was considered necessary to inform senior members of the crew concerning details of the drill, the majority of the crew should not be informed.

Even so, the degree of forewarning meant that the passengers and crew were alert to the impending drill well in advance. This meant that some passengers did not take the drill very seriously. In addition, a considerable number of passengers disengaged from their normal activities, for example bars and recreation spaces, including the casino were closed and ceased trading, and passengers returned to their cabins and were even donning lifejackets well in advance of the sounding of the alarm. Other passengers were moving towards the designated assembly areas prior to the commencement of the drill.

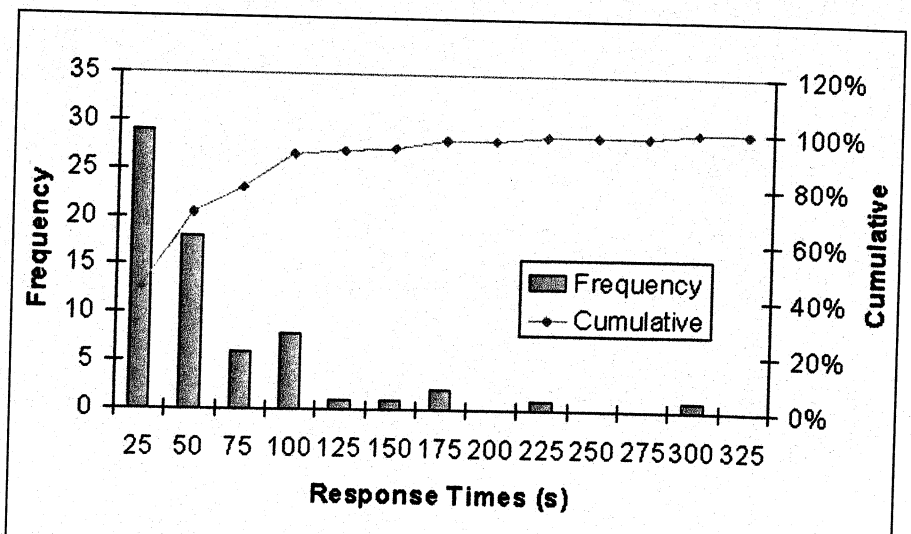
This had the effect of reducing the number of people from which useful response time data could be measured and perhaps of more importance, made the actual measured response time data less reliable as the precise start time for the process was unclear.

In situations with a reduced forewarning, passenger response time may be expected to be longer, with a greater period of time between the sounding of the alarm and the first movement of passengers. In addition, it is possible that levels of congestion experienced in various corridors and other regions of the vessel may be reduced due to the staggered nature of the passenger response.

This is not to say that the data produced in these trials was not representative of some shipboard emergency situations. In some actual shipboard emergency scenarios it is likely that a certain degree of passenger forewarning of the possible need to evacuate will be given prior to the general call to assemble, for example the *Sun Vista* and *Ecstasy* fire incidents.

The response time represents the time between the call to assemble (ie the start of the sounding of the alarm bleeper) and the time that the passenger makes a purposeful movement to leave their location and move towards the assembly area. It was noted that some

Figure 2: Histogram of the frequency distribution of the response times from the bar area across the two trials.



* Recommendations on the nature of passenger response time distribution to inform document MSC 1033 on assembly time analysis based on data derived from sea trials.

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Collection of Evacuation Data for Large Passenger Vessels at Sea

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Abstract In the past decade, significant effort has gone into the planning and execution of full-scale sea trials in an attempt to improve, calibrate and validate existing evacuation models for passenger ships. In September, 2009 two assembly exercises were conducted at sea onboard the RO-PAX ferry SuperSpeed 1 by team members of the EU-funded project SAFEGUARD. The exercises were conducted with passengers during routine sailings between the ports of Kristiansand, Norway and Hirtshals, Denmark. Between both trials, a total of 1,769 passengers were assembled, on day one, 902 passengers and on day two 867 passengers. As part of the data collection exercise, passenger response time data was collected – using video cameras – and passenger movement data was collected using a novel infrared (IR) based position logging system. This paper briefly describes the development and testing of the data acquisition system and briefly discusses preliminary results.

Introduction

Understanding how people behave in emergency situations within maritime settings is vital if we are to; design and develop evacuation efficient vessels and evacuation procedures, train crew in the management of evacuation situations, develop reliable ship evacuation models and regulate the design and operation of vessels. An essential component of this understanding is the collection and characterisation of human performance data. Unfortunately, little data relating to passenger response time or full-scale validation data in maritime environments exists. In the first International Maritime Organisation (IMO) document to specify protocols for the use of ship evacuation models in the analysis and certification of passenger ship design, IMO MSC Circ. 1033 [1], an arbitrary uniform random distribution was set to represent the response time behaviour of passengers. It has been shown that this is unrepresentative of actual passenger response time and liable to produce incorrect or misleading conclusions concerning the suitability of ship design for evacuation [2]. As part of the EU Framework V project FIRE EXIT [3], passenger response time data was collected for a passenger ship at sea [3, 4]. This

The SAFEGUARD project: Collection and Preliminary Analysis of Assembly Data for Large Passenger Vessels at Sea

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Abstract

In the past decade, significant effort has gone into planning and executing full-scale sea trials in an attempt to improve, calibrate and validate existing computer models that simulate evacuation on passenger ships. In September, 2009 two assembly exercises were conducted at sea onboard the RO-PAX ferry SuperSpeed 1 by team members of the EU-funded project SAFEGUARD. The exercises were conducted with passengers during routine sailings between the ports of Kristiansand, Norway and Hirtshals, Denmark. Between both trials, a total of 1,769 passengers were assembled; on day one, 902 passengers and on day two 867 passengers. As part of the data collection exercise, passenger response time was collected using video cameras and passenger movement was collected using a novel infra-red (IR) based position logging system. This paper briefly describes the development and testing of the data acquisition system and discusses preliminary results.

1. Introduction

Understanding how people behave in emergency situations within maritime settings is vital if we are to; design and develop evacuation efficient vessels and evacuation procedures, train crew in the management of evacuation situations, develop reliable ship evacuation models and regulate the design and operation of vessels. An essential component of this understanding is the collection and characterisation of realistic, representative human performance data. Unfortunately, little data relating to passenger response time or full-scale validation data in maritime environments exists. In the first International Maritime Organisation (IMO) document to specify protocols for the use of ship evacuation models in the analysis and certification of passenger ship design, IMO MSC Circ. 1033 (*IMO, 2002*), an arbitrary uniform random distribution was set to represent the response time behaviour of passengers. *Deere et al. (2006)* showed that this is unrepresentative of actual passenger response time and liable to produce incorrect or misleading conclusions concerning the suitability of ship design for evacuation. *Galea et al. (2007)* collected passenger response time data for a passenger ship at sea as part of the EU Framework V project FIRE EXIT (*FIRE EXIT, 2005*). This data was accepted by the IMO and used in the formulation of IMO MSC Circ. 1238 (*IMO, 2007*), the modified protocols for passenger ship evacuation analysis and certification. However, the response time data produced by FIRE EXIT related to only a single passenger vessel. As such the data cannot be considered representative of passenger ships in general. The IMO Fire Protection (FP) Sub-Committee in their modification of MSC Circ. 1033 at the FP51 meeting in February 2007 (*IMO FP, 2007*) invited member governments to provide, "…further information on additional scenarios for evacuation analysis and full scale data to be used for validation and calibration purposes of the draft revised interim guideline". To this end, project SAFEGUARD was proposed and successfully funded through the EU framework 7 programme. The project aims to address this IMO requirement by providing relevant full-scale data and proposing and investigating additional benchmark scenarios that can be used in certification analysis. Six full-scale data sets will be collected as part of SAFEGUARD - two trials on each of three different types of passenger vessels; one with cabins, one without cabins and a cruise liner.

This paper concentrates on the first two data sets collected on the first vessel - a large RO-PAX ferry without passenger cabins operated by Color Line AS called SuperSpeed 1, Fig. 1. The vessel can carry approximately 2000 passengers and crew and over 700 vehicles. It operates on the route