

Evacuability of Passenger Ships at Sea

By

D. Vassalos, G. Christiansen, H.S. Kim, M. Bole and J. Majumder

The Evacuation Group of the Ship Stability Research Centre, Department of Naval Architecture and Marine Engineering of the Universities of Glasgow and Strathclyde, Scotland, UK

SUMMARY

The term *Evacuability* (passenger evacuation performance capability) entails a wide range of capabilities encompassing evaluation of evacuation time, identification of potential bottlenecks, assessment of accommodation module layout, life saving appliances, passenger familiarisation with a ship's environment, crew training, effective evacuation procedures/strategies, intelligent decision support systems for crisis management and design/modification for ease of evacuation. From a technical point of view, the mass evacuation of thousands of people from an extremely complex environment with unknown inaccessibility problems exacerbated by (potentially co-existing) incidents such as progressive flooding, cargo shift, foundering, fire/smoke and the inherent uncertainty deriving from unpredictability of human behaviour, is a problem with severe modelling difficulties at system, procedural and behavioural levels. In this respect, *Evacuability* represents a risk measure of passenger evacuation at sea, expressed as an index. Addressing the above, this paper focuses on the development of a passenger evacuation simulation model developed by SSRC in collaboration with Deltamarin, RCI and Color Line. Code-named *Evi* (*Evacuability index*), it represents the state-of-the-art computer simulation-based capability for the prediction of passenger mustering and evacuation whilst accounting realistically for human and ship behaviour in a sea environment. Unlike earlier models, *Evi* has been developed from the outset for application to passenger ships in a sea environment, including the largest cruise liners and Ropax. Purposely conducted shipboard experiments coupled with valuable input and feedback from owners/operators helped refine and render the model a practical tool for ship designers, operators and regulators. Modelling uncertainty in all the parameters that may affect evacuation times and ability for real time interaction/interrogation/visualisation and play back of any given (or online devised) scenario as video, provide for wide-ranging capability in dealing with the most complex of evacuation scenarios. As a result, *Evi* is currently used routinely for evacuation analysis of existing and new designs and is being systematically assessed by shipyards and classification societies for use in ship design and certification. Following definition of the shipboard evacuation problem and an outline of the modelling involved in *Evi*, sample results from recently conducted benchmarking tests, devised by the IMO Working Group on Evacuation Analysis, are presented and discussed and recommendations given on the way forward concerning development and implementation of advanced tools to ship design, training and operation.

1. INTRODUCTION

Recent well-published disasters of Ro-Ro/passenger ships together with trends of largely increased capacity of passenger carrying ships have brought the issue of effective passenger evacuation, being the last line of defence, in an emergency to the centre of attention of the maritime industry worldwide. With passenger numbers now ranging up to 6,000 on a single large cruise liner, with ships often trading in pristine environmental areas and with rapidly growing consciousness for safety and environmental protection among ship operators, assurance of both these issues at the highest of levels have become the main targets for technological innovation in the maritime industry as well as key factors for gaining and sustaining competitive advantage. However, the process of evacuating a large passenger ship is a very complex one, not least because it involves the management of a large number of people on a complex moving platform, of which they normally have very little knowledge. These characteristics make ship

evacuation quite different to evacuation from airplanes and buildings as the first only involve relatively simple geometries, whilst the second imply steady platforms, normally with no need for assistance to be given to its occupants during an evacuation and no need for their preparation to survive a harsh environment following a successful evacuation. These inherent problems, coupled to limitations in time to the extent that evacuation may often be untenable, render decision making during a crisis a key to successful evacuation and any passive or active support encompassing design for ease of evacuation, crew training, evacuation plans/procedures and intelligent systems onboard critically important.

In response to emerging needs, the 1995 International Conference on the Safety of Life at Sea (SOLAS '95) addressed this issue specifically by the adoption of a new regulation SOLAS II-2/28.3, where it is stated that escape routes onboard Ro-Ro ferries shall be evaluated by a suitable evacuation analysis. In view of the above, in January 1999, the International Maritime Organisation (IMO) decided to develop *Interim Guidelines* for the execution of the evacuation analysis. Following this, a Working Group within IMO was set up to study the practicality of these guidelines, to monitor the evolution of passenger ship evacuation simulation tools and to oversee the development of suitable rules and regulations and of procedures and systems for existing and new ships. The industry on the other hand is trying to adopt a proactive approach to passenger evacuation by addressing this problem in all its facets pertaining to design, training and operation whilst exploiting the possibility for developing a shipboard integrated and co-ordinated real time decision support system. Furthermore, in May 2000, the IMO Secretary-General called for a general review of the safety of large passenger ships. The Secretary-General noted that the compliance with current safety standards of recently built large cruise ships is not in doubt, since all such ships comply with SOLAS. However, in his words: "what merits due consideration is whether SOLAS and, to the extent applicable, the Load Line Convention requirements, several of which were drafted before some of these large ships were built, duly address all the safety aspects of their operation – in particular, in emergency situations". There is, therefore, an increasing demand for technological innovation in the most lucrative marine sector of passenger ships. This comes at an opportune time where onboard ships computerisation is featuring highly in most shipping companies in this sector, thus bringing a change of attitude in the use of technological advances to improving the efficiency and safety of shipping operations. Attempts in this direction by the SSRC evacuation group are the subject of this paper.

2. THE SHIPBOARD EVACUATION PROBLEM

Much as there are generic elements in the simulation of passenger evacuation equally applicable to ships, buildings or aircraft, there exist critical differences between them which are likely to have a significant (and hence crucially important) effect on the outcome that ought to be addressed at the outset. These include the following:

2.1 Modelling the ship (virtual) environment

Geometry: Innovation in capturing the complexity of ship geometry is required, to account for the almost infinite number of possible escape routes. The difference between innovative and brute-force modelling could be an order of magnitude in the time taken to produce a virtual ship model and a similar margin is expected concerning the size of data set. *Evi* works seamlessly with a purposely developed graphic environment editor module (*EvE*) that converts CAD drawings in DXF format of the most complex passenger ship into an evacuation simulation environment and virtual reality model typically in a few days.

Topology: Closely connected to ship geometry and hence unique to ships are topological issues and schemas of evacuation "flow", for example multiple configuration layouts that could lead to disorientation and confusion of passengers.

Semantics: Most semantic specific information is crucially affecting evacuation, mainly because of the geometric complexity but also due to adversity of the sea-ship environment, reinforced by uncertainties in the time available, distance to land, functionality of Life Saving Apparatus, etc.

Platform: Ships move, on occasions severely, which further exacerbates disorientation and reduced mobility, whilst other contributing factors more often than not worsen this situation further, e.g., progressive flooding that may also curtail evacuation time to the extent that evacuating thousands of people in situations that may include restricted access became untenable.

Sea environment: Evacuation pertaining to dry land-based scenarios, means escaping to safety. In ships, it usually means escaping to sea, where rescue is far from complete.

2.2 Modelling human behaviour

Passenger numbers: In the majority of cases, evacuation from other enclosed spaces does not involve very large numbers of people. This in itself presents modelling problems in terms of macroscopic and microscopic movement of people, processing capacity and information handling. These, in turn, give rise to needs of multi-threaded programming and parallel processing, particularly for use in immersive technology and/or employing the navigation interface of a virtual reality integrated environment.

Way-finding and path selection problems: Deriving from the ships' geometric complexity, these problems are exacerbated by the moving base, often severe time constraints and the anticipation of an awaiting unfriendly environment, thus complicating most aspects of human behaviour.

Uncertainty modelling: This derives from the unpredictability of human behaviour as well as the inherent structural instabilities associated with the passenger ship evacuation problem.

2.3 Passenger mustering/evacuation process modelling

Procedures: Evacuation strategies, procedures and decision support systems are likely to affect drastically the success of passenger evacuation in ships, more so than in other enclosed spaces, again primarily because of the plethora of parameters likely to affect evacuation in such a complex environment with so many people.

Evacuation scenarios: In addition to evacuation strategies that may be considered (abandon ship, transfer to refuge centres or a combination of the two) and the range of possible incidents (fire, collision, progressive flooding, cargo shift, foundering), it is in the multitude of scenarios that innovative thinking is imperative.

Holistic approach: It would be sub-optimal to model the various procedures (assembly, embarkation, launching of life boats, etc) separately or indeed sequentially. A holistic approach is necessary to understand the evacuation process in ships and to properly model and analyse it for design, operational and regulatory purposes.

Ship abandonment: When transfer to refuge centres is not an option, ship abandonment is most important aspect of passenger evacuation and wholly ship specific (albeit there is strong similarity with offshore platforms) involving such aspects as ship and LSA dynamics and LSA functionality issues whilst accounting for human behaviour.

Considering the above, direct transfer of knowledge from land-based experience to passenger ship evacuation is inappropriate, the latter demanding a wholly different approach at an altogether different level.

3. MATHEMATICAL MODELLING

3.1 General aspects

The mathematical modelling used in the development of the evacuation simulator is explained in detail in [2]. The main strength of the modelling derives from the ability to utilise high and low level planning

interchangeably (*Evi* is the only mesoscopic model currently available for passenger evacuation analysis) and to account for human behaviour realistically by adopting multi-agent modelling techniques. Moreover, *Evi* treats space as a continuum unlike other models that treat the ship area as a mosaic of square grids, a quantization of space, which represents a problematic (e.g., ensuring synchronisation between different events and loss of flexibility in design) as well as an unnecessary deviation from reality. These features, coupled to minimal geometric modelling techniques allow for very high computational efficiency, thus rendering *Evi* suitable for routine application to evacuation analysis for the largest of passenger ships.

3.2 The environment model

Modelling the environment model is one of the most important aspects of multi-agent modelling. In the whole, this consists of three aspects - geometry, topology and domain semantics. The perception model for the agents will be able to use the information in these three abstractions at different levels of the decision processes. The whole ship layout is segmented into Euclidian convex regions with local co-ordinate systems and a structure of a linear space, directly connected if they have a common gate. This connectivity topology, for all computation and analysis purposes can be represented by a *graph*. In ship layout terms regions are defined as cabins, corridors, public areas (or subsets of these), each with its own co-ordinate system and connectivity, defined by the gates (these may be actual or artificial doors). Figures 1-3 next illustrate schematically these ideas. The path of the agents leading to the embarkation station is determined by searching the connectivity graph of the doors. Currently, the length of the path is taken as the criterion of optimality for network flow.

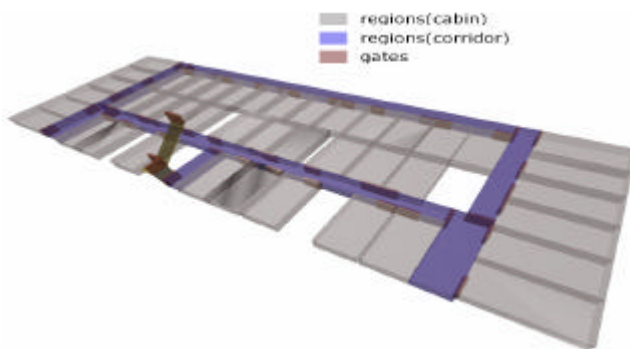


Figure 1: Minimal VR geometry model of a deck

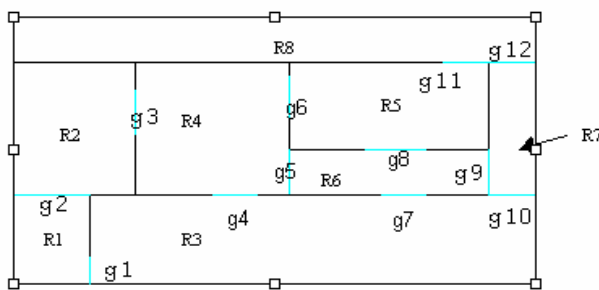


Figure 2: An example layout of regions and gates

A minimal description of the ship layout will enable designers to modify the layout easily (add a new corridor or a staircase in virtually no time without having to draft the details of it using an elaborate CAD tool), hence obtaining evacuation performance faster, and thereby making simulation an ideal design tool. The contrary can be also easily achieved – by simply blocking areas, regions or whole fire zones one can easily examine the effect of these changes and therefore the sensitivity of each different part of the vessel on evacuation capability.

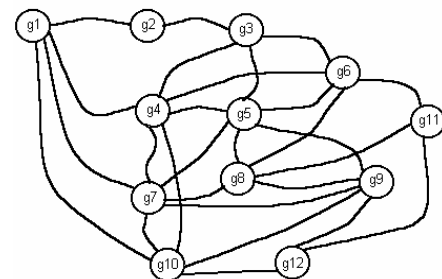


Figure 3: Gates graph corresponding to Figure 2

Furthermore, the availability of 2½D and 3D models allows for real time visualisation, in which the complete geometric details of the ship and human agents may be utilised to provide an extremely realistic

representation. As an alternative, the code can also be executed separately, allowing a much faster evaluation of a simulation and leaving visualization as a post-processing alternative.

3.3 High and low level planning

High level – Path planning and graph search

With increasing complexity of the minimal geometry of the ship to thousands of doors and regions, it is very important to have an efficient path-planning process. The path-planning algorithm adopted is illustrated in Figure 4, explaining how only the distance information from each door to the embarkation station needs to be left with the door's id.

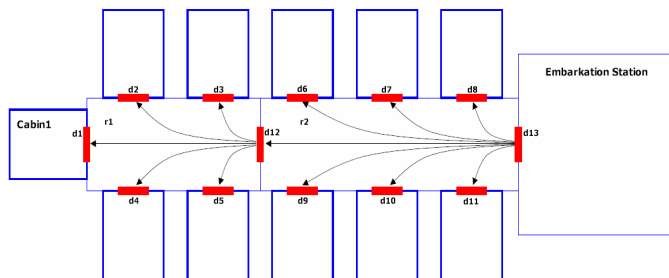


Figure 4: Simple illustration of the path-planning

When an agent is located in a region, the distance information from each door of the region can be obtained, thus allowing the agent to simply head to the shortest path leading to the destination area. Re-planning during evacuation is also possible if, for example, there is a dense crowd 'blocking' the path or a blackout in the presence of fire or smoke.

Low level – Steering of agents

Pursuit of a static target acts to steer the agent towards a specified position in global space. This behaviour adjusts the agent so that velocity is radially aligned towards the target. The "desired velocity" is a vector in the direction from the agent to the target representing global "flow speed", adjusted on the basis of local density, as explained in the following.

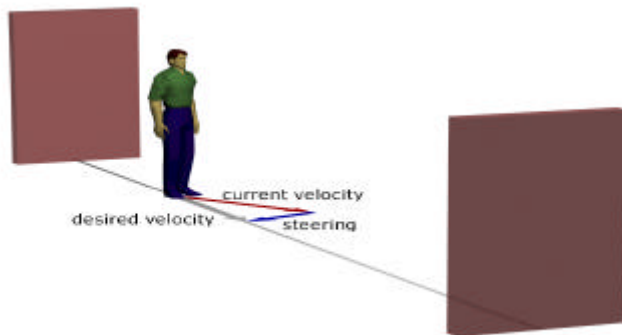


Figure 5: Pursuit of a static target

The steering vector is the difference between this desired velocity and the agent's current velocity, as shown in the adjacent Figure 5. In the absence of any obstacle and other evacuees, every agent will "flow" along the evacuation direction field (passing through the gates unobstructed), hence avoidance heuristics are used to avoid collision with the neighbouring agents and obstacles present along the evacuation path.

4. MODELLING HUMAN BEHAVIOUR

4.1 Framework adopted

To cater for the plethora of behavioural parameters that are likely to affect the evolution and the outcome of an evacuation scenario, there is a need to adopt a framework that allows for as many behavioural parameters as deemed appropriate to be considered. The framework adopted in the development of *Evi* treats passengers as intelligent agents with attributes modelled as an array of "genes". These, for example, determine the behaviour of a mother searching for her child before abandoning the ship, the father taking a leadership role in a crisis, the child following parents, the members of a family forming a group and so on.

“Genes” may be active or inert depending on circumstance, time and domain semantics. For example, if the current leader of a group becomes incapacitated, a new leader (someone with the right “gene”) would take this role. Hard data has in the main been obtained from open literature. An overview of the behavioural parameters currently being considered is provided in [2]. Some additional relevant information on modelling human behaviour is provided next.

4.2 Speed of advance

Speed of advance is the compounded outcome of all that is going on onboard a ship in an emergency at sea during evacuation. As per the IMO Interim Guidelines, the speed of an agent is determined by the density of the crowd in the region. In general, the crowd density is non-uniform and it may strongly depend on the size of the area considered in the density calculation. If the crowd is concentrated near a gate in a big region the remaining part of which is empty, on dividing the number of occupants by the total area of the region may give a small value of density which clearly fails to capture the situation. To overcome this drawback the concept of *local density* is used as shown in Figure 6.

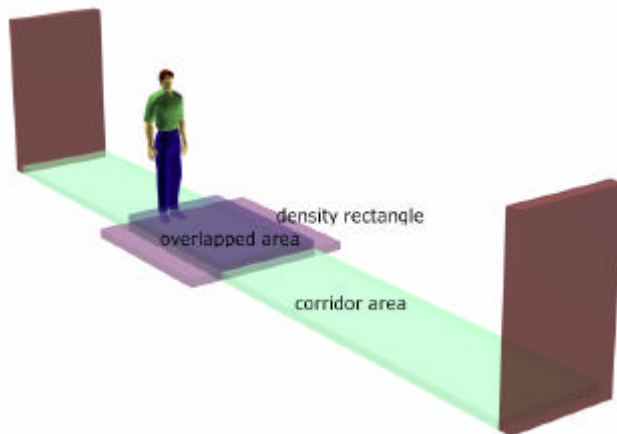


Figure 6: The concept of local density

The local density in a region in front of the agent (a rectangle of 2.14m x 2.14m) is computed and the IMO speed values assigned in accordance with this local density value. This makes the scheme conformant with IMO without sacrificing realism. Additionally, when long queues are being formed, the effect on the speed of advance is calculated on the basis of the crowd queue length. Dependence of speed on other parameters is modelled by using multiplication factors that are functions of relevant parameters, the total product being treated of as a **mobility index**.

4.4 Effect of ship motion

In Evi, results from MEPdesign research [1] are adapted to the mustering and evacuation scenarios. The way of approaching this topic is to relate the reduction in speed to the roll angle. To this end, a maximum roll angle of 20° is assumed, at which the speed reduction becomes 100%. The reduction in other angles follows a relationship derived on a basis of a scheme in which the weighted average of the roll angle values experienced in the immediate past N time steps (over a few roll cycles) is used.

4.5 Modelling uncertainty

Human behaviour parameters

The psychological and physiological attributes of humans are non-deterministic quantities. Even in a contrived experiment one can hardly reproduce human actions/reactions even if all of the conditions remained the same. This inherent unpredictability of human behaviour, especially under unusual and stressful circumstances, rules out the possibility of a deterministic program to model evacuation correctly. For this reason, human behaviour has to be modelled with some built-in uncertainty. To this end, in Evi every parameter is modelled as a random variable with a predefined distribution. This is to eliminate the occurrence of unrealistic behaviour, for example, everybody of the same age reacting exactly at the same time to an alarm call.

Monte-Carlo Method

The inherent uncertainty in human behaviour will give rise to a reasonable amount of variation in the result of simulation in different instances of execution. Thus, some statistical aggregate quantities evaluated over several simulation runs (forming a cumulative probability distribution as shown in Figure 7) have to be defined that must have the property of approaching a limit as the number of ensembles grows indefinitely.

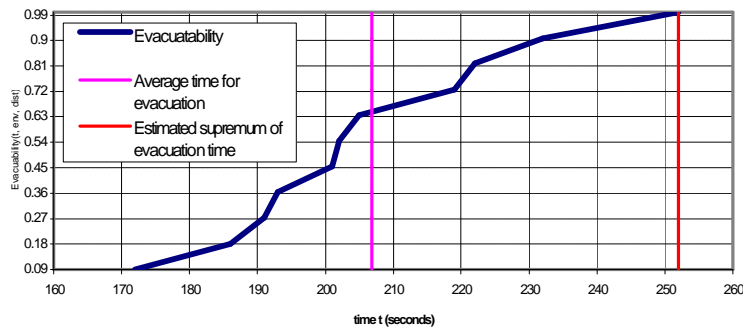


Figure 7: A typical *Evacuability* graph (using the Monte Carlo method)

The term *Evacuability* is defined to be the probability of an environment being completely evacuated no later than a given time elapsed after the alarm went off, in a given state of the environment and a given state of initial distribution of people onboard. With this formalism a sound rule may be proposed, e.g., *Evacuability (60 min., entire ship-worst anticipated conditions-, worst passenger distribution) > 0.99.*

5. POTENTIAL APPLICATIONS

Evi is available in the form of a computer program that can be customised to any vessel environment. The vessel information required pertains to semantics, topology and geometric data, the latter varying from very simple (allowing quick calculations for high level planning) to a 3D virtual environment and up to a level that replicates the actual ship with an efficiently tailored user interface and Run Time Simulator (RTS) that allows for setting up almost any evacuation scenario. Typically, it takes 2 days to train a ship superintendent to become an efficient user of the simulation package. A second version of the passenger evacuation simulation model has recently been released that allows simulation to be fully controlled by a custom command language. In addition, the following features are available:

- ? The user can interactively create scenarios and make changes while the simulation is running.
- ? All user interactions can be recorded for a lightweight playback, which in turn can also be interacted with.
- ? Evacuation announcements can be made as and when required.
- ? It has an event scheduler with the use of which one can implement cause-effect and timed event chains during the simulation.
- ? Properties of different entities of the simulation can be changed before and during the simulation.
- ? It has the capability of simulating evacuation of 10,000 people in real time.
- ? All operations can be fully automated and one can create batch-processing scripts either by writing macros or generating them by way of recording interactions.
- ? The user can probe and plot every interesting quantity – queue lengths at each door of interest, occupancy of each region, cumulative gate crossings of regions of interest etc.
- ? *Evi* now works seamlessly with software tools developed for GA optimisation to design for ease of evacuation considering the topological load of areas of congestion and the quality of the evacuation plan whilst accounting for geometric constraints.

A typical page during the evacuation of 3,500 passengers from a large cruise liner with some of the controls available in the RTS is shown in Figure 8 below.

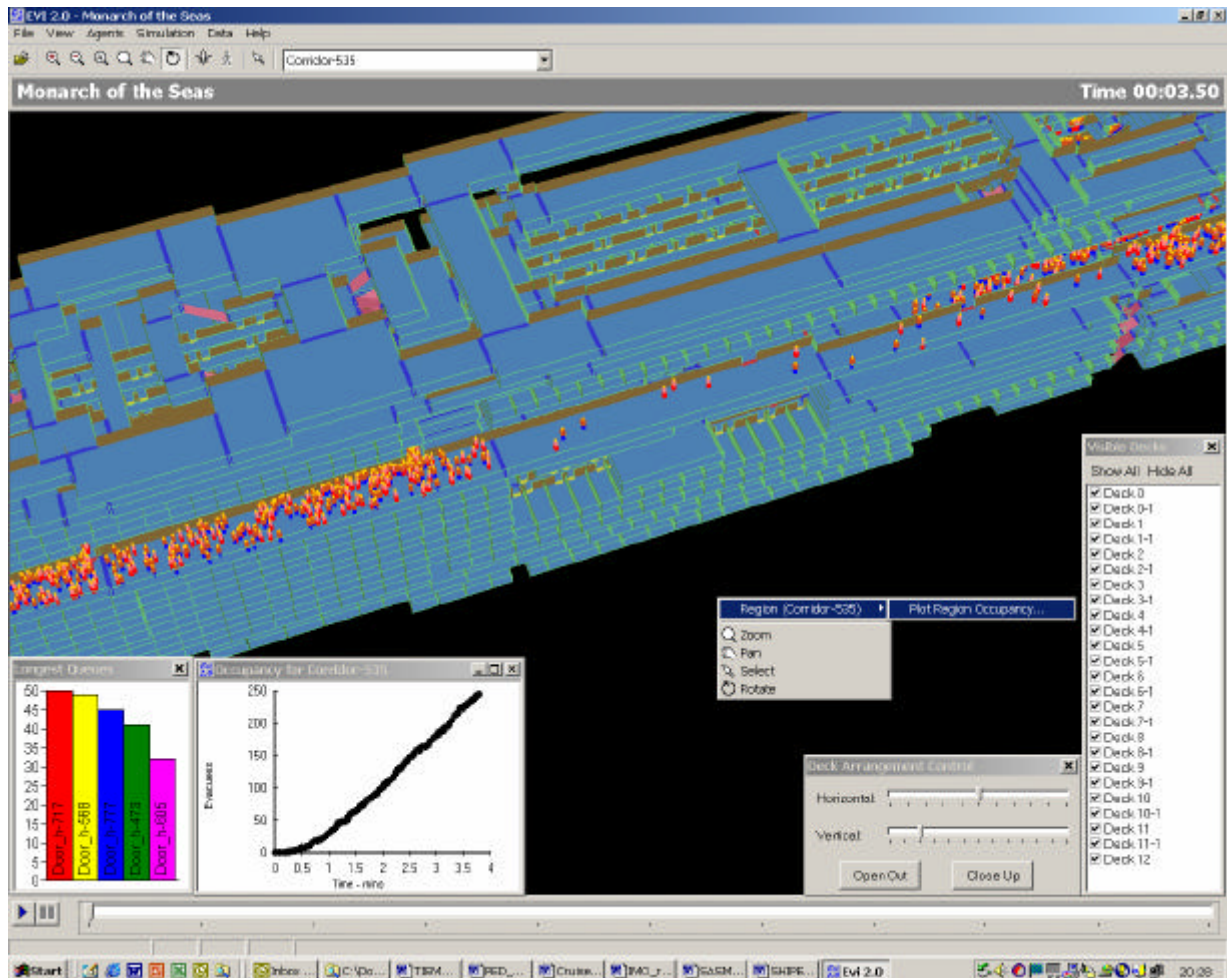


Figure 8: Evi Run Time Simulator during an evacuation exercise

As a result, a wide range of developments concerning design, training and operational tools and guidelines for enhancing “*Evacuability*” have now been made possible including:

- ? Evaluation of evacuation time for certification purposes.
- ? “What if” scenarios for crew training
- ? Passenger familiarisation with a ship’s environment – Particularly the large cruise liners and passenger/Ro-Ro vessels being built today.
- ? Design/modification for ease of evacuation. This involves systematic parametric investigation to identify governing parameters of the ship environment (e.g., corridors, staircases, number and location of mustering stations, life saving appliances, signage) within a pre-defined set of human behaviour parameters and mustering and evacuation procedures. This would allow design optimisation for enhancing evacuation performance, where parameters being considered include: evacuation time and components contributing to it; time history of occupancy of regions of interest; queue size time history (bottlenecks); rate of crossing through doors, etc.).
- ? Optimisation of mustering/evacuation routes and procedures. This involves the identification of optimal passenger flow (minimum total evacuation time) concerning choice of routes and procedures to achieving this. Heuristic approaches based on experience and engineering judgement are used in

combination with self-searching and tuning algorithms to automate this process. The latter will also form the input to the next level of development, described below.

- ? Crisis management and decision support. This involves integrating and interfacing the simulation software with distributed monitoring and detection systems onboard ships leading to an online decision support system for crisis management during an emergency by intelligent fusion of the collected information.

6. IMO BENCHMARKING TESTS

To demonstrate the type of evacuation analysis that is likely to be used for certification purposes, it would be of interest to present sample results of the cases currently being considered for adoption by the IMO Working Group on Evacuation Analysis. Two test cases have been proposed – one where all passengers are in cabins (night case) and one where passengers are located in public areas (representing a day case). The Interim Guidelines do not describe any crew responsibility or the effect this might have on evacuation, so for these cases, crew members are treated as passengers. Two different ship models were introduced in order to illustrate the night and day cases as outlined next.

6.1 Night case

The ship model for the night case is made up of one main fire zone (MFZ) over seven decks, decks 5-11. The passengers are distributed on decks 5-7 and 9-11 in their respective cabins as outlined in Table 1. Deck 8 is the assembly deck consisting of centrally located assembly station and port and starboard embarkation stations. There are no passengers or crew present on deck 8 at the start of the simulation.

Table 1: Passenger distribution for Night case

Deck	Number of Cabins	Number of Pax
11	46	110
10	46	96
9	46	110
8	-	-
7	27	30
6	59	118
5	33	66
Total	256	530

The decks are connected by staircases, the location and dimensions of which are given in Table 2 below:

Table 2: Deck connectivity by stairs

Connecting Deck	Type of staircase	Number of staircases	Frame	Width (m)
11-10	Double	1	97 - 102	1.6
10-9	Double	1	97 - 102	1.6
9-8	Double	1	97 - 102	1.6
8-7	Single	1	97 - 102	1.4
7-6	Single	2	114-118 132-137	0.9 0.9
6-5	Single	1	132-137	0.9

At the start of the simulation the passengers start moving along the shortest route towards the assembly station and from there to the embarkation station on deck 8. The simulation stops when all passengers have reached their destination.

6.2 Day case

The ship model for the day case is made up of one main fire zone (MFZ) over four decks, decks 6-9. The passengers are distributed on decks 6, 7 and 9 as outlined in Table 3 below. As in the night case, deck 8 is the assembly deck, with centrally located assembly station and port and starboard embarkation stations. From the assembly station there is a choice of three routes to the embarkation stations. There are no passengers or crew present on deck 8 at the start of the simulation.

Table 3: Passenger distribution for Day case

Deck	Number of Pax
9	200
8	-
7	464
6	474
Total	1138

The decks are connected by staircases as indicated in Table 4, below:

Table 4: Deck connectivity by stairs

Connecting Deck	Type of staircase	Number of staircases	Frame	Width (m)
9-8	Double	1	97 - 102	1.6
8-7	Double	1	97 - 102	1.6
	Single	2	145 - 150	2.0
7-6	Double	1	97 - 102	1.6
	Single	2	146 - 151	1.0

At the start of the simulation the passengers start moving along the shortest route towards the assembly stations and from there to the embarkation station. The simulation stops when all passengers have reached their destination.

6.3 Creating the model

The model of the IMO ship was created using EvE, the Evacuation Editor which combines the standard interface and geometry development tools available in AutoCAD with an Object Inspector style interface used to manage the parameters of large numbers of objects, as seen in Delphi, Visual Basic, AutoCAD 2000i. The specification model management of *Evi* comprises:

- ? A fully interactive CAD interface allowing the user to develop the simulation model using General Arrangement drawings without the need for AutoCAD
- ? Very fast development of model database (targeting 3 hours)
- ? Object Snap drawing assistants
- ? Automatic region geometry generation using CAD data
- ? Automatic door generation between regions
- ? Property Inspector for editing all parameters of the *Evi* topology

? Facilities to generate the visualisation geometry, automatically from the *Evi* model for a quick visualisation and manually for more complete models, without the need for AutoCAD and 3D Studio Max.

As the *Evi* regions software already models the major data structure of *Evi*, development has concentrated on the CAD interface and better data management through the use of Delphi's RTTI (Run Time Type Information).

6.4 IMO Interim Guidelines

Details of how the analysis should be carried out according to IMO Interim Guidelines, [3] are given below together with the corresponding assumptions used in *Evi*:

IMO Interim Guidelines and Assumptions	<i>Evi</i> – IMO Basis Case
All passengers and crew will begin evacuation at the same time, and will not hinder each other.	This is not the case in <i>Evi</i> – every parameter (in this case reaction time) is modelled as a constrained random variable with a predefined distribution.
<i>Awareness time</i> is set to 5 and 10 minutes for day and night cases, respectively.	The same <i>Awareness time</i> has been added for calculating evacuation time even though 'awareness' itself is treated as a random variable.
<i>Travel time</i> is the time taken for passengers to move from their initial location to the assembly station and onwards to the embarkation station.	As the time spent by passengers in the assembly stations is not given in the interim guidelines, passengers move via the assembly stations directly to embarkation station, without any delay.
<i>Walking speed</i> depends on the density of persons and the type of escape facility and it is assumed that the flow is only in the direction of the escape route and that there is no overtaking.	In <i>Evi</i> the concept of perceived density is used, i.e., local density. This represents a consistent modelling of <i>Walking speed</i> and a more accurate representation of human movement. Passengers overtake depending on circumstances.
No passengers or crew have disabilities or medical conditions that will severely hamper their ability to keep up with the flow.	This is also the case in <i>Evi</i> . However, age and gender are also treated as constrained random variables and hence the speed of advance will vary accordingly.
In the IMO Interim Guidelines, counter flow is accounted for by a counter flow factor equal to 0.3.	In <i>Evi</i> counter flow is simulated rather than accounted for by a multiplication factor. However, in the cases considered here all passengers and crew are moving towards the same assembly stations and flow will be unidirectional.
Passenger load is assumed to be 100%	Same in <i>Evi</i> 's IMO basis case
Full availability of escape arrangements is considered.	Same in <i>Evi</i> 's IMO basis case
Effects of ship motion, passenger age and disability, restricted visibility due to smoke, etc, are accounted for by a safety factor of 2.0.	In what is termed in <i>Evi</i> as <i>IMO Basis case</i> the effect of ship motion, smoke or disabilities are not included. Normally, all these effects will be accounted for, as required.

Passengers and crew are asked to take the shortest route to the assembly deck, which causes certain routes to be more heavily used than others. The effect of this on evacuation time could be significant. To

illustrate this, the passengers were allowed to choose the most “economic” way to their destination in the night case scenario. Finally, the population considered in the simulations has the following age and gender distribution:

- ? 50/50 - female/male
- ? 35% of the pax are over 50 years old
- ? 10 % of pax are under 15 years old
- ? The remaining 55% are between 15-50 years old.

6.4 Sample results

Results from the case studies presently considered are shown as *Evacuability* graphs.

(a) Night case

“Optimum” Route Scenario

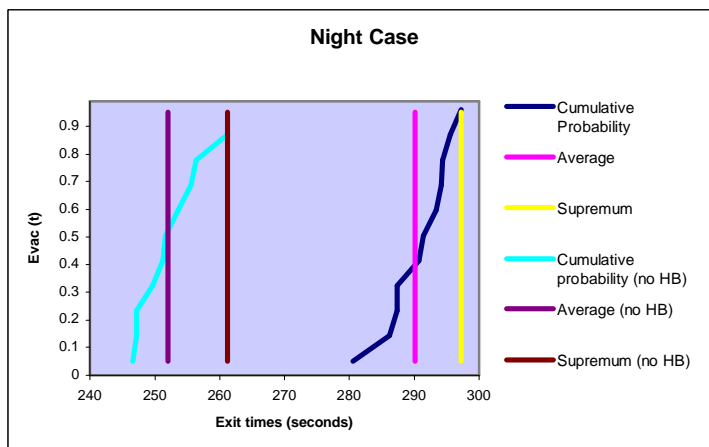


Figure 9: *Evacuability* Graph – “Optimum” route scenario night case

The mustering time for the night case varied from 280 sec to 297 sec as shown in Figure 9. Due to the narrow spread of evacuation times, 10 runs were considered sufficient for the night case. Evacuation times without taking into account uncertainties with regards to age, gender and initial reaction time have also been calculated for comparison purposes and the *Evacuability* graph presented also in Figure 9. This gives a shorter evacuation time – generally 40 sec less.

Shortest Route Scenario

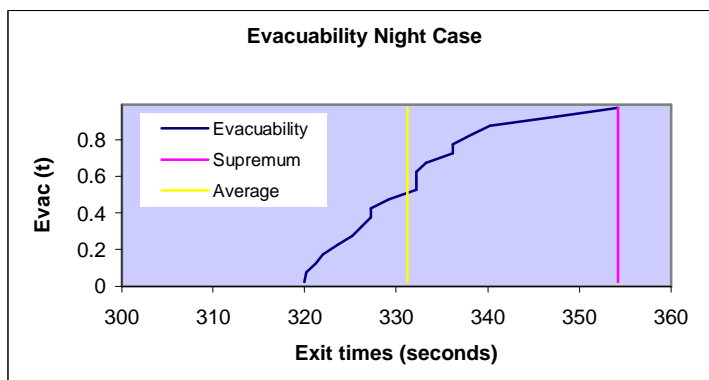


Figure 10: *Evacuability* Graph – Shortest route scenario night case

As expected, evacuation times become more conservative in this case, typically by 50 seconds on average as illustrated in Figure 10.

(b) Day Case (shortest route scenario)

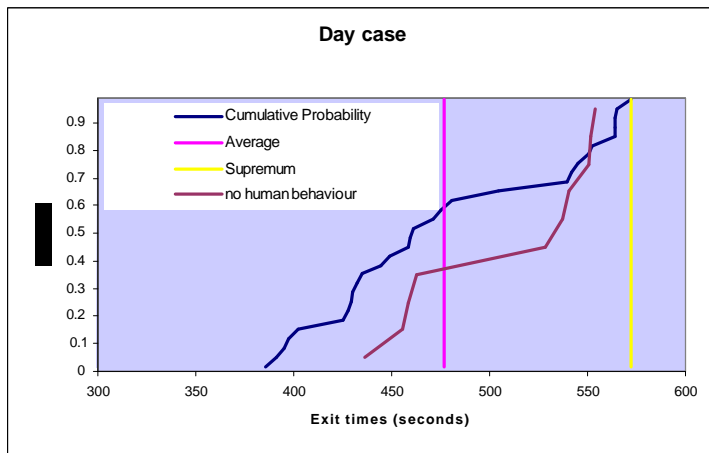


Figure 11: Evacuability Graph – Day case (shortest route scenario)

Unlike the night case the number of runs for the day case was set to 30 because of the largest spread of evacuation times, as shown in Figure 11. The without-human behaviour case was run only for 10 times, as this was considered sufficient for illustration purposes.

Coincidentally, this fact serves to indicate the dependence of the maximum evacuation time on the number of runs.

The answers derived concerning the average values of the mustering times for the day (? 8 minutes) and night (? 5.5 minutes) cases are similar to those obtained from the macroscopic model, when the assumptions made reduced the degrees of freedom of *Evi* which could account for differences in the results as the shortest and “optimum” route scenarios for the night cases demonstrated (15%). The spread of evacuation times could vary considerably, however, as the day and night cases illustrate, which tends to reinforce the need for dealing with the evacuation problem in probabilistic terms.

(c) Identification of bottlenecks and congestions

Various degrees of congestion could be observed in all decks, particularly at points where pax move from wide to narrower corridors (e.g. decks 9-11) and in front of staircases – decks 9-10 and 5-7, where one staircase has to be shared by pax from a number of decks. The worst congestion point is on deck 8 – as pax from all 6 accommodation decks merge onto one deck, on their way to the assembly station. Bottlenecks were also identified as pax are moving out of the assembly station towards the embarkation station. Figure 12 is an example from deck 7, leading to the staircases forward –congested and saturated areas are marked as red. Quantitative information on the above is shown in Figure 13.

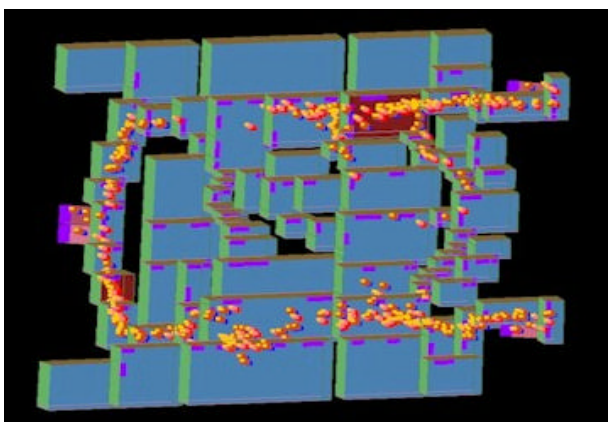


Figure 12: Problem areas – Day case (shortest route scenario)

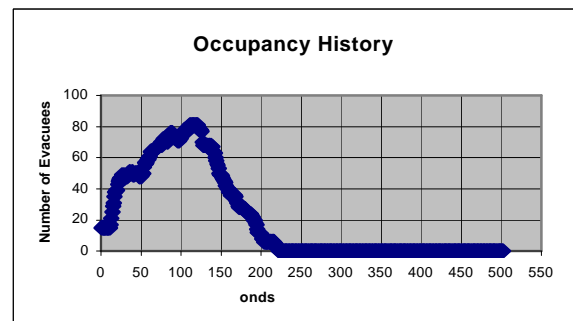


Figure 13: Problem area (in front of the exit at the lower RHS of deck 7 - shown in Figure 12)

Similar information is shown in Figures 14 and 15 below for the night case.

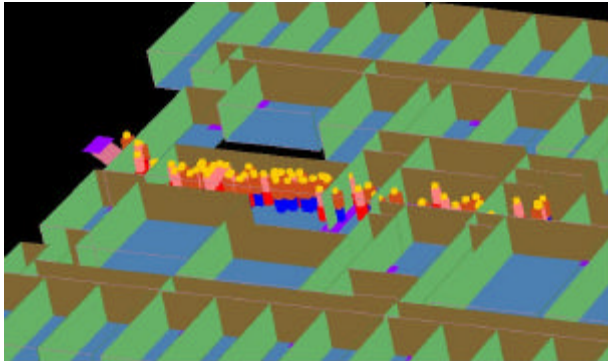


Figure 14: Problem areas – Night case (Deck 7 corridor leading to single staircase)

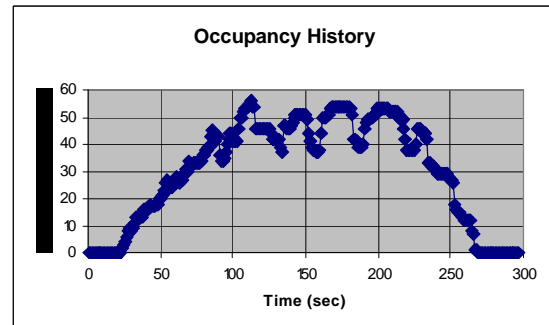


Figure 15: Problem area (shown in Figure 14)

7. CONCLUDING REMARKS

Considering recent and expected developments on the passenger evacuation simulation the following remarks may be made:

- ? Work at IMO is currently addressing the problem of evacuation of large passenger ships as a matter of priority. In this respect, it has been demonstrated that *Evi* can deal with the sheer size of the problem at hand from a computer modelling and simulation viewpoints.
- ? Efforts are now being directed towards finalising scenarios for benchmarking purposes, following which validation and verification of these scenarios against “real” data will be sought, aggregate results to be considered for checking macroscopic modelling and controlled focused experiments to address the governing human behaviour parameters.
- ? The industry at large appear to be more interested on utilising the advanced tools being developed in a number of ways ranging from the initially intended identification of bottlenecks to design of new buildings for ease of evacuation, for crew training and more importantly to interfacing the simulation software with integrated safety management systems onboard aiming towards on line decision support for crisis management. One way or another, the maritime industry is becoming technologically adept faster than most people’s prediction and this offers real possibilities for innovative solutions to enhance the safety and efficiency of ship operations.

8. REFERENCES

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