Evi – Passenger Evacuation Performance Assessment in Ship Design and Operation

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Abstract

Evi (***Ev**acuability **i**ndex*) is a passenger evacuation software developed specifically for a ship-sea environment, capable of real time evacuation simulation of the most complex of scenarios in the largest cruise ships and Ropax whist accounting realistically for human and ship behaviour at sea. Video replay in virtual reality, real time interaction, on line decision support and a customised Run Time Simulator (an efficiently tailored user interface) are standard features. The computer program was developed by SSRC at the University of Strathclyde in collaboration with Deltamarin Ltd and is currently being applied routinely to existing and new designs of cruise liners and passenger/Ro-Ro vessels (e.g., RCI, Color Line, Brittany Ferries). Typically, mustering simulation of 5,000 passengers on a 17-deck vessel can be achieved in real time. Valuable input and feedback from owners/operators helped refine and render the model a practical tool, which coupled to modelling of uncertainty in all the parameters that may affect evacuation, provide for wide-ranging capabilities in passenger evacuation analysis, namely: evaluation of evacuation time, potential bottlenecks, assessment of accommodation module layout and sensitivity analyses to assist design for ease of evacuation, passenger familiarisation with a ship's environment, "what if" scenarios for crew training, devising effective evacuation planning procedures/strategies and decision support to manage a crisis. Representative results for a large Ropax vessel are presented and discussed.

INTRODUCTION

Background

A number of drivers have brought passenger evacuation to the forefront of priorities of the European shipbuilding industry triggering the need for the development of tools and procedures in support of performance-based design for evacuation to ensure cost-effective treatment of this important issue:

- Ro-Ro ferry accidents have brought about the realisation that "*ship and cargo survival*" might have to be addressed separately from "*passenger survival*" in that these vessels can capsize very rapidly, when damaged, thus not allowing sufficient time for evacuating passengers and crew.
- An amendment to SOLAS '74 requires "Ro-Ro passenger ships constructed on or after 1 July 1999, to have escape routes evaluated by an evacuation analysis early in the design process".

- The consequence of accidents involving large loss of life could drive shippers out of business, as the Estonia tragedy has amply demonstrated. Such consequences are bound to reach intolerable levels when addressing new concepts such as cruise liners carrying well over 5000 passengers.

Deriving from the above, there is an immediate need to address the capability of the whole passenger evacuation system pertaining to mustering routes and procedures, life-saving appliances, decision support and management. In turn, this leads to the necessity to focus on the development of evacuation analysis and simulation tools for the prediction of evacuation performance, thus allowing for a meaningful evolution of passenger ship designs with enhanced evacuation performance (minimum time for safe evacuation of passengers and crew). Successful mustering and evacuation can avert disaster as last lines of defence even after the safety measures linked to structural reliability and enhanced ship survivability have failed. In this respect, the development of tools in the form of computer simulation models for the prediction of evacuation scenarios, evacuation time and probability of success in different conditions must be addressed as a top priority. The same tools could also be used to aid decision making onboard the ship, thus tackling the same problem as an operational rather than a design issue. Attempts in this direction by the SSRC-Deltamarin team are the subject of this paper.

MATHEMATICAL MODELLING

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 as well as an unnecessary deviation from reality. These features, coupled to minimal geometric modelling techniques allows for very high computational efficiency, thus rendering suitable for routine application to passenger evacuation analysis.

The environment model

Modelling the environment 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, 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 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. Currently, the length of the path is taken as the criterion of optimality for network flow. 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 examine the effect of these changes and therefore the sensitivity of each different part of the vessel on evacuation capability.

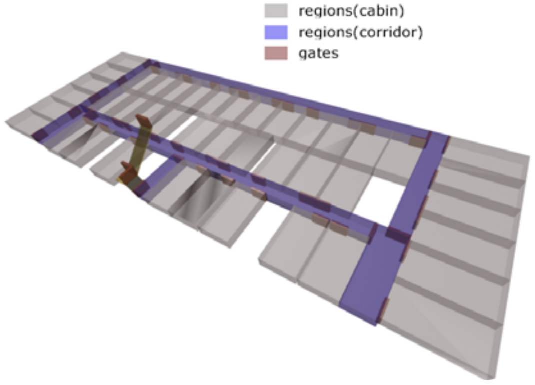


Figure 1: Minimal VR geometry model of a deck

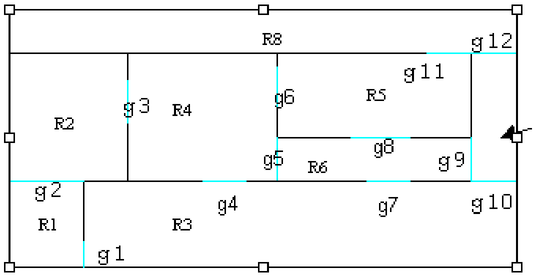


Figure 2: An example layout of regions and gates

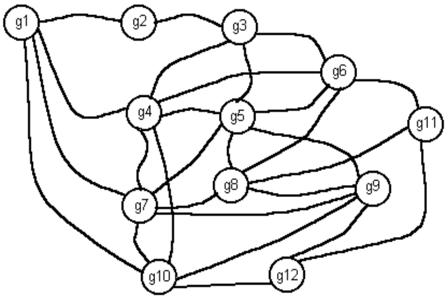


Figure 3: Gates graph corresponding to Figure 2

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 will be utilised to give rise to 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.

MODELLING HUMAN BEHAVIOUR

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 largely been obtained from open literature. An overview of the behavioural parameters currently being considered is provided in [3]. Some additional relevant information on modelling human behaviour is provided next.

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 [4], the speed of an agent is determined by the density of the crowd in the region. In general, 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, in which the local density in a region in front of the agent (a square of 2.14m x 2.14m) is computed and the IMO speed values assigned in keeping with this local density value. This makes the scheme conformant with IMO without sacrificing realism. Additionally, when long queues are form, the effect on speed of advance is calculated on the basis of the 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**.

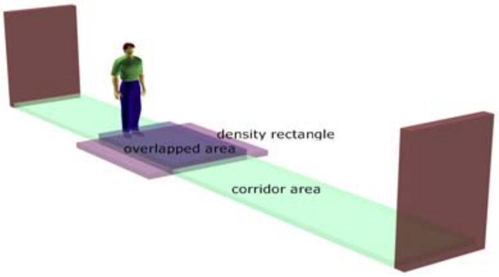


Figure 6: The concept of local density

Modelling Uncertainty

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 8) have to be defined that must have the property of approaching a limit as the number of ensembles grows indefinitely.

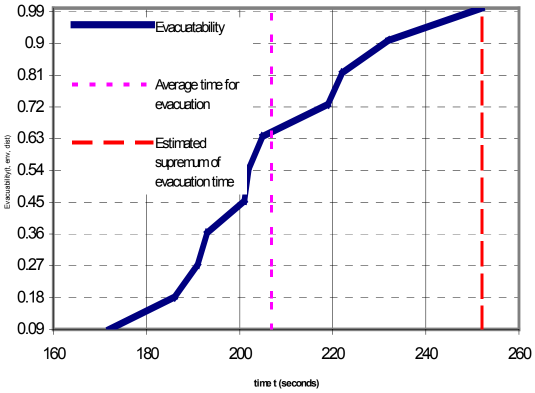


Figure 8: A typical *Evacuability* graph using the Monte Carlo method

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.*

POTENTIAL APPLICATIONS

A wide range of developments concerning design and operational "tools" and guidelines for enhancing "*Evacuability*" (Evacuation Performance Capability), including:

- Evaluation of evacuation time for certification purposes.
- 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 development of effective management and decision support systems for risk containment during a crisis as active means to averting catastrophes (e.g., an onboard evacuation simulation platform to aid decision-making for effective mustering/evacuation in a range of incidents).
- "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.

EVI AND THE RUN TIME SIMULATOR

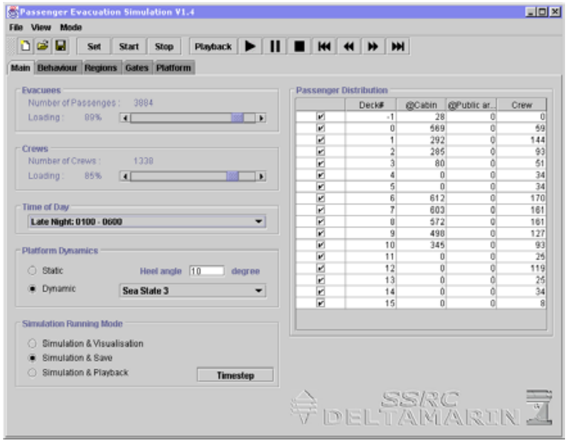
The passenger evacuation simulation model –*Evi*

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 up to a level that replicates the actual ship with an efficiently tailored user interface and Run Time Simulator (RTS) that allow for setting up almost any evacuation scenario over a range of incidents. Typically, it takes 4 weeks to complete a full investigation and to deliver a comprehensive report together with an RTS.

Run Time Simulator

Evi's user interface includes a number of pages, addressing the ship environment, behavioural issues and the running of the simulators, as outlined briefly next. By way of illustration, the main page is shown in Figure 9.

The Main page: Adjustable loading condition (of passengers and crew); choice of which deck to include in the simulation; time-of-day; sea states; simulation mode.



Evacuees
Number of Passenges : 3884
Loading : 89%

Crews
Number of Crews : 1338
Loading : 85%

Time of Day
Late Night: 0100 - 0600

Platform Dynamics
○ Static Heel angle 10 degree
● Dynamic Sea State 3

Simulation Running Mode
○ Simulation & Visualisation
● Simulation & Save
○ Simulation & Playback

Passenger Distribution

	Deck#	@Cabin	@Public ar...	Crew
☑	-1	28	0	0
☑	0	569	0	59
☑	1	292	0	144
☑	2	285	0	93
☑	3	80	0	51
☑	4	0	0	34
☑	5	0	0	34
☑	6	612	0	170
☑	7	603	0	161
☑	8	572	0	161
☑	9	490	0	127
☑	10	345	0	93
☑	11	0	0	25
☑	12	0	0	119
☑	13	0	0	25
☑	14	0	0	34
☑	15	0	0	8

Figure 9: *Evi* – The Main page

The Behaviour page: Choice of Behaviour to be included (both for crew and passengers).
The Region/Gate page: Add/Edit/ Remove Regions; Block Door/ Area/ Staircase/ Decks/MFZ.
The Platform/Playback: Choice of simulation visualisation mode: playback, save or combination.
The Run Time Chart/Visualisation: Chart showing progress during evacuation.

CASE STUDIES

To demonstrate the use of the simulator, a number of scenarios are considered for a Ro-Ro passenger ship operating in international waters. The vessel consists of 12 manned decks – 6 of which contain cabins. The assembly stations are located within a centralised atrium (fire zone 3) on deck 3-8 and in a large public area aft on deck 5. Embarkation stations are located as indicated below, with number of LSAs and total capacities.

Deck 7	Liferafts	(capacity 20 pax)	x48	960
Deck 5	Lifeboats	(capacity 98 pax)	x4	392
Deck 5	Lifeboats	(capacity 55 pax)	x2	110
Deck 3	MES (Marine Evacuation Shutes)	(capacity 400 pax)	x2	800

There are no arrows indicating the main escape route – this is due to the fact that there is always an option of two routes to the assembly/embarkation station (the above is an attempt to avoid scenarios such as onboard *Scandinavian Star* where some passengers ended up entering areas affected by the fire by following EXIT arrows). Instead of arrows, the corridors in accommodation areas are marked by LLL (low location lighting), luminous green horizontal lights along the length of the corridor and vertical lights marking doorframes along the escape routes.

Information on passenger distribution and demographic details was obtained from passenger lists from 2000/2001. All cases describe a passenger load of 1533. The simulation runs typically continue until 99% (approx 1518) of the evacuees have arrived at their destination (assembly/embarkation station) the obvious reason being that in some cases a very small number of passengers could have a very large effect on the evacuation time. The simulations were run with passengers present in their cabins at the start of the simulation, which is referred to as ‘night case’ in the IMO Interim Guidelines. A ‘day case’ is one where passengers are situated in public areas (e.g. restaurants, sun decks, etc.).

Results

Relevant results for assembly exercises and actual evacuations from various cruise ships are given in [2]. These results indicate assembly exercise times varying from 7-20 minutes. The great variance was due to differences in the preparation of passengers. In five cases, where incidents resulted in evacuation of the vessel – the total assembly time varied between 17 and 28 minutes.

Results from the case studies presently are considered and their description given in the charts below. The results are presented as two different charts: one showing the Average Assembly time (passengers arriving at their destination as a function of time) and one showing *Evacuability*. This is a result of Monte Carlo simulations (50 runs for each case) and is defined to be the probability of any ship being completely evacuated of human occupants no later than a time *t* elapsed after the alarm went off for a given scenario and a given initial distribution of people in the ship.

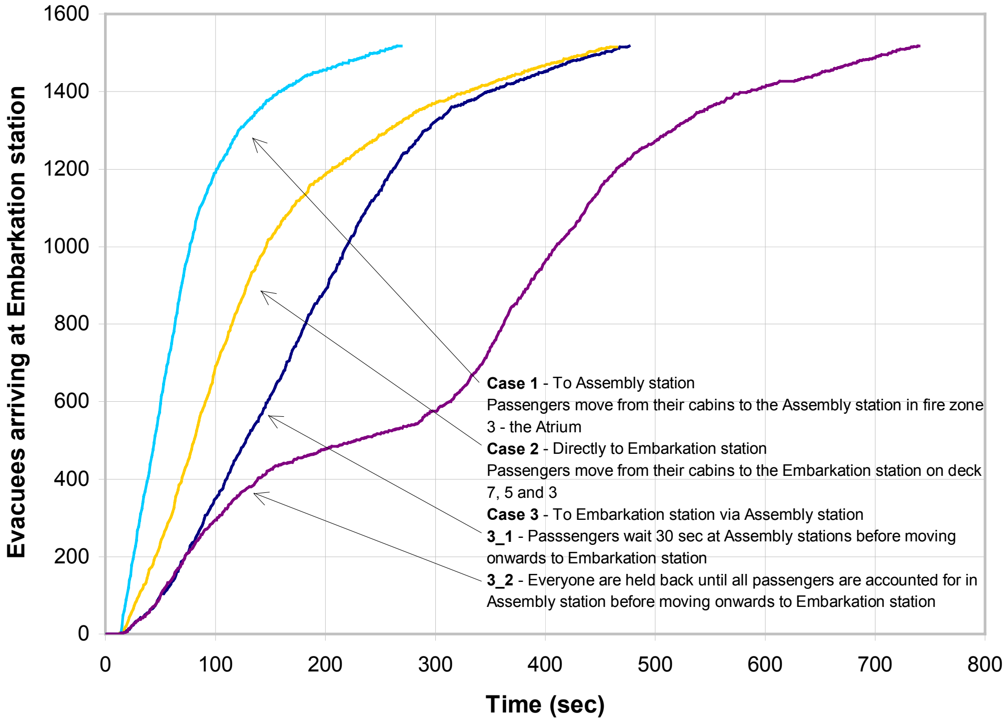


Figure 10: Average Assembly time for the three cases considered

Case 1 – From Cabin to Assembly Station

At the sound of the general alarm the passengers start moving from their respective cabins to the Assembly Station. Passengers are distributed according to passenger lists. Reaction time and uncertainties concerning age and gender, which affect speed of advance are assigned.

Case 2 – From Cabin to Embarkation Station

At the start of the simulation the passengers move from their cabins to the Embarkation station on decks 7, 5 and 3 following the shortest route and without stopping at the Assembly station. Passenger distribution and uncertainties associated with human behaviour are applied as above. This case represents a real incident.

Case 3_1 - To Embarkation station via Assembly station

Passengers move to Assembly Station as in Case 1. Once passengers arrive at the Assembly Station, they wait for 30 seconds; this relates to time taken to receive instructions from crewmembers on further actions. Following this they move to Embarkation station on decks 7, 5 and 3 choosing the shortest route.

Case 3_2 - To Embarkation Station via Assembly Station

Same as previous apart from when passengers arrive at the Assembly station, they wait until all (99%) passengers have arrived before moving onwards to Embarkation station. This describes the existing assembly procedures onboard the vessel; all passengers are kept in the Assembly Station until the crew reports that all cabins are empty and all passengers accounted for. After this waiting period the passengers are instructed to move towards the Embarkation station on decks 7, 5 and 3.

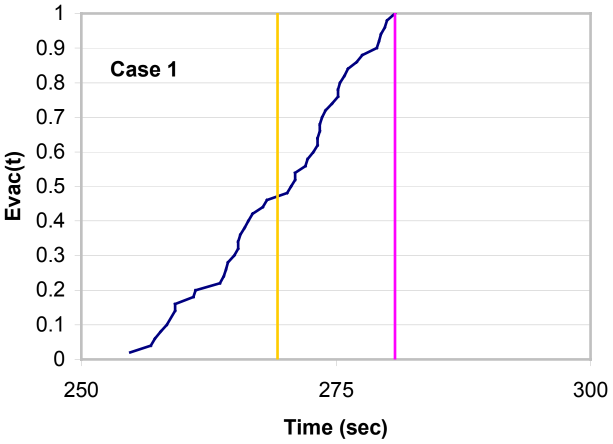
Comments on the results

Case 1 has the shortest assembly time. This is due to the fact that the majority of the passengers are simply moving from their cabins to an Assembly Station at the same deck (apart from passengers on deck 1 who have to traverse stairs up to deck 3). Since the passengers are distributed between 5 Assembly Stations – there is little sign of queuing – illustrated by a steep, ‘straight’ curve.

Case 2 – here the passengers, rather than going to Assembly Stations, are instructed to go directly to embarkation station. Comparing with Case 1, the number of destinations is reduced from 5 [assembly stations] to 3 [embarkation stations]. As the same number of people are heading for a smaller number of destinations more queuing is observed, which can be detected by a less steep curve towards the end of the simulation.

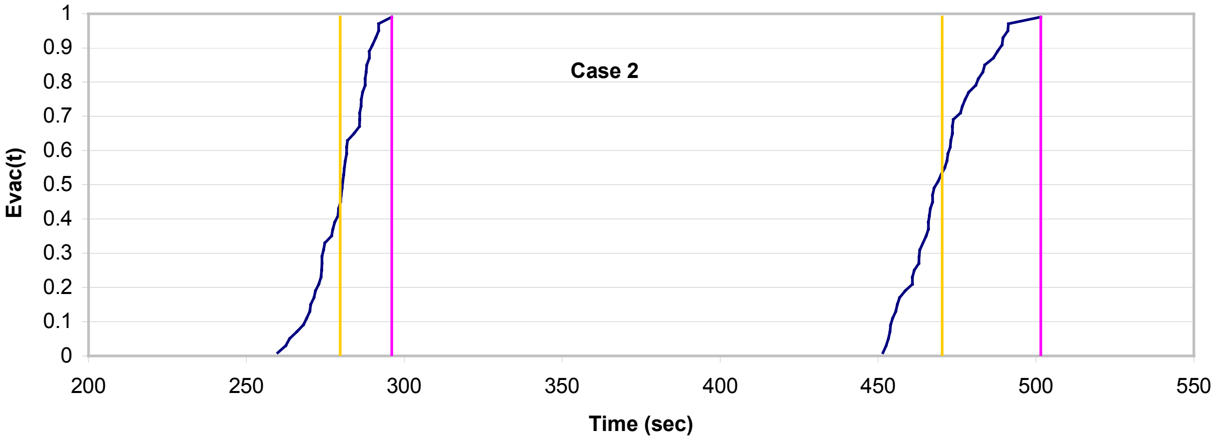
Studying the result of Case 3_1 – one can see that the total time is similar to Case 2 - despite the fact that the passengers generally have to travel a longer distance (as they first go to Assembly Stations, then to the embarkation stations). One can also observe that towards the end of the simulation, the curve becomes steeper (again compared with Case 2). This means that there is less queuing (compared to Case 2) because the flow is controlled by having passengers waiting a short period in the Assembly Station.

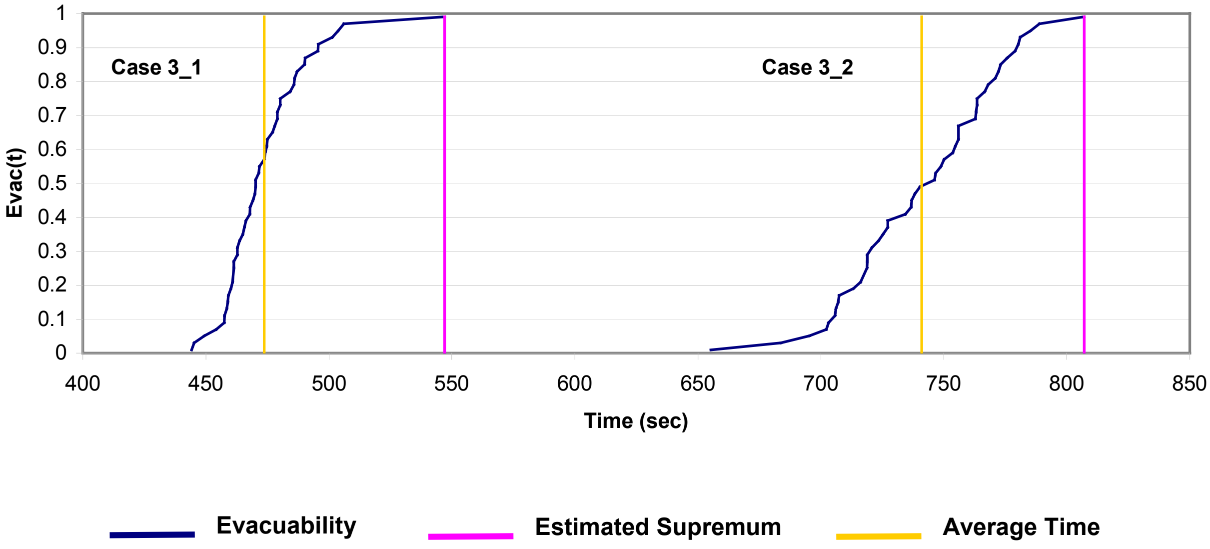
Case 3_2 has the longest assembly time – due to the fact that everyone has to wait in the Assembly Stations until all passengers have been accounted for. The ‘hump’ on the curve is caused by the fact that on deck 3 the Assembly Station and embarkation station are in the same location (hence deck-3&1-passengers’ arrival at the Assembly Station coincide with their arrival at the embarkation station).



The following graphs show the cumulative probability distributions of the three cases considered.

This type of illustration is explained earlier in the paper while one might comment on the two graphs in Case 2. In the first (shorter) of the evacuation runs, the passengers choose the embarkation station closest to their starting position, while in the second; the passengers are instructed to evacuate using specified embarkation stations, e.g. passengers from deck 5&6 should use the embarkation station on deck 5. Generally, the time difference between the two cases is largely due to that in the latter of the two the distance the passengers have to travel while evacuating is longer.





The areas in direct connection to assembly and embarkation stations appear to be prone to blockage due to the large number of passengers attempting to enter over a short period of time. This problem is solved in normal evacuation by assembling the passengers in groups (as illustrated in Case3_1). The crew has to co-ordinate the assembly so that the passengers do not move towards the assembly stations until there exists sufficient area to accommodate the envisaged crowd capacity. Crew by the assembly stations have to monitor the number of people there and to communicate to the crew responsible for a given group of passengers (in any particular part of the vessel) to start moving.

One should consider having people waiting for example in public areas until their passage to the embarkation station is clear. This is to prevent queuing in staircases or corridors. Passengers will be more relaxed and co-operative if they rest in an environment (like a restaurant) rather than a (often small and narrow) corridor.

CONCLUDING REMARKS

Based on the work presented in the foregoing, the following conclusions may be drawn:

- 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 specifying a number of 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.

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