Ship Evacuation Simulation: Challenges and Solutions

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ABSTRACT

In the wake of major maritime disasters such as the Herald of Free Enterprise and the Estonia, (and several offshore rig disasters), 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. The High Speed Code introduced the concept of performing critical path analysis of the evacuation arrangements, SOLAS regulation II-2/28-1para 3 required Ro-Ro passenger ships built after 1 July 1999 to have an early design stage evacuation analysis performed and more recently IMO has developed and issued Guidelines for a Simplified Evacuation Analysis on Ro-Ro passenger vessels[1]. However, emphasis to date has been on the physical arrangements with little consideration of the human, behavior and environmental factors associated with emergency evacuation. IMO has also recently started to develop guidelines for more detailed simulation tools for analyzing evacuation from passenger ships. This paper describes the development of such a tool and aspects associated with the collection of marine specific human performance data.

The simulation of evacuation requires quite complex modeling of human behavior and the environment, and a number simulation tools have been developed in other industries. The well-established EXODUS evacuation model suites used in the building and aviation sectors are described and are the basis for the development of a ship evacuation model. The newly developed models have a high level of sophistication in handling of human performance, accounting for population variance, decision-making, and the interaction of people with various environmental factors. However, in order to accommodate the variety of ship based scenarios – such as movement of passengers and crew on heeled passageways – it is essential that appropriate human performance data is collected and incorporated within these models. The paper describes a unique experimental facility that has been constructed to assist in this data collection.

INTRODUCTION

In the wake of major maritime disasters such as the Herald of Free Enterprise and the Estonia, as well as several offshore rig disasters, 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 Code introduced the concept of performing critical path analysis of the evacuation arrangements, SOLAS regulation II-2/28-1para 3 required Ro-Ro passenger ships built after 1 July 1999 to have an early design stage evacuation analysis performed and more recently IMO has developed and issued Guidelines for a Simplified Evacuation Analysis on Ro-Ro passenger vessels [1]. IMO has established standard times for evacuation from passenger vessels, and owners are required to demonstrate compliance through full-scale tests.

Demonstrating compliance with evacuation requirements through full-scale evacuation exercises is expensive and difficult to organise, and the circumstances bear little resemblance to what would happen in a true, emergency-driven evacuation. Consequently this form of proof of concept is more of an index allowing comparative evaluation, but providing little indication of what might happen in a real emergency.

This is recognised by the community, and it has been accepted that simulation-based evacuation analysis tools are the way of the future. There is, therefore, considerable interest in the development of

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simulation tools to explore the evacuation phenomenon. Emphasis to date has been on the physical arrangements for evacuation – (location of exits, and firefighting gear, width of passageways, etc.) with little consideration of the human and environmental factors associated with emergency evacuation. A number of researchers [2],[3],[4], are developing computer simulations for the study of marine evacuation, accounting for the human performance and the effects of the environment in addition to the physical layout. This paper describes the modeling challenge, introduces such a tool, discusses aspects associated with the collection of marine-specific human performance data, and calls for a co-ordinated effort to collect the necessary data.

**Defining Evacuation**

In this paper, the term “evacuation” refers to all that activity which takes place from the sounding of an alarm to leaving the ship. It is generally divided into two stages:

“Mustering” in which passengers assemble at pre-defined assembly points onboard the ship – generally close to the point where they will embark on a lifeboat or enter an escape chute, (this is also referred to “Escape”, and

“Abandonment” when the passengers actually leave the vessel using various means to transfer to other vessels, survival craft, or the water. In some work this is referred to “evacuation”.

Of course the mustering station is frequently not directly adjacent to the evacuation system. It is more convenient to muster passengers or crew in a large space for briefing, checking personnel lists, life vests, etc., and awaiting the abandonment order, and only thereafter do people move to their designated lifesaving stations, this time as a controlled group.

The complete evacuation process therefore embraces:

- Reacting to the alarm – hearing it, determining it is real, etc.
- Deciding where to go - head for the exit or go to a lifeboat or to a cabin to fetch life jacket, in search of valuables, family, friends, etc.
- Retrieving and putting on life jacket –
- Getting to the Muster stations
- Moving as a group to the abandonment station ( if not the muster station)
- Deploying the Life Saving Appliance, establishing its functionality, explaining its use, and
- Abandoning the ship –, going down a slide, climbing down a ladder, jumping into the sea, lowering the lifeboat, etc.

A further stage – “Rescue” is not dealt with in this paper.

A further definition used in this paper is **LSA** – Life Saving Appliance, being a term covering lifeboats and rafts as well as Marine Escape Systems such as chutes and slides.

**The Ship Evacuation Modeling Problem**

Evacuating occupants from any inhabited enclosure is a complex and difficult task. There are a multitude of factors that come into play and can influence the nature of the evacuation. There has been much research in this area for building and aircraft evacuation. While buildings and ships (and trains and aircraft) may be very different types of physical structures, when it comes to evacuation issues, they have a surprising number of features which they share in common, as well as a number of features which are unique to the particular type of enclosure. In developing analysis tools for ship evacuation it would be wise to draw heavily on this research and knowledge base.

Large passenger ships comprise cabins (rooms), passageways, public spaces, stairs, etc., and have doors and elevators, similar to a building. Smaller passenger craft such as high speed ferries and tour boats may comprise high density aircraft style seating. Therefore, a universal ship evacuation simulation model can benefit from the significant work carried out for buildings and aircraft. While there are physical similarities, the human and operational aspects of evacuation from ships may be quite different. For example, 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. Unlike building situations, but similar to situations on trains and aircraft, the orientation of the ship may impede easy rapid movement of passengers. However, unique to shipping applications, in extreme situations, the orientation of the escape paths may be time dependent due to increasing list or trim, and, in addition, may be subject to motion.

Also unique to ship situations, a good deal of time consuming preparatory activities must be completed prior to the actual evacuation. Passengers are instructed to collect life jackets (usually located in cabins or assembly stations) and passengers are usually further required to gather in pre-defined assembly (or muster) stations prior to attempting to disembark. Unlike the situation in buildings where the way out of a structure is normally to proceed to street level, on board ship, the way off requires passengers to seek this muster station. This could require passengers to travel to an apparently arbitrary location above or below their current position and to the port or starboard. Furthermore, the routes can be complex and confusing to passengers not accustomed to the marine environment. Even the term
“muster station” may be unfamiliar to many passengers and there has been a suggestion that this be replaced with a more understandable “Assembly Station”

Finally, unlike in buildings, where getting to an external exit usually marks a successful evacuation, passengers in ships are usually faced with the additional ordeal of getting from the exit to a place of safety. This can mean getting onto an evacuation slide or getting into a life raft/boat and thereafter perhaps facing additional hazards due to weather/exposure, etc. The fact that the evacuating passenger’s ordeal may not be over after the evacuation has taken place may have significant psychological effect on the behavior during evacuation.

In short, modelling the ship evacuation process introduces a number of unique challenges as the vehicle, environment and operating situations are quite complex.

**IMO Regulations**

IMO has introduced prescriptive regulations for passenger ships and defined some maximum target times for steps in the process. For example, in the SOLAS Chapter III Regulation 21 para 1.4, the maximum time from the time the abandon ship signal is given to prepare all survival craft for abandonment is set at 30 minutes. In the High Speed Craft Code there is a requirement to evacuate the entire vessel in a timeframe that is based on a formula that incorporates the structural fire protection time, margins of safety and recognizes an initial 7-minute detection and extinguishing time. However, it is recognised that these times are somewhat arbitrary and fail to address the unique situations that can arise in a given situation.

Ideally, it is desirable to be able to calculate the available safe time for evacuation (ASET) in every possible emergency scenario, choose the worst one and then calculate the actual (or required) (RSET) evacuation time for the population that is onboard to show that it is less than the worst ASET. Given the number of possible scenarios in most cases however, this is hardly practical.

Nevertheless, IMO has recognized that analyzing evacuation arrangements by addressing the layout aspects only (width of passageways, location of exits, etc.) is inadequate, and is working on the development of guidelines for performing simulations. In 1999, the Interim Guidelines for a Simplified Evacuation Analysis of Ro-Ro Passenger Vessels was introduced [1] and has been exercised on a number of occasions. IMO has recognized that these guidelines, while better than that which existed before, make some critical simplifying assumptions, and are an interim approach. More sophisticated modeling is desirable and achievable. The work is continuing through the Fire Prevention Sub-Committee Correspondence Group to FP46. In addition to reviewing the interim simplified analysis with a view to drafting guidelines for application to Ro-Ro passenger and other passenger ships, the correspondence group is currently working towards some standards for more sophisticated simulation tools, developing validation guidance for these tools, and addressing how these analyses will be applied to existing ships.

This activity will include:
- development of philosophy and methodologies that are suitable for computerized evacuation analysis,
- definition of the parameters of importance requiring modeling, and
- validation criteria.

Since the range of potential emergency scenarios to be modeled is large, it is anticipated that some standard scenarios will be defined – perhaps differing from one type of passenger ship to another – and these will be used with the developing simulation models to assess designs, etc.

Much detailed progress is currently being made in this area and can be gauged through recent FP reports [e.g. 5,6]. This IMO effort represents an opportunity for countries with an interest and capability in this area to work together to address this complex issue.

**Modelling Evacuation**

In order to fully assess the potential evacuation efficiency of a ship, it is essential to address the configurational, environmental, behavioral and procedural aspects of the evacuation process [7].

**Configurational** considerations are those generally covered by conventional methods and involve enclosure layout, number of exits, exit type, corridor width, travel distance, etc. However, as noted above, there are important, additional considerations. In the event of fire or flooding, **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 and/or water ingress, on travel speeds and way-finding abilities. In addition, for ship-based environments the sea conditions can impact on the environment causing list or rolling 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 **behavioral** 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.

Traditional methods for evacuation arrangement design and analysis fail to address all these issues in a
quantitative manner preferring to rely almost totally on judgement and a set of “prescriptive rules”. As these “prescriptive rules” have an almost total reliance on configurational considerations such as travel-distance and exit width, they can prove to be too restrictive. Furthermore, as these traditional methods are insensitive to human behavior or likely emergency scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency.

As an alternative to the prescriptive approach, simplistic “hand calculations” are often used and it is this approach that is embodied in Reference 1. These calculation methods tend to concentrate solely on the capacity of the various components of the ship’s interior and as a result, this methodology is often referred to as a “hydraulic” model. To illustrate this point the following are some of the assumptions listed in the Interim Guidelines [1]:

- All passengers and crew begin the evacuation at the same time and will not hinder each other.
- Passengers and crew will evacuate via the primary escape route.
- Flow is only in the direction of the escape route and there is no overtaking.
- No passengers and crew have disabilities or medical conditions that will severely hamper their ability to keep up with the flow.
- Full availability of escape arrangements is considered.
- People can move unhindered.

As with the prescriptive rule approach, by ignoring the human, environmental and procedural factors, these assumptions concentrate the analysis once more on the configurational aspects of evacuation. In an apparently more sophisticated, yet still crude approach, computer models in which the behavior of individuals is essentially ignored have been developed. The direction and speed of egress is determined by physical considerations only (e.g., population densities, exit capacity, etc.). This methodology is often referred to as a “ball-bearing” model as individuals are treated as unthinking objects that automatically respond to external stimuli.

Sophisticated evacuation models [7] are being developed that attempt to address each of the identified factors that influence evacuation. Some of these models are being used in a routine manner in the design of buildings and in the evaluation of aircraft concepts. One such model, buildingEXODUS [8-9] is routinely used in 18 countries for the design of airport terminals, shopping centers, museums, hospitals, etc., and a sister program airEXODUS [10,11] has been used in design evaluation projects for Airbus, Boeing, British Aerospace and Bombardier. This “EXODUS” suite of programs is designed to simulate the evacuation of large numbers of people from a variety of enclosures.

On the basis that ships share many of the features/conditions of evacuation with buildings and aircraft, the EXODUS suite was chosen in the project described herein, to develop a ship evacuation simulator. MaritimeExodus is a derivative of this EXODUS suite of software tools designed by the Fire Safety Engineering Group of the University of Greenwich. While this paper is based on the MaritimeExodus model, the principles discussed are relevant to a number of similar models.

General Features of Evacuation Simulation Models

The two primary parameters in an evacuation simulation are space and time. These spatial and temporal dimensions in the model 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. Layouts with multiple decks can be made up of multiple grids connected by stairways, with each deck being allocated a separate window on the computer display. The ship layout can be specified using either a “.dxf” file produced by a CAD package, or the interactive tools provided, and may then be stored in a geometry library for later use. The grid is made up of nodes and arcs with each node representing a small region of space (generally about 0.5m by 0.5m) and each arc representing the distance between each node.

It is worth noting that one of the principal differences among the models under development is the “coarseness” of this node-arc mesh. A spatial representation, such as is noted above, is deemed a “fine mesh” model (the term, “microscopic model” has been adopted by the IMO working group). Other models (e.g., Ref. 2) assign a single node to a whole space or compartment – a “course-mesh” model.

Individuals travel from node to node along the arcs. Figure 1 shows the grid mesh for a single deck of a sample ship layout, and Figure 2 is a close-up showing the node arc arrangement. In the current model, meshing progresses automatically and rapidly, and logical adjustments are made to cell sizes to fit actual geometries such that all habitable space is covered.

Nodes are of different types, and have different attributes. The most common node is a “free space” node that allows unhindered movement. Other nodes include boundary nodes that are adjacent to an obstruction, stair nodes, and specialist nodes for seats, LSAs and others.

Core attributes common to all nodes include an identifier and location, and a primary attribute is “potential” – essentially the physical distance from the
nearest exit, which, combined with the exit attractiveness, forms the “potential map” which controls the movement of occupants. Node attributes also include the environmental factors at the node (temperature, toxic gas or smoke density).

Figure 1: Meshing of a Deck Plan

Figure 2: Details of Arc-node Mesh

The input allows the user to use a number of default scenarios such as those that may be defined by IMO for analysis, and default performance attributes. However, the informed user can override many of these to investigate the effects of changes or additional information. The program may also be set to run in a batch mode, which will generate a large number of runs in order to provide the necessary statistical output. It is
anticipated that the exact nature of these choices in the final version of the program will be designed to meet guidelines that may be produced by working groups within IMO over the coming months.

Once the physical configuration of the vessel is defined, the user provides data used by the Maritime EXODUS sub-models. Like others in the EXODUS suite, these comprise five core interacting sub-models: the Occupant, Hazard, Toxicity, Behavior, and Movement sub-models (Figure 3). The software describing these sub-models is rule-based, the progressive motion and behavior of each individual being determined by a set of heuristics or rules.

![Figure 3: Interaction of Maritime EXODUS Modules](image)

The Occupant Sub-model allows the nature of the population of crew and passengers to be specified. This 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, and its escape arrangements, response times etc. This information can be provided to each occupant individually or in groups. Table 1 lists the Occupant attributes considered.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Fast Walk Speed</td>
</tr>
<tr>
<td>Age</td>
<td>Walk Speed</td>
</tr>
<tr>
<td>Weight</td>
<td>Leap Speed</td>
</tr>
<tr>
<td>Height</td>
<td>Crawl Speed</td>
</tr>
<tr>
<td>Response Time</td>
<td>Up-Stair Speed</td>
</tr>
<tr>
<td>Mobility</td>
<td>Down-Stair Speed</td>
</tr>
<tr>
<td>Agility</td>
<td>Target Exit</td>
</tr>
<tr>
<td>Drive</td>
<td>Familiarity</td>
</tr>
<tr>
<td>Patience</td>
<td>Itinerary</td>
</tr>
</tbody>
</table>

While many of the attributes listed are self-evident, a number warrant some further explanation:

- The Mobility attribute allows the introduction of physical disabilities, and/or the introduction of response to the environment such as toxic gases. Mobility is used in conjunction with travel speed and agility.
- The Agility attribute is used in conjunction with the mobility attribute, but is a reflection of the prowess of the occupant and their ability for example to leap over a seat or table.
- The Drive attribute is an indicator of an occupant’s assertiveness and modifies the behavior, for example, when competing for possession of a node.
- The Patience attribute is the amount of time an occupant is prepared to wait before considering another action.
- The Response time is the time the occupant takes between the first sounding of the alarm and reacting. This is a critical value, having a significant effect on the evacuation time.
- The Target Exit attribute allows the user to specify a LSA and to ignore the potential map approach to exiting. This will be used commonly in passenger vessel evacuation.
- Familiarity allows the user to account for the occupant's knowledge of the LSAs. This can either be a single LSA (default) or a list up to all (e.g., Crew member). This influences local behaviour.
- The itinerary attribute is the attribute that allows the user to specify “tasks”. In essence, this lists nodes to which the occupant must go to prior to making for the LSA, and is where one sets the requirement to go to
cabin first, or to muster stations or to the location of other occupants.

While the scope of the data is comprehensive, much of the data is present by default. While much of this data for these characteristics has been built up from years of experiments in buildings, data specific to mobility in a ship are required. For example, modification of the speed on a stair is required to accommodate steeper stairs and ladders, and is accomplished by modifying the value in the defined characteristic by a modifier that is an attribute of the actual item (stair, ladder) and is also a function of an individual's personal attributes.

The Hazard sub-model controls the atmospheric and physical environment in both spatial and temporal terms. In the former case, this includes the spatial and temporal distribution of fire hazards (CO, CO\(_2\), O\(_2\), O\(_3\), depletion, etc.) heat, and smoke, and water. This model also sets any physical restrictions such as the opening and closing times of doors, etc.

The Hazard sub-model will impose these hazards on the escapees as they move through the model. This sub-model also has the capability to accept experimental data or numerical data from other models. For example, output files from certain fire spread models can be directly read into the program.

An example of manual specification of a hazard would include:

a) (spatial) defining the zones in which the hazard is growing: (Zone 1 is stairwell, Zone 2 is corridor and cabins 1 to 4, Zone 3 is cabins 5 to 8, etc).

b) (temporal)

   For 0<\(t<10\)
   
   Temperature = ambient + 0.01*\(t^2\)

   For \(10<\(t<100\)

   Temperature = ambient + 0.1*\(t^2\)

The Toxicity sub-model determines the physiological impact of the environment (Hazard) on the occupant. For example, the core toxicity model implemented is the Fractional Effective Dose (FED) model of Purser [12]. 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 behavior, the occupant is allowed to stagger through smoke filled environments and is given the ability to select another exit path when faced with a smoke barrier based on their familiarity with the structure. Furthermore, as the smoke concentration increases and visibility decreases, the travel speed of the occupants is reduced according to experimental data. Movements may slow and eventually result in casualties.

While it is expected that the flooding model will be dealt with similarly, it is still under development as there is little or no data on which to base the model.

On the basis of an individual's personal attributes, the Behavior sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement sub-model. The model has the capability of implementing two behavioral regimes: NORMAL and EXTREME behavior. Under NORMAL behavior, an occupant is prepared to wait until it is possible to make the desired move. Under the EXTREME regime, occupants will wait patiently until a period of time equal to their user defined “patience attribute” has been met, before taking actions that result in them jostling around or possibly recommitting to another course of action.

The Behavior sub-model is the most complex module, and incorporates adaptive capabilities that include, structural knowledge, reaction to communication, affiliative behavior, occupant motivation and a stochastic element to the queuing recommitment behavior. The basis of the model is a series of rules.

The Behavior sub-model functions on two levels. GLOBAL behavior involves implementing an escape strategy that may lead a passenger to exit via their nearest serviceable exit, an assigned exit, or most familiar exit. As noted above, the evacuee's familiarity with a particular ship layout may be set by the user prior to commencing the simulation, thus enabling a distinction between crew and passenger. This important feature can be used to examine, for example, the effect of crew/passenger ratios. Also as noted it is possible to assign individuals with an itinerary of tasks – for example visit a pre-defined location such as a cabin (to fetch lifejackets) - that must be completed prior to evacuation. This is an essential feature if one is to simulate crew who must take up duty stations during an evacuation. Finally, each individual or a group of individuals can be assigned a specific muster station or LSA for their target exit.

As an example of how the exit strategy is modeled, in the case where the occupant is exiting via the nearest exit, the occupant follows the potential map which is formed around the exits, moving always to a lower potential, side stepping to a node of equal potential if no lower is available, and waiting if only higher potentials are available. The potential – (or attractiveness) of exits can be changed which can reflect the occupant familiarity, available signage or visibility of the exit.

LOCAL behavior includes such considerations as determining the passenger's initial response to the call to evacuate, i.e., will the passenger react immediately or after a short period of time or display behavioral
inaction, conflict resolution, overtaking and the selection of possible detouring routes. The manner in which an occupant will react to local situations is determined in part by their attributes. As certain behavior rules, such as conflict resolution, are probabilistic in nature, the model will not produce identical results if a simulation is repeated.

An evacuation model based on building evacuation is missing two significant aspects required if a comprehensive ship evacuation simulation is to be developed. First, the abandoning phase – step 5 above – is not modeled, and second, there is little or no data available to support the performance of evacuees under conditions of an angled deck – due to heel or trim - or motions. We address these issues in the next sections.

The Abandonment Phase

In a ship environment, it is often best practice to remain on the ship in an emergency unless it is deemed that the ship is doomed. Consequently much emphasis is placed on the process of getting to the muster station, dressed appropriately and ready to evacuate. This is surely a more common event than an actual full evacuation. The discussion earlier in this paper has addressed some of the modelling issues during this musterling stage where passengers and crew may be moving independently and under duress.

However, the abandonment phase is also of significance. It is here where prescriptive rules have been set for maximum times to lower lifeboats, for example. A ship evacuation simulator must model all 5 stages of the process, but must have the ability to report performance during the mustering stage separately from that of the abandonment phase.

The abandonment model includes the definition of lifesaving appliances (LSA) (survival craft and MES), their location, type performance data and their status. Passengers may be assigned to a craft or MES. Crew are also assigned to an LSA, so if a lifeboat requires two crew to be present before it can be operated, this criteria must be met before the device is operational. Again, these options are dealt with by defaults that can be overridden by the user if desired.

Marine Evacuation Systems (MES) such as slides and chutes, with their accompanying platforms and liferafts are treated at component level – that is the slide has performance criteria, as does the platform at the bottom, etc. This approach has two major benefits: 1) the program can readily accommodate other configurations of MES which may emerge in the future, and 2) the program can be used to assess the “design” of such systems – e.g., the impact of a double slide/single platform, versus a single slide/ single platform on evacuation times.

Figure 4 is the LSA dialogue box and shows the characteristics that have to be specified for LSAs – the “Active” characteristics being dependent on the type of LSA defined.

This dialogue includes such items as hesitation at the top of a chute, system preparation time, and for lifeboats, the lowering speed and the height. It is here that default data from manufacturers and from trials will be inserted.

![LSA Dialogue](image)

With Marine Evacuation Systems in the form of chutes and slides, it is possible to draw on the experience of many evacuation exercises from aircraft. For example, in the absence of marine-specific data, data for passenger hesitation at the top of the slide may be deduced from aircraft experience. However, data collection from escape system certification and other trials is required.

The second marine-specific issue is that of the effect of ship attitude and motion. While some work in this area has been carried out recently [Refs 13,14] in the absence of the necessary data, a facility was constructed in which to collect this vital information, as discussed later in the paper.
Program Output

The model produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running (see Figure 5). Output times for individuals, total time to muster and evacuate, and graphs of numbers evacuated versus time are produced for comparison against prescribed standards. The user can observe the evacuation as it takes place, and can interrogate occupants and events. A “population density” mode provides immediate indication of points of congestion. A data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. The track of any individual, or the longest track, etc., can be shown. To aid in the interpretation of the results produced by the model, several data analysis tools have been developed. These are intended to be used once a simulation has been completed and enable large data output files to be searched and specific data selectively and efficiently extracted.

In addition, a post-processor virtual-reality graphics environment has been developed (vrEXODUS), providing an animated three-dimensional representation of the evacuation (see Figure 6). This presentation is most useful for demonstrating where counterflow is causing problems in passageways. One of its features is that individuals who carry out the “fetch lifejacket” task are shown to change upper body colour (to yellow) when they are wearing their lifejacket – after a pause to put it on!

Figure 5: Interactive Two-Dimensional Animated Graphics
Figure 6: vrEXODUS representation of maritimeEXODUS predicted ship evacuation.

Example

The example of MaritimeEXODUS prototype that is shown in the previous figures is a section of a hypothetical passenger ship. The section under investigation consists of two decks containing passenger cabins and public rooms (see figure bottom right of Figure 6). 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 assembly 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 situation, the emergency occurs during daylight hours and in calm conditions. The following types of behavior 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 returns to their cabins and pick up their life jackets.
- 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 that 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.
- The majority of passengers move to their muster stations once their life jackets have been retrieved. Figure 6 (top right) 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 6 (top left) depicts a scene from the upper deck. As can be seen, some passengers are moving along the corridors to the staircases, some passengers are still in their cabins while other passengers are still gathered in the public spaces.
- 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 6 (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. The example shown is for a larger vessel with accommodation type arrangements. However the program – using the development work for airEXODUS – can readily address the smaller vessel outfitted with high density seating. Behavior attributes address the behavior of passengers in such seating and their mobility as they move across other seats into a clear passageway.

The emphasis in this area must now be in collecting valid data and validating these simulations. It is noted that even if a simulation has not been validated to the extent that the full-scale behavioural measures are not precisely predicted, it can still be very useful in trend analysis or in assessing the relative difference in performance among design options. In concluding this section, we note that computer-based evacuation models that can address configurational, environmental, behavioural and procedural aspects of
the evacuation process have additional roles to play in the following areas:

- Design and development of ship interiors bringing safety matters to the design phase while the proposed layout is still on the drawing board.
- Implementation of safer and more rigorous certification criteria.
- Development of improved and more efficient operating procedures.
- Improved crew training.
- Accident investigation.

Data

Associated with the development of computer-based evacuation models is the need for comprehensive data collection/generation related to human performance under evacuation conditions. Empirical data regarding the evacuation process is essential to the development of computer evacuation models. Evacuation models have a high reliance on empirical in order to:

(a) Identify the physical, physiological and psychological processes that contribute to, and influence the evacuation process and hence formulate appropriate models.
(b) Quantify attributes/variables associated with the identified processes.
(c) Provide data 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 (i.e., item (a) above) that needs to be simulated.

Full-scale and component tests can be used to quantify, the behavior and occupant performance attributes (i.e., item (b) above). When undertaking experimentation, it is essential to ensure that a representative population is used for data collection, and it is important to make use of data that already exists in other sectors whenever possible, provided that care is taken to use appropriate data.

Finally, data is required for validation purposes.

Validation

The validation of such models is a subject worthy of an entire paper and is discussed in Ref [15].

There are at least four forms of validation/testing that evacuation models should undergo. These are: (i) component testing; (ii) functional validation; (iii) qualitative validation; and, (iv) quantitative validation.

While each of these four components is essential to the validation process, quantitative validation relies heavily on the availability of considerable amounts of data. Quantitative validation involves comparing model predictions with reliable data generated from full-scale evacuation demonstrations. Here it is essential to emphasize the reliability of the data namely the integrity of the data, the suitability of the experiment and the repeatability of the experiment.

The basic model suite on which the program described herein is based has been well validated over the years against building and air evacuations. References [16] and 17 are cited. Validation against historic data, comparisons of “blind” model predictions with historic data, and comparing the nature of predicted human behavior with expectations have all been carried out. Quantitative validation requires comparison with Repeated trials data because of the variability in human behaviour, and this has been largely in the aviation industry. An example of a comparison of an AirExodus simulation with a series of tests on a B737 is shown in Figure 7.

![Figure 7: Comparison of AirExodus Simulation](image_url)
However, to date there is limited validation for a ship evacuation simulation. The IMO Correspondence Group is currently using a standard case study to compare emerging models. It is possible that a full-scale evacuation of a passenger vessel will be organised for validation purposes. Partial validation can be achieved with limited full-scale exercises, and a number of opportunities are presenting themselves this year. As this paper goes to print, two exercises – one on a FPSO and the other on a small passenger vessel are being planned and the data from these will be used for validation.

Ship Evacuation Behaviour Assessment Facility (SHEBA)

As noted above, there is very little published data on human performance specifically in some of the environments and configurations that may be specific to a ship evacuation. The most obvious examples of this are:

- Movement of people along a passageway or across a room with the deck at an angle due to heel or trim;
- Movement of people when the deck is subject to motion;
- Movement of people up and down stairways and ladders whose steepness is outside those of building stairways for which data is available.

In order to acquire some of this data, a facility has been constructed at Fleet Technology Limited’s laboratory in Kanata, near Ottawa, Canada in which human performance in a typical ship passageway and stairway can be studied and mobility data collected.

The facility is known as the Ship Evacuation Behaviour Assessment Facility (SHEBA), and has been funded in part by Transport Canada and also by research funding assistance from British Maritime Technology (of which FTL is an affiliate company).

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 25°. The steel structure reproduces a ship’s corridor and stair, with handrails and facilities to insert a doorway with sill, etc. Figure 8 is an artist’s rendering of the completed facility and Figure 9 is a recent picture during initial commissioning runs.

Recording instruments include 4 video cameras and 5 optical sensors for accurately measuring timing in the passageway and on the stairs.

Test subjects enter the assembly “cabin”, while the facility is level and the facility is tilted to the test angle only after all “passengers” are in and have secured themselves. Raising the test facility to the test angle after passengers are “aboard” will prevent them seeing the test angle, and the possibility of them prematurely developing a strategy to deal with the angled deck.

Test subjects pass through the passageway and the stairs, individually and in groups, with and without lifejackets. They are timed along the passageway and up (or down) the stairs and video records are taken of the activity in the test area. 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 are conducted in both directions.

The stairway has been designed to allow its steepness 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 because of the construction inside a watertight enclosure, it is possible to introduce a few centimeters of water to the deck of the passageway.

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. Heel angles up to 23° will be examined, with no group repeating any angled conditions.
Figure 8: The Ship Evacuation Behaviour Assessment Facility (SHEBA)

Figure 9: Recent Photo during Final construction stage
Commissioning of the facility is taking place in June 2001 and it is expected that data will be available shortly thereafter.

Figure 10 shows the MaritimeEXODUS model of the facility. Predictions of behaviour in the SHEBA facility have been made and show that at level attitude the egress time from entering the passageway to exit will be about 45 seconds. The screen capture shows 10 males and females grouping at the bottom of the stairs, 7 on the stairs (off to the side in the drawing and showing the individual “cells”) and three on the exit passageway. We would expect the pattern to change considerably as the angle of heel increases.

The growing interest in evacuation safety of passenger vessels has provided an opportunity for the development of sophisticated simulation tools to replace prescriptive and generally arbitrary analysis methods. Such tools must draw on the considerable effort and resources that have been invested in establishing the knowledge base required to develop evacuation modeling tools and the data required to confidently use them in the building and aerospace environments.

The shortcomings in simple analysis tools that focus on the physical layout of the evacuation arrangements, and the significant limitations of tests and experiments carried out under ideal conditions can be offset by quite sophisticated simulation tools which incorporate complex behavioral capabilities. The first generation hydraulic and the second generation ball-bearing models are making way for behavioral models with adaptive capabilities that include, structural knowledge, reaction to communication, affiliative behavior, occupant motivation and a stochastic element to the queuing recommitment behavior. However, for this development to occur and to establish an acceptable level of confidence in the results produced, more data is required concerning the decision-making process. In order for evacuation models to achieve their full potential, it is essential that industry and regulators work together to provide the data essential for the further development and validation of these models.

Opportunities to collect meaningful data are being lost, and it is hoped that a concerted effort to collect and distribute the relevant data can be made with little impact on current activities and reporting requirements.

Additionally, the challenge facing regulators and approval authorities is to develop an understanding of this new modeling technology and to specify relevant design standards and protocols. As the models become more sophisticated, the range of parameters that can be investigated increases, and it is essential that a minimum range of relevant design scenarios as well as acceptance criteria be agreed.

This paper has discussed the issue in general and outlined one particular model that represents the state-of-the-art in this field, as well as some efforts that are being made to establish the necessary database.

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