ADVANCED EVACUATION ANALYSIS – TESTING THE GROUND ON SHIPS

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ABSTRACT

This paper focuses on testing the applicability of the International Maritime Organisation (IMO) current guidelines for advanced evacuation analysis[1] to a large passenger ship and examines critically and exhaustively the sensitivity of the parameters involved. Simulation results are presented and discussed, leading to clear indications of how to ensure confidence in the information provided from such a limited-scope analysis.

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.

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-2/28-1.3, 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 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, which recently led to revised Interim Guidelines for passenger evacuation that address both simplified and advanced analyses[1].

Considering the wider environment, it is therefore rather disappointing but understandable that the IMO Interim Guidelines for an advanced evacuation analysis were influenced considerably by the preceding guidelines and thinking of the simplified evacuation analysis, to the extent that the usefulness of such an analysis it is at best questionable. There is no surprise here really considering that the maritime community is rushing yet again to provide solutions to a problem that still lacks rigorous definition and in depth understanding. Moreover, a stochastic treatment of the problem necessitates that some basic rules must be adhered to if the results are to be representative and hence useful. Yet, we advanced into guidelines before setting and observing the rules! Even though it is early days still, there is no time soon enough in attempting to fill these big gaps. This constitutes the aim of this paper.

EVACUABILITY AND EVACUATION ANALYSIS

Before proceeding with the intricacies of evacuation, it is important to define the problem we try to solve and the degree to which this problem is defined adequately for any evacuation analysis, conducted through numerical simulations, to be meaningful. In general, the ability to evacuate a ship environment within a given time and for given initial conditions (Evacuability) may be defined as follows (see Figure 1):

$$E = f\{\, env, d, r(t), s(n_i);\, t \,\}$$

Thus, Evacuability is a function of a set of initial conditions, ***env***, ***d*** and ***r(t)***, and evacuation dynamics, $s(n_i)$, as explained next.

Initial Conditions: the following initial conditions (***env***, ***d***, ***r(t)***) should be defined and remain fixed during the execution of the simulation:

- ***env***: Ship environment model, pertaining to geometry, topology and domain semantics. For any comparisons to be meaningful we need to assume a time invariant environment for evacuation simulations. An environment changing with time (e.g., blocking doors and exits online) could not easily allow for quantifiable assessment of these effects, as it would be very difficult to repeat any such action in precisely the same state of the simulation model. However, the ability to change the environment online could offer a strong basis for crew training and for decision support in crisis management. Moreover, fire/smoke spreading and progressive flooding, the principal hazards giving rise to the need to evacuate, result in a time varying environment. Hence for any comparisons concerning global and local effects to be meaningful, any environment changes ought to be affected in a deterministic way.
- ***d***: Initial conditions of the evacuation problem, pertaining to spatial and temporal demographics of the people onboard. People in the environment will actually be randomly distributed with the possibility of fixing some initial values, e.g., placing handicapped people on the embarkation decks and/or near an exit. As such, the initial distribution of people's demographics ought to be sampled to identify its effect on evacuability. The latter could be avoided if the distribution is known with sufficient accuracy (confidence) that a specific spatial distribution in a given time is taken to define a specific scenario for any operational or design purposes.
- ***r(t)***: Response time, which according to the IMO definition, is intended to reflect the total time spent in pre-evacuation movement activities beginning with the sound of the alarm. This includes issues such as cue perception provision and interpretation of instructions, individual reaction times, and performance of all other miscellaneous

pre-evacuation activities. In addition, in-situ response time or any change in the state of a moving agent through intervention of e.g., crew ought to be considered. Response (awareness) time is certainly a random variable hence it has to be sampled for various distributions in order to evaluate its effect on evacuability

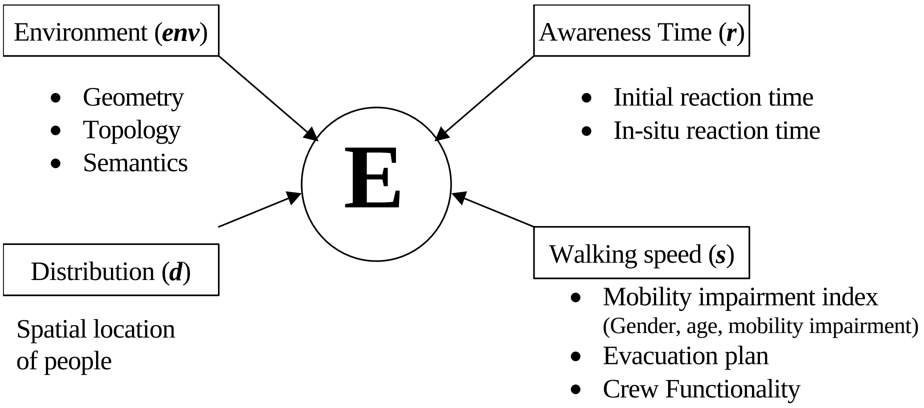

Figure 1: The concept of *Evacuability* (E)

Evacuation Dynamics: Relates specifically to walking speed, which constitutes the main motion variable of evacuation dynamics.

- **$s(n_i)$**:Walking speed of individual flow units (agents/persons). The fact that each person onboard is dealt with as an individual flow unit and that every procedural (evacuation plan) / functional (crew assistance) / behavioural (microscopic behaviour) parameter could be accounted for as a multiplicative factor ascertaining walking speed, provides for a unique and relatively easy way for simulating evacuation, essentially being able to deal with the effect of all of these parameters by simply following a given evacuation plan, accounting for crew assistance in some agreed quantifiable way and then sample walking speed for each individual flow unit from a corresponding distribution dependent on the environment and demographics. Using the relevant mobility impairment index (MII) the walking speed in each case can straightforwardly be calculated. From a development of realistic simulation of evacuation point of view, a great deal of effort may have to be expended to accurately quantify MII for all the pertinent microscopic behaviour as well as for specific crew assistance.

On the basis of the above thinking, it may be stated that evacuability is a well-defined problem that can be formulated and solved (simulated) for given initial conditions and passenger flow parameters.

THE MARITIME CONTEXT

Flooding and fire onboard ships constitute the principal hazards that may lead to passenger evacuation. If these hazards develop into an uncontrollable situation, it must be ascertained a priory that ALL people on board can be evacuated safely. Evacuation analysis should therefore be aimed at developing a system (a minimum standard of Evacuability) that guarantees this assertion to an acceptable level by utilising advanced consequence analysis tools for flooding, fire and evacuation within a risk assessment framework. Evacuability in this respect represents a risk measure of passenger evacuation at sea expressed as an index, for a given pertinent scenario, environment, passenger distribution and demographics and initial response time. Developing such a system will ensure focus on passenger safety in a systematic and all embracing way that safeguards against the consequences from the principal hazards leading to abandoning a ship or mustering to a safe refuge onboard, by providing an active link between the two. In this respect, one can deal cost-effectively with design/operation/ regulation/training issues. This constitutes the main target of the Evacuation Group of the SSRC utilising an advanced evacuation simulation tool, code-named Evi (Evacuability index), currently in its 3rd version, developed from the outset for application to the largest cruise liners and Ropax in a sea environment.

EVACUABILITY INDEX (*EVI*)

The mathematical modelling used in the development of the evacuation simulator is explained in detail by Vassalos *et al* [2]. The main strength of the modelling derives from the ability to utilise high and low level planning interchangeably (macro- and microscopic modelling respectively, referred to as mesoscopic model) and to account for human behaviour realistically by adopting multi-agent modelling techniques. In terms of low-level planning, Evi treats space as a continuum – unlike other models that treat the ship area as a mosaic of square grids [4,5] – and the process of an agent moving from one door to another becomes a process of pursuing a static target. The choice of direction of movement in the presence of other agents and/or obstacles, is approached by combining grid-based techniques and social forces model (hybrid approach, see Figure 2) thus utilising the effectiveness of grid-based techniques with the flexibility of social force methods. In order to simplify calculations, a range of discrete decisions is established around the agent with the objective of identifying the one that will allow the agent to travel as fast as possible (given its nominal speed) toward the local target. In addition, a continuous local (social/personal) space is established around each agent which other agent will aim to avoid. This space is used to prevent deadlock situations when the number of agents in an area becomes too high (density increases). The agents make a decision of the best use of its personal space to resolve any conflicts that may arise. As a result, this approach allows the evacuation process to be modelled in sufficient detail and still run in real time.

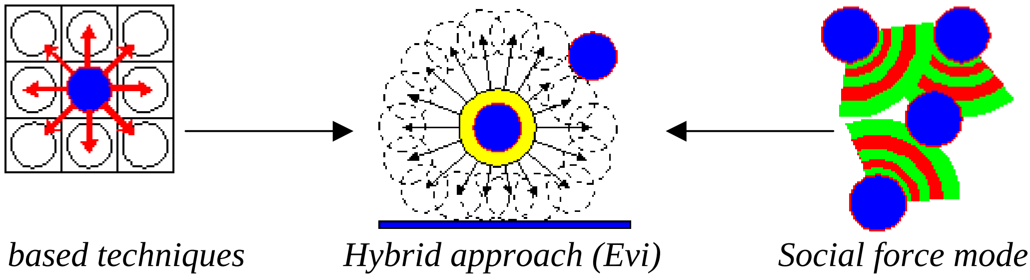

Figure 2: Space modelling techniques

One of the primary objectives of the development of Evi-3.0 was the definition of a coding model that could be easily adapted to the future needs and directions of evacuation simulation within the industry. This combined with the introduction of an intuitive user interface, standardised data files based on Extensible Markup Language

(XML) and a range of supporting tools allows the program to be operated as well for any main stream software application. Evi's continuous space, discrete decision pedestrian motion model can flexibly adapt to the complexities of any ship's geometry and topology. In Evi 3.0, agents are considered as a vehicular transport system capable of carrying information, interacting with other agents and autonomously travelling around the ship environment. By programming individual agents to perform certain tasks with elements called Objectives, it is possible to reproduce any evacuation procedure by incorporating the actions specified in e.g. the vessels' muster list. Crew responsibilities such as, checking cabins, alerting passengers who are not aware of the emergency, searching for lost passengers and controlling stairways, are straightforwardly incorporated by means of Objectives and the underlying message structure (allowing agents to interact with and influence other agents). More complex tasks can also be defined by scheduling of the Objectives. As evacuation procedures may differ between different ship types and operators, Objectives provide a fundamental technique for accurately defining appropriate responses to any emergency scenario. The system utilises a modern graphical user interface within a virtual reality environment.

IMO ADVANCED EVACUATION ANALYSIS

An advanced evacuation analysis is taken to mean a computer-based simulation that represents each occupant as an individual that has a detailed representation of the layout of a ship and represents the interaction between the occupants and the layout. The purpose of such analysis is to identify and eliminate, as far as practicable, congestion which may develop during an evacuation (mustering + abandonment), due to normal movement of passengers and crew along escape routes, taking into account the possibility that crew may need to move along these routes in a direction opposite the movement of passengers. Also it is aimed at demonstrating that escape arrangements are sufficiently flexible to provide for the possibility that certain escape routes, assembly stations, and embarkation stations or survival craft may be unavailable as a result of a casualty.

The passenger and crew are modelled as individuals, with demographic attributes (percentage, gender, age, response time and speed) mainly derived from building standards[3] and adapted to use for a shipboard environment. The response time is intended to reflect the total time spent in pre-evacuation movement activities beginning with the sound of the alarm. This includes issues such as cue perception, provision and interpretation of instructions, individual reaction times, and performance of all other miscellaneous pre-evacuation activities. It is modelled as a uniformly distributed random variable with mean value of 300 s and 600s, for the day and night cases scenarios, respectively and a variation coefficient of 0.173. The walking speed is given for a predefined demographic distribution of the passengers and crew population, and is sampled from a uniform distribution with parameters taken from relevant studies into pedestrian dynamics (Ando *et al* (1988)[1]; Galea *et al* (1998)[1]).

As regards performance criteria, the simulated evacuation time for Ro-Ro passenger vessels should be less than 60 minutes, which includes the estimated travel time (T, referred to also as assembly time) and the 2/3 of the time needed for embarkation to and launching of the lifeboats (E + L), assumed to be at least 30 minutes (it is assumed that E+L starts before all the agents reach the assembly station). This criterion reflects the required survivability (time-based) criterion for progressive flooding, one of the most prevalent causes of Ro-Ro ship losses. It is also congruent with the 60-minute structural fire integrity criterion of any independent main vertical zone within the ship's structure. For the calculation of T, a safety margin of Δ=200s and 600s, for day and night case, respectively, has to be added in order to account for model omissions, assumptions and the limited number and nature of the evaluated benchmark scenarios. Assumptions include: crew ready at their duty stations immediately, passengers know exactly where to go, following signage and crew's instructions, presence of smoke, heat and toxic fire products do not affect passenger/crew performance, family group behaviour is not considered and effect of ship motion, heel and trim are not considered.

CASE STUDY – EVACUATION ANALYSIS OF A LARGE RO-RO/PASSENGER SHIP

Advanced evacuation analyses were undertaken for an existing passenger Ro-Ro vessel in accordance with the IMO guidelines. For the purpose of this paper, only the primary cases were evaluated (day and night time scenarios, with full availability of escape routes). The vessel, 205m long and 27m wide, with a capacity for 1,900 passengers and 600 cars, spans 11 manned decks (including 2 vehicle decks).

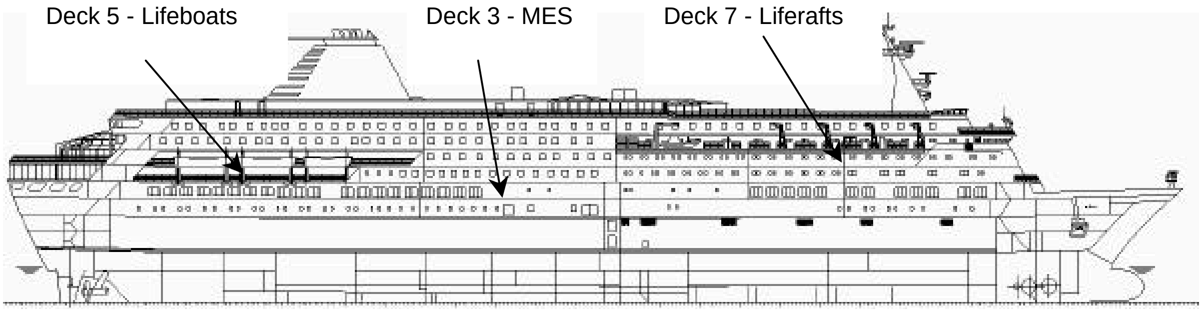

Figure 3: Vessel's profile

The passenger cabins are located on decks 1, 3, 5-8; passenger public areas are on decks 3, 4 and 9 and aft part of decks 5 and 6. The crew accommodation and recreation areas are located on decks 3 (aft), 5 and 7 (forward). The assembly stations are located on decks 3 through to 8 in a centrally located atrium hall in addition to a restaurant area (aft) on deck 5. There are three pairs of embarkation stations with three different types of Life Saving Appliances (Marine Evacuation Slides (MES), lifeboats and life-rafts) on decks 3, 5 and 7. A total of 1,892 people were considered in the analyses (1,698 passenger and 194 crew). The passengers and crew were distributed according to the vessel's Escape plan, while the demographic distribution of the population was defined as specified in the IMO guidelines[1]. The results of the simulations, illustrated in Table 1, indicate that the sample ship complies with the IMO criterion for the primary evacuation cases. In both day and night time scenarios, the 95 percentile of the assembly time results in an estimated evacuation time (including the safety margin and embarkation time), which is lower (by 20% and 33%, case 1 and 2) than the prescriptive maximum of 60 minutes. However, considering the degree of uncertainty in the parameters that drive the evacuation process (***d***, ***r(t)*** and ***s(n_i)***), it is essential to quantify the uncertainty of the simulation results, which can be done by assessing the sensitivity of the calculated assembly time to variations and/or inaccuracy in the input parameters. An attempt to quantify this uncertainty is presented in the next section for the sample ship on the basis of the IMO assumptions.

Table 1: Results of advanced evacuation analysis according to IMO guidelines[1]

Primary Cases	Simulation result T_{95}	Safety margin D	Travel time $T = T_{95} + \Delta$	Evacuation time $T_I = T + \frac{2}{3}(E+L)$
Night	1050.25s	600s	1650.25s	2850.25s
Day	1015.50s	200s	1215.50s	2415.50s

SENSITIVITY ANALYSIS

Do changes in input parameter values lead to "reasonable" changes in output values, both in magnitude and direction of change? Can the main variables be examined? Does the evacuation simulation model predict average test results accurately? Sensitivity analyses constitute the normal route to finding answers to these questions. The calculated assembly time depends, on one hand, on the performance of the evacuation model itself (the simulation tool), and on the other, on a number of assumptions regarding the parameters comprising the input to the model and drive the evacuation process. However, much has to be done to ensure that the ensuing assumptions are appropriate and that whenever there is uncertainty, this can be quantified. In view of the lack of appropriate and relevant experimental or full-scale trials data, an exhaustive analysis of the sensitivity of evacuability to variations in the input parameters is absolutely essential for two reasons: (i)-to quantify the uncertainty in the results given the uncertainty in the input parameters with a view to asserting a degree of confidence that can be placed upon the results, and (ii)-to assess the robustness of the evacuation model (simulation tool) itself, with a view to evaluate consistency and identify differences among the different approaches, so that knowledge and understanding can be progressed further.

In the sensitivity analyses presented in this section, an attempt was made to quantify the uncertainty associated with the assembly time calculated on the basis of the IMO benchmarking night and day time scenarios (case 1 and 2) by estimating the robustness of the 95 percentile of the calculated assembly time distribution (referred subsequently as Assembly Time) to variations in the input parameters in relation to the values implicit in the IMO guidelines. Thus, considering that evacuability is driven by four principal parameters: ***env*** (environment – the ship's layout), ***d*** (spatial distribution of people on board the ship), ***r(t)*** (response/awareness time of each person), and ***s(n_i)*** (walking speed of each person), the following has to be explained and emphasised:

- ***env***: For any comparisons to be meaningful we need to assume a time invariant environment for evacuation simulations; thus the geometry, layout, topology and semantics of the ship's layout were kept unchanged.

- ***d***: The spatial distribution of people during the day time, will differ considerably from that of the night time scenario. In the night time scenario, most people are assumed to be in their cabins, spaces with more or less simple and repetitive geometry and topology (cabins & corridors), hence the variability of the spatial distribution is likely to be very limited, and so will be its effect on the calculated assembly time. During the daytime scenario however, people usually occupy all available accommodation spaces (public spaces, open decks, etc.) at different numbers. The randomness of the spatial distribution of people in the day case scenario, coupled with increased (with respect to cabin/corridors) complexity in terms of geometry and topology of the corresponding spaces, will tend to increase the degree of uncertainty in the calculated assembly time.
- ***$r(t)$***: The response time of each person, is a random variable modelled with a uniform distribution. The current IMO definition of the expected value and variability of awareness time is arbitrary; hence the effect of inaccuracy in the prediction of both parameters (mean and standard deviation) ought to be evaluated as well as the impact of the choice of the probability distribution function (probability model).
- ***$s(n_i)$***:The walking speed of each person, is a random variable modelled with a uniform distribution, with a different expected value and variability for each demographic band of the population. Similarly to response time, the impact of choice of the probability distribution function and its parameters ought to be evaluated. It is expected however, that the choice of probability distribution function (normal, uniform, etc.) in this case will have little or no impact in the calculated assembly time, as the speed achieved by each individual person is very much affected (reduced) due to evacuation dynamics.

On the basis of the above reasoning, a number of simulation cases (D_i, R_j, S_k agents' distribution, response time and speed of movement respectively) were carried out for the same vessel evaluated in the IMO case study (***env***=*const*) in order to address the above aspects. The results of these simulations are presented and discussed next. The size of the sample distribution for estimating the assembly time comprises at least 20 runs, which has been found to be sufficient to ensure good statistical reliability.

RESULTS AND DISCUSSION

D1: Simulations with a typical night and day time spatial distribution of people were carried out for six nominal values of response time (constant coefficient of variation, COV=0.1734) and speed according to the IMO guidelines. For all the range of evaluated response times, the day time distribution of agents consistently resulted in assembly times longer than for the night time distribution. The difference was of the order of 15% to 25%, as illustrated in Figure 4. It must be noted that this difference is likely to be an estimate of the maximum effect of the spatial distribution on the calculated assembly time, as the evaluated cases are based on extreme assumptions (Night time: all passengers in cabins, Day time: all passengers in public spaces).

R1: The response time modelled as a random quantity uniformly distributed is defined by two parameters: mean and standard deviation[1] given in the IMO guidelines. Simulations were carried out for various response time distributions with constant COV. The results demonstrate that whilst the total assembly time increases with increasing response time (mean value), the individual travel times decrease, due to reduced congestion and bottlenecks (see Figure 4) an hence increased individual travel speed. The COV of the input response time distribution had a less significant effect, as the variation of the resulting assembly time was of less than ±5%.

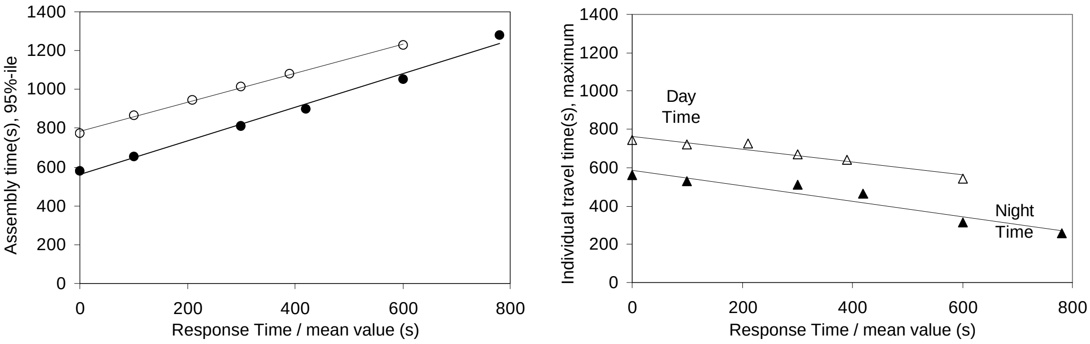

Figure 4: Impact of response time in the total assembly and individual travel time (COV$_{\text{Response}}$=const)

In terms of the values implicit in the IMO guidelines, the results indicate that a variation of ±30% of the expected nominal (mean) value of the response time would result in variations of ±7% and ±18% for the day and night time distribution, respectively (response mean is 300s and 600s, respectively; see Figure 5-left).

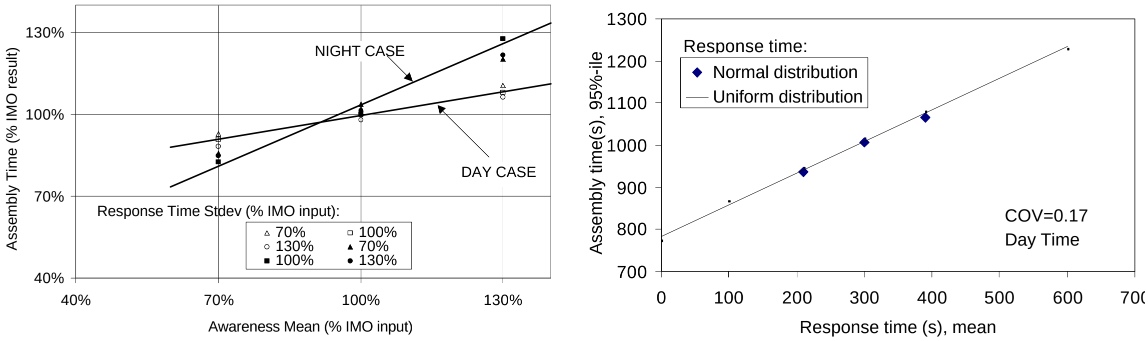

Figure 5: Response time and assembly time

R2: Simulations with two different probability distribution functions of the response time for various nominal values with constant COV were carried out for the day case IMO scenario. The results, illustrated in Figure 5-right, indicate that the effect of the shape of the distribution is negligible (up to 1%).

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[1] Defined by the minimum and maximum values as follows: *stdev=(max-min)/2*

S1: The walking speed is also modelled with a uniform distribution is defined by two parameters: mean and standard deviation[1] given in the IMO guidelines for specific demographic bands. Simulations were carried out for variations of these values (between –50% and +200%) with respect to the corresponding IMO speed band values. The results, illustrated in Figure 6 indicate that a variation of ±30% of the expected nominal (mean) value of the walking speed bands would result in variations of the assembly time of approximately +18% (if speed under predicted by 30%) and –8% (if speed over predicted by 30%) and this is consistent for both day and night time IMO scenarios. The effect on achieved individual travel speed is even larger (Figure 6-right). The effect of the spatial distribution of people is consistent with the observations from case ***D1*** in that for the night time scenario the assembly time is lower than for the day case for all nominal speed values by approximately 16%.

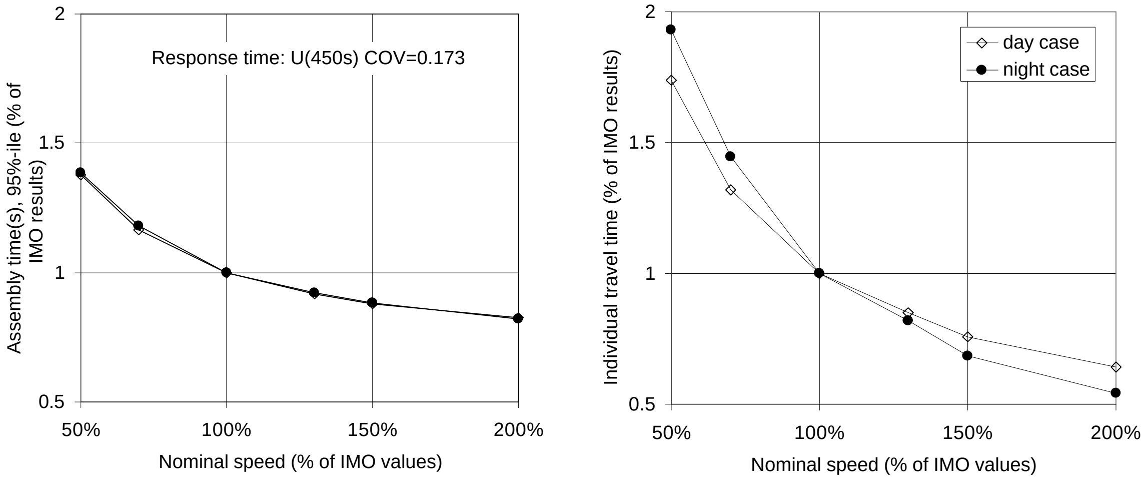

Figure 6: Impact of walking speed (with IMO demographic distribution) in the total assembly and individual travel time

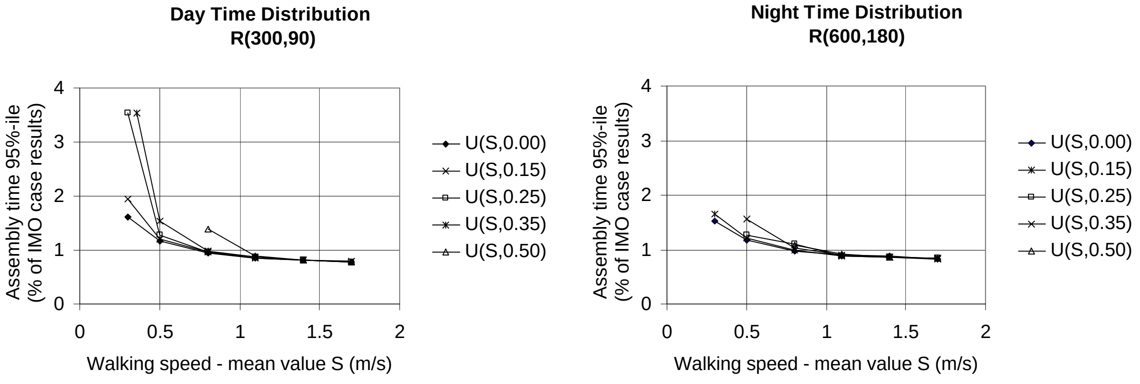

Figure 7: Speed variation (*COV = 0.05 - 0.57*) and assembly time

The effect of different coefficients of variation of the uniformly distributed speed variable is insignificant for nominal values above approximately 1 m/s. Below 1 m/s, the variation of speed, in conjunction with decreasing mean value, will result in a significant increase in the assembly time, as illustrated in Figure 7. It can also be observed, that systematic increase in the nominal speed would not reduce proportionally the travel time, which can be expected, as the actual speed is likely to be largely affected by the dynamics of evacuation, congestion in particular.

S2: Simulations were carried out with the IMO demographic distribution (7/7/16/10-% of the population assigned different speeds) and compared with a corresponding case in which the demographic distribution is equally distributed (10/10/10/10/10-% of the population assigned different speeds). The results indicated that the distribution of the speed bands among the population has no significant effect (less than 2%) in the total assembly time. Equally, if male/female average speed is assigned to all speed bands (demographics ignored), the calculated assembly time does not change by more than 5%. Moreover, assigning the speed to the IMO demographic distribution bands gives conservative results, in the sense that this results in longer assembly time.

S4: Simulations to address the effect of nominal speed without taking into account the demographic composition of the people were also undertaken. As can be observed in Figure 8, a nominal speed of approximately 0.8 m/s would result in travel times similar to those calculated from simulations with the IMO demographic distribution. This value may reflect the average actual (achieved) walking speed of all people in the simulation.

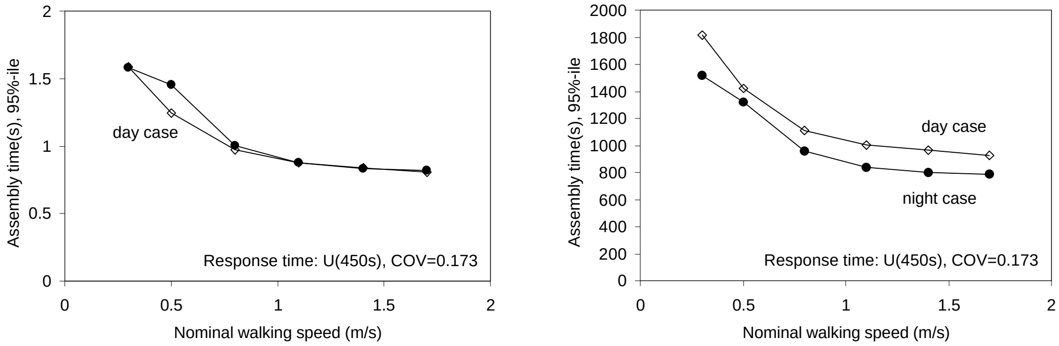

Figure 8: Average speed and assembly time (No demographic distribution)

In synthesis, the above results demonstrate that:

- The expected maximum impact of the spatial distribution on the assembly time is of the order of 15% to 25%, which corresponds to the difference in results between the night and day case distributions, used in the IMO analysis. The uncertainty in the spatial distribution within one scenario (day or night) is likely to be high, therefore this should be investigated further with a view to avoiding subjectivity and ensure consistency among different initial conditions.
- The choice of the probability distribution function and the variability of the response (awareness) time appear to have a negligible effect (well below 5%) on the calculated assembly time. However, a ±30% inaccuracy in its nominal value would result in significant variations of the calculated assembly time (of the order of ±7% and ±18% for the day and night time cases, respectively).
- Whilst the assembly time decreases with increasing nominal response time (mean), Moreover, the individual travel time increases with increasing response time.
- The choice of the probability distribution function and the variability of the walking speed, appear to have little effect on the calculated assembly time.

However, other factors like demographic distribution and nominal speed values appear to have significant impact on the calculated assembly time. It would appear that due to the dynamics of the evacuation process (congestion), a global average value of the actual speed would produce assembly times very close to those predicted with a full demographic distribution resulting in various speed bands, as suggested in the IMO guidelines.

- The implemented evacuation model appears to be very robust to most of the input parameters despite the implicit uncertainty. The obtained COV for a set of initial conditions and evacuation dynamics is of the order of 1%-4%.

CONCLUDING REMARKS

Undoubtedly, advanced evacuation simulation tools – used within an appropriate evaluation framework (of the type suggested in the IMO guidelines), will allow for a rigorous quantification and valid evaluation of the evacuation performance of a ship, being it for design or operational purposes. In this respect, it has to be emphasised that in the actual IMO guidelines, the evaluation of evacuability is currently made on the basis of 60 minutes as the life safety criterion (40 minutes for assembly time). It is felt that the adoption of a prescriptive (fixed) criterion is rather inconsistent with the performance-based approach adopted in the evacuation analysis. Instead, such a criterion should derive from life safety and/or performance criteria from a number of ship-related critical scenarios associated with fire and/or large scale flooding of the vessel's hull, or both; these constitute the two principal hazards for which a ship may need to be evacuated. On the basis of this study, the first systematic evaluation of the IMO guidelines onboard a real ship of the type these guidelines are meant to apply, it can be stated that there is still some ground to cover, aiming towards close form expressions of evacuability as functions of the aforementioned variables if application to other ship environments demonstrated tendency to shape functions that can be standardised. Moreover, there is still considerable effort required to address sensitivity of design and operation-related variables to populate data bases or in time create knowledge bases to facilitate design for ease of evacuation or to address the risk of passenger evacuation in an all embracing risk-based approach. These are some of the issues of ongoing research at SSRC, results of which will be reported in the near future.

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