The Computer Simulation of Passenger Ship Evacuation Performance

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1.0 Abstract
In the wake of major maritime disasters such as the Herald of Free Enterprise and the Estonia and in light of the growth in the numbers of high density, high-speed ferries and large capacity cruise ships, issues concerned with the evacuation of passengers and crew at sea are receiving renewed interest. So, when designing a new passenger ship or modifying an existing design, how do we ensure that the proposed design is safe from an evacuation point of view? In the building and aviation industries, computer based evacuation models are being used to tackle similar issues. This paper briefly examines the issues of ship evacuation and describes the development of the maritimeEXODUS evacuation model and further discusses issues concerning data requirements.

2.0 Introduction

Evacuating passengers from ships is a complex task that both shares features with and yet is very different to evacuations involving other enclosures such as buildings, aircraft and rail carriages. First of all, following a ship incident, a decision has to be taken as to whether an evacuation is necessary. Similarly in rail emergencies, but unlike most incidents in buildings or aircraft, it is not always prudent to attempt to evacuate passengers *from* ships. In many situations the safest course of action is to remain onboard the ship as the environment outside can be more perilous than that on board [1]. In such cases the evacuation does not require passengers to abandon ship but to seek safe refuge away from the immediate threat. Secondly, unlike buildings but similar to situations on trains and aircraft, the orientation of the ship may impede easy rapid movement of passengers[2]. However, uniquely to shipping applications, the orientation of the escape paths may be time dependent due to roll.

Thirdly and uniquely to ship situations, a good deal of time consuming preparatory activities must be completed prior to the actual evacuation (e.g. collecting life jackets and assembling at a predefined location). In Exercise Invicta (where 842 volunteer passengers and crew were evacuated from a ferry), the mustering operation required between 11 and 20 minutes[3] effectively delaying and prolonging the evacuation process. Finally and again uniquely to ship situations, for most passengers, the evacuation path is counter intuitive, where the way out of a structure is to normally proceed to street level, on board ship, the way off requires passengers to seek the muster station requiring passengers to travel to an apparently arbitrary location above or below their current position.

3.0 Factors Influencing Evacuation

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), grounding (e.g. Saint Malo Ferry[4]), equipment failure (Estonia[2]) or human error (Herald of Free Enterprise[5]). The layout of the ship interior, the nature of the passenger population, and crew procedures are some of the essential ingredients that need to be considered when designing passenger ship interiors for evacuation purposes. While full-scale evacuation demonstrations with human volunteers provides a means of obtaining some of this information, this process poses considerable ethical (the threat of injury to volunteers limiting the realism of the event), practical (only a single trial is usually conducted) and financial (trials are expensive) problems that bring into question the value of their overall contribution to passenger safety. While useful in demonstrating evacuation capabilities, Exercise Invicta[3] suffered from these shortcomings.

In order to fully assess the potential evacuation efficiency of an enclosure (i.e. ship, building, aircraft, etc), it is essential to address the configurational, environmental, behavioural and procedural aspects of the evacuation process[6]. Configurational considerations are those generally covered by conventional methods and involve ship layout, number of exits, exit type, corridor width, travel distance etc. In the event of fire, environmental aspects need to be considered. These include the likely debilitating effects on the passengers of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding abilities. In addition, the sea conditions can impact on the environment causing heal, list or roll conditions making egress more difficult. Procedural aspects cover the actions of crew, passenger prior knowledge of the ship interior, emergency signage etc. Finally, and possibly most importantly, the likely behavioural responses of the passengers must be considered. These include aspects such as the passengers' initial response to the call to evacuate, likely travel directions, family/group interactions etc.

In the built environment and aviation, sophisticated evacuation models[7] have been developed that attempt to address each of these issues. These models are being used in a routine manner in the design of buildings and in the evaluation of aircraft concepts. If evacuation models are to fulfil their potential, they must be capable of addressing all aspects of the evacuation process. Computer based mathematical models describing the ship evacuation process have the potential of addressing all the factors identified above. In addition they have a role to play in the design and development of ship interiors, the implementation of safer and more rigorous certification criteria, the development of improved and more efficient crew procedures, improved crew training and as a tool for accident investigation.

4.0 Evacuation Models and Data Requirements

Associated with the development of computer based ship evacuation models is the need for comprehensive data collection/generation related to human performance under evacuation conditions. Here it is essential to identify what part of the evacuation process is to be modelled. From the modelling perspective, there are at least five components to a ship evacuation. These are the recognition by passengers of the need to evacuate (i.e. response time), the performance of preparatory actions/behaviours (e.g. reunite family), the progressive evacuation to a place of relative safety (i.e. mustering), the preparation/ deployment of the escape system and finally the act of abandoning the vessel. Depending on the nature of the scenario being simulated, some or all of these aspects may need to be modelled. To perform the required simulation reliably requires a comprehensive evacuation model with the appropriate set of capabilities and access to the necessary data.

The development of evacuation models relies heavily on factual data. Data is first required to identify the physical, physiological and psychological processes that contribute to, and influence the evacuation process. Data is then required to quantify attributes/variables associated with the identified processes and finally data is essential for model validation purposes. Three forms of data are useful in providing the required information. Accident investigation reports that contain human factors analysis and survivor interview accounts are vital in providing information to identify the human element that needs to be simulated. Once identified, the behaviours and passenger performance attributes must be quantified. Data from full-scale and component tests can be used for this purpose and for validation.

The importance of data collection, in all of its forms, cannot be underestimated in the modelling process. The development of useful evacuation models is dependent upon the collection and application of appropriate and useable data. In the next section the development of the maritimeEXODUS model is described. Associated with this is the generation of data relating to passenger performance under conditions of list.

5.0 The EXODUS Suite of Evacuation Models

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. Development on EXODUS began in 1989. The family of models consists of buildingEXODUS[7-8] and airEXODUS[9] for the built environment and aviation applications respectively. The most recent addition to the family is maritimeEXODUS[10-12] intended for use in the shipping and off-shore industry. EXODUS comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models. 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.

The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The spatial grid maps out the geometry of the structure, locating exits, internal compartments, obstacles, etc. Geometries can involve multiple floors, connected by staircases. The structure layout can be specified using either a DXF file produced by a CAD package, or the interactive tools provided. The grid is made up of nodes and arcs with each node representing a small region of space and each arc representing the distance between each node. Individuals travel from node to node along the arcs.

The Population Sub-model allows the nature of the passenger population to be specified. The population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the ship layout, response times etc. On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model. The Behaviour Sub-model functions on two levels. These levels are known as GLOBAL and LOCAL behaviour. GLOBAL behaviour involves implementing an escape strategy that may lead an occupant to exit via their nearest serviceable exit or most familiar exit. The desired GLOBAL behaviour is set by the user, but may be modified or overridden through the dictates of LOCAL behaviour, which includes such considerations as determining the occupants initial response, conflict resolution, overtaking and the selection of possible detouring routes. In addition a number of localised decision-making processes are available to each individual according to the conditions in which they find themselves and the information available to them. This includes the ability to customise their egress route according to the levels of congestion around them, the environmental conditions and the social relationships within the population. Social relationships, group behaviour and hierarchical structures are modelled through the use of a "gene" concept[13], where group members are identified through the sharing of social "genes". Passengers are able to adapt their evacuation strategy according to a rational use of the information available to them e.g. they may wish to communicate information to other passengers, identified as a group member

The Toxicity submodel determines the physiological impact of the environment upon the occupant. To determine the effect of the fire hazards on occupants, EXODUS uses a Fractional Effective Dose (FED) toxicity model[14]. This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour. The thermal and toxic environment is determined by the Hazard submodel. EXODUS does not predict these hazards but can accept experimental data or numerical data from other models including a direct software link to the CFAST fire zone model[15]. EXODUS produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running that allows the user to observe the evacuation as it takes place. The graphics are interactive allowing the user to interrogate occupants and events. In addition, a data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. To aid in the interpretation of results, a post-processor virtual-reality graphics environment known as vrEXODUS has been developed, providing an animated three-dimensional representation of the evacuation.

In the remainder of this paper, marine specific features of the maritimeEXODUS software will be discussed.

5.1 The Generation of Marine Relevant Human Performance Data

Suitable data concerning the performance of passengers under conditions of pitch and roll are not generally available. Data is needed to describe passenger movement rates in corridors, on stairs and ladders, and across large rooms under conditions of pitch, heal and roll. Indeed, not only are the movement rates of individuals required, but insight into possible changes in passenger behaviour under such conditions is also required. While some experiments have been conducted in an attempt to generate this type of data, in general these experiments have involved small test sections generating questionable results or have focussed on the generation of individual data and ignored the effects of crowds. Furthermore, this data has not been made generally available. As such the current version of maritimeEXODUS does not posses marine specific data for the performance of passengers under such conditions. In order to acquire some of this data, Fleet Technology of Ottawa and FSEG with funding from the Canadian Transportation Development Centre have constructed a facility in which human behaviour and performance in a typical ship passageway and stairway can be studied and mobility data collected. As maritimeEXODUS has the flexibility to allow the user to alter all of the pre-set default values, it is easily adaptable when new data becomes available.

The facility comprises a 7m by 4m "cabin" attached to which is a 10m by 2m passageway at the end of which is a stairway. This entire structure is mounted on hydraulic rams capable of tilting the facility to up to 30^{o}. The steel structure reproduces a ship's corridor and stair, with handrails (removable) and facilities to insert a doorway with sill, etc (see Figure 1). Test subjects enter the assembly "cabin" at bottom left of the picture, while the facility is level and the facility is tilted to the test angle only after all "passengers" are in and have secured themselves. Test subjects pass through the passageway and the stairs, individually and in groups. Their behaviour is recorded on video and their movement is timed along the passageway and up/down the stairs. Passengers exit on a fixed platform at the top of the stairs, designed to ensure that passengers clear the test area quickly and do not influence those passengers still in the test area. Tests will be conducted in both directions.

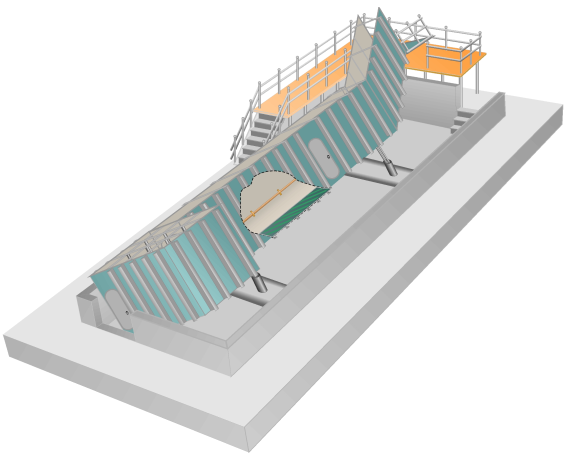


Figure 1: The Ship Evacuation Behaviour Assessment Facility (SHEBA)

The stairway has been designed to allow its gradient to be varied, and the passageway and stairway may be varied in width. Other features that can be introduced to the facility include doors and openings with sills, non-toxic smoke, lighting changes and a few centimetres of water to the deck of the passageway can also be included.

The testing protocol has been developed based on years of experience with such tests in other environments. A full range of "people attributes" has been sought for the tests spanning age, gender, and physical condition. Once the data collection is complete, the data will be incorporated within maritimeEXODUS.

This process represents an attempt to acquire experimental data that relates specifically to inadequacies in the current data available and to an important aspect of evacuation at sea; namely the impact of the angle of the ship on passenger movement.

5.2 THE maritimeEXODUS Abandonment Model

One of the most important additional components of maritimeEXODUS is the development of a flexible and comprehensive abandonment submodel. Conceptually, the abandonment submodel treats the egress system from the ship to external places of safety as independent entities. These entities are themselves formed through the combination of so-called constituent "Life Safety Apparatus". These may be a chute, platform, life-raft, escape pod, davit launched lifeboat, etc. This enables several LSA components to be 'chained' together in order to form a more complex abandonment system. By providing a modular system, a variety of complex and diverse abandonment systems can be represented within maritimeEXODUS (see Figure 2) from several LSA components.

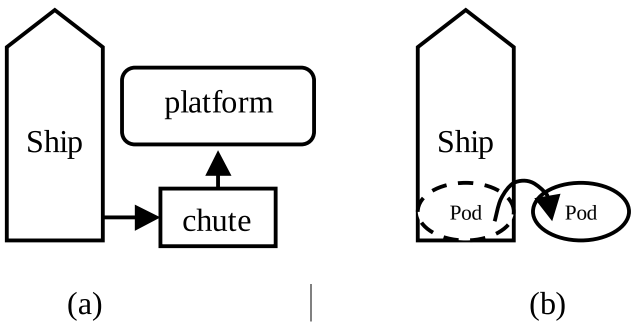


Figure 2: Two examples of the way in which LSA components can be combined to form an egress system.

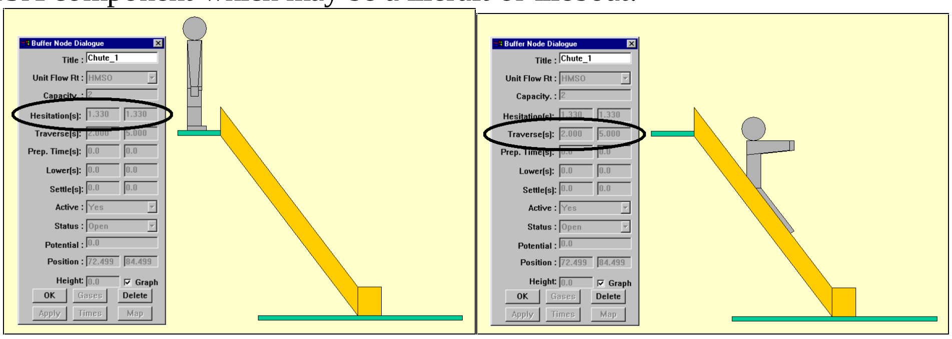
Once a passenger has entered an LSA, his/her path is no longer followed as an individual. Instead the number of passengers simultaneously occupying an LSA is recorded and displayed on the screen. A single means of abandonment is therefore represented as a nodal network formed from separate LSA components. The flow of passengers through the system is controlled by a combination of the attributes of each of the LSA components, the number of passengers moving through the system and the number of passengers that can enter an LSA component simultaneously. Each LSA component has a number of attributes that control the flow of passengers across them. This data is either provided by the user or set via the default library settings, provided for specific types of LSA (e.g. chute, platform, life-raft, davit launched lifeboat, etc.). The attributes associated with each LSA component within the model are:

Capacity- The maximum number of passengers that can occupy an LSA at any given time.
Hesitation (sec) - The time for a passenger to enter the system.
Traverse (sec) - The time for a passenger to travel through the system.
Prep. Time (sec) - The time for the system to be prepared.
Lower (m/s) - The rate at which the system is lowered.
Settle (sec) - This is the time for the LSA to settle into the water.
Height (m) - This represents the initial height of the LSA above the water.

LSA entities are connected together by arcs. These arcs have an associated 'width' attribute which determines the number of passengers that can enter an LSA simultaneously. For instance, the width attribute for an arc connected to a chute LSA would represent the number of lanes into the chute while the arc width connecting a lifeboat LSA would represent the number of vantage points at which passengers may enter the lifeboat. While all of these attributes may not be appropriate for all types of LSA components, by using a combination of attributes, all abandonment systems can be represented. Where an attribute is not required, it is simply set to zero and therefore has no impact on the system.

The design approach adopted for the abandonment model was selected as it was considered to be sufficiently flexible to cater for current and future designs of abandonment systems. Furthermore, the behaviour of individual passengers within each LSA is either unknown or difficult to ascertain, thereby precluding the detailed modelling approach adopted for the bulk of the maritimeEXODUS model.

To demonstrate the use of this submodel a simple slide/chute has been selected as an example. Here, the Preparation, Lower and Settle time attributes have no actual meaning and are therefore set to zero. Upon reaching a slide/chute each passenger will typically experience a hesitation prior to committing to jump (see Figure 3a). The hesitation time is calculated randomly for each individual between experimentally determined minimum and maximum values specified within the dialogue box. When a passenger has waited for their calculated hesitation time they can then set about traversing the slide/chute LSA (see Figure 3b). Once again, the time taken to traverse the LSA is calculated randomly for each individual between experimentally determined minimum and maximum values. Having traversed the slide/chute LSA each passenger can then progress to the next LSA in the chain. In this case it would be a platform, with another set of attributes, from the platform the passenger would move onto the next LSA component which may be a liferaft or lifeboat.



(a) (b)

Figure 3: Evacuation via a slide/chute

5.3 Other maritimeEXODUS Developments

In addition to the development of the abandonment model, a number of other developments are underway or already implemented within the maritimeEXODUS prototype. These are briefly described in this section. Prior to passengers abandoning the vessel, they must collect their life-vests or be issued with life vests. The nature of this behaviour will be dependent upon the time of day that the emergency takes place (i.e. day or night), the type of vessel involved (e.g. passenger ship, high speed craft, ferry, etc) and the specific procedures employed. Therefore passengers may have to return to their cabins (e.g. passenger ship), their seats (e.g. high-speed craft) or head directly towards a muster station (e.g. ferry), prior to abandoning the vessel. Within the maritimeEXODUS prototype, all of these factors can be determined by the user, as can the requirement of staff at the muster stations, the passenger allocation to each muster station and the location of the muster stations.

As maritimeEXODUS has a number of behavioural capabilities, the user can select one of two default settings. These enable either the set-up of a so-called “certification scenario” or a more “general scenario” to be selected. Certification scenarios will involve the activation of a limited set of behavioural capabilities. These will be more clearly defined once either IMO or national regulatory groups establish a set of guidelines appropriate for certification analysis. However, under the certification setting, it is envisaged that the hazard and toxicity capability will be deactivated and passengers will move directly to their assigned muster stations from their starting locations. Starting locations can be assigned depending on whether a day or night scenario is being considered. For the more general setting the full behavioural capability will be available allowing the simulation of any number of different scenarios.

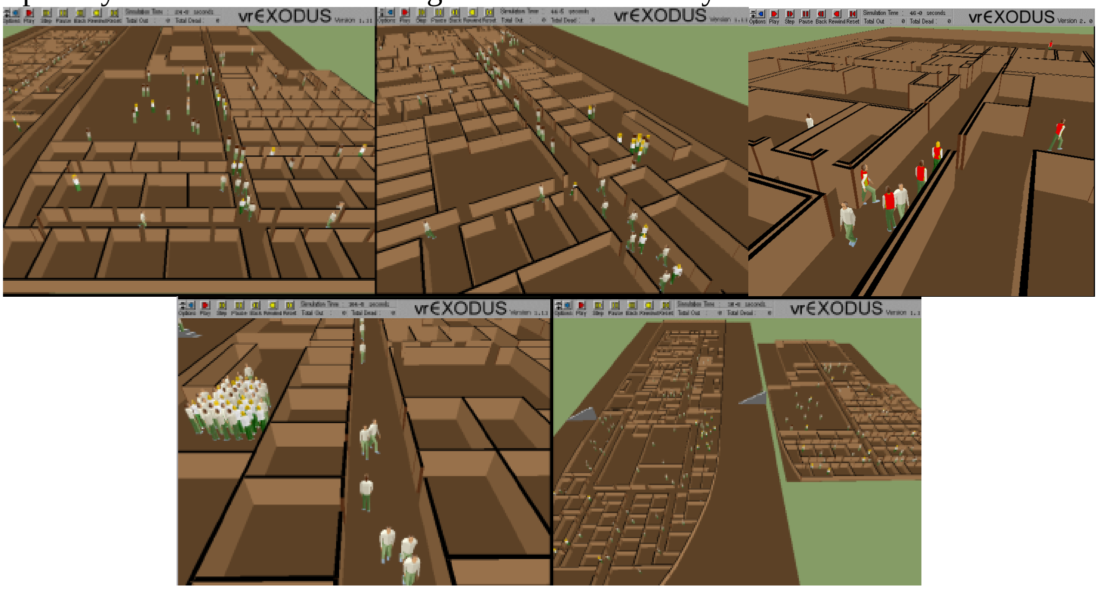


Figure 4: vrEXODUS representation of maritimeEXODUS predicted ship evacuation.

A simple demonstration of the current capabilities of the maritimeEXODUS prototype is presented using a section of a hypothetical passenger ship. The section under investigation consists of two decks containing passenger cabins and public rooms (see Figure 4 bottom right). In the section shown, two main stairways link the two decks, one on the port and the other on the starboard side of the ship. A total of 200 passengers are located in the section under consideration, most of which are positioned in their cabins. In the scenario under consideration, the muster stations are located on the lower deck. In the simulation passengers must retrieve their life jackets from their cabins before moving to their particular assembly stations. In this particular “what if” situation, the emergency occurs during daylight hours and in calm conditions.

The majority of passengers move to their muster stations once their life jackets have been retrieved. Figure 4 (top centre) shows a scene from the lower deck with the corridors filling with people as they make their way to their muster stations. A small group can be seen already located at a muster station. Figure 4(top left) depicts a scene from the upper deck. As can be seen, some passengers are moving along the corridors to the staircases, where some passengers are still in their cabins while other passengers are still gathered in the public spaces.

The following types of behaviours are included in the scenario:

- Not all the passengers react initially to the command to gather at the assembly stations. Some of the passengers require time to react.
- The majority of passengers return to their cabins and pick up their life jackets. Once a life jacket is donned, the passenger changes colour to yellow (see Figure 4, top right). This allows for easy identification in the VR animation.
- Some passengers go in search of their group members prior to retrieving life jackets. Thus passengers from the lower deck go to the upper deck which creates contra-flow situations in the corridors and more importantly on the staircases.
- Some passengers undertake a room to room search for lost group members.
- Some passengers go to the wrong muster station and are redirected to their correct muster station, again creating contra-flow situations in the corridors.
- Crew members are moving towards various duty stations, this also creates contra-flow situations within the corridors and staircases.
- Once at the muster stations, passengers gather in groups awaiting the command to evacuate. Depicted in Figure 4 (bottom left) is a large group of passengers gathered at a muster station however, several passengers are still moving along the corridor heading towards their muster stations.
- Once the command to abandon is given, passengers exit the vessel.

6.0 Concluding Comments

Evacuation models are an established reality in the building and aviation communities. In these industries, these models are becoming a cost effective way to achieving safer and more functional design solutions, allowing designers to seek answers to questions that can not be addressed using conventional approaches. Evacuation models are also appearing in the maritime industry.

The maritime industry must co-operate and work together to provide the data essential for the further development and validation of these models. The challenge facing regulators and approval authorities is to develop an understanding of the modelling technology being developed and with that understanding specify relevant design standards and protocols. It is essential that a minimum range of relevant design scenarios as well as acceptance criteria become universally accepted. These should encompass the:

- nature of the target population being investigated e.g. movement capabilities, response times, etc,
- emergency conditions under which the evacuation takes place e.g. night/day, fire/no fire, etc, and
- performance requirements that the proposed design much achieve to satisfy a deemed to comply requirement.

It is hoped that industry and regulatory authorities will explore these issues as they hold the potential to make already safe form of transport safer by design.

7.0 Acknowledgements

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