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EVACUATION SIMULATION OF SHIPBOARD FIRE SCENARIOS

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ABSTRACT

Fire accidents onboard ships are statistically the most frequent hazards that ships encounter at sea. Indeed, several large-scale marine disasters have been caused by fires. The fast developments in ship design and the increasing trend towards innovative layouts, especially in passenger ships, could render prescriptive, rule-based design for safety obsolete. This is compounded by the introduction of regulations for alternative design which rely on evaluation of the design performance by marine authorities and, in turn, requires the use of state-of-the-art simulation tools in order to measure safety, i.e. ensure sufficient evacuation time for passengers and crew onboard. Fire and evacuation modelling is essential to assess the hazards associated with fire scenarios. These tools build on recent advances in field models in the civil sector and continuous improvements on evacuation and human behavioural modelling. The integration of both fire and evacuation models allows a more realistic assessment approach by including the health consequences of fire effects on human evacuees. This paper makes use of this integration of fire simulation and evacuation modelling in order to assess the safety performance of passenger ships when critical fire scenarios occur.

INTRODUCTION

Safeguarding against fire hazards onboard ships to date has been achieved through compliance with prescriptive rules which are issued by regulatory bodies. These rules are usually formulated in the wake of high profile maritime accidents and thus express a reactive approach to the pertinent issue of safety at sea. However, this tendency is bound to change by the introduction of performance-based design in the marine sector, which has instigated practical investment in prevention (as opposed to mitigation) and triggered the wide demand and use of first-principles modelling tools (Vassalos et al, 2010).

Ease of evacuation at sea is a crucial feature of any ship design. Escaping from a compromised space to a safe refuge area should be accomplished smoothly and timely. In more critical situations, ship abandonment might be required in the case of an uncontrollable fire or a progressive flooding. In these instances, failure to evacuate quickly can lead to heavy casualties. Several marine accidents such as that of the *Al Salam Boccaccio 98* (Panama Maritime Authority Casualty Investigation Branch, 2006) have been caused by onboard fires.

Assessing the ease of evacuation through full-scale evacuation trials is impractical due to the ethical and financial problems posed by such experiments (Galea et al, 2003). Modelling and simulation, on the other hand, provide a convenient way by which to assess ship design with respect to ease of evacuation at sea.

Actual evacuation in hazardous situations can differ greatly from drills and even from real evacuation from an intact vessel. Flooding can severely affect the mobility of evacuees due to ship heeling, the reliance of passengers and crew on using handrails to maintain balance on stairs, and possibly flooded escape paths (Pennycott and Hifi, 2010). Similarly, fire effects can impose serious obstructions on the passengers required to evacuate from a fire zone or the entire ship. Besides the known complexity of evacuation in compact shipboard spaces, fire effluents afflict evacuees with excessive heat, toxic gases, and reduced visibility. As a result, in order to account realistically for the fire conditions and their effects on evacuation, several additions and modifications to software normally used to simulate evacuation scenarios in non-critical situations are needed.

The evacuation model EVI, which is specifically developed for assessing the ease of passenger egress in shipboard environments, is discussed in this paper and a general description of its application will be provided. The main focus is on the work done on integrating simulated fire conditions into the evacuation model and modelling and quantification of fire effects on the exposed occupants. The simulation of an evacuation scenario is presented as an illustration of the application of the software.

IMO GUIDELINES ON EVACUATION

For most simulation scenarios, the demographic distribution of the passengers complies with the International Maritime Organization guidelines for evacuation analysis (IMO, 2007). Passenger distribution for both males and females have defined proportions of persons younger than 30, between 30 and 50, and older than 50 years old with and without mobility impairment. IMO also defines the evacuees' walking speed according to gender, age and evacuation route type (such as corridors and stairs, etc.).

The response time taken by passengers to start the evacuation procedure follows the truncated logarithmic normal distribution for day and night cases defined in (IMO, 2007). IMO considers the response time as the total time spent in pre-evacuation movement activities beginning with the sound of the alarm. In the case of a day evacuation the response time is between 0 and 300 seconds, while at night it ranges between 400 and 700 seconds. The detection time preceding the response is calculated in the fire simulations. Heat and smoke detectors are installed in the cabin according to the Fire Safety Systems code (FSS, 2007). The smaller detection time between heat detector (140 seconds) and smoke detector (20 seconds) is added to the above-mentioned response time.

EVACUATION SIMULATION WITH EVI

Overview of Evacuation Modelling

Evacuation from a ship involves movement and decisions of hundreds or, in the case of large cruise vessels, even thousands of people from an environment of complex geometry and topology. The ability of the passengers to find their way to the muster stations depends on signage and assistance from crew members.

Further factors which can have a large impact on the time taken and ease of evacuation include the starting positions of the passengers and crew, their reaction times (people do not react instantaneously to a casualty situation or alarm) and other characteristics of the people onboard such as travel speed. The factors influencing evacuation and which consequently need to be included in the simulation software are summarised in Figure 1.

In EVI, each passenger or crew member is modelled as an individual "agent". Each person tries to reach their assigned muster station using the ship's signage. The process of each person finding their route is modelled using a graph structure as shown in Figure 2. The graph allows people to select the appropriate next door to proceed to their destination; the position of this door is then used as a waypoint.

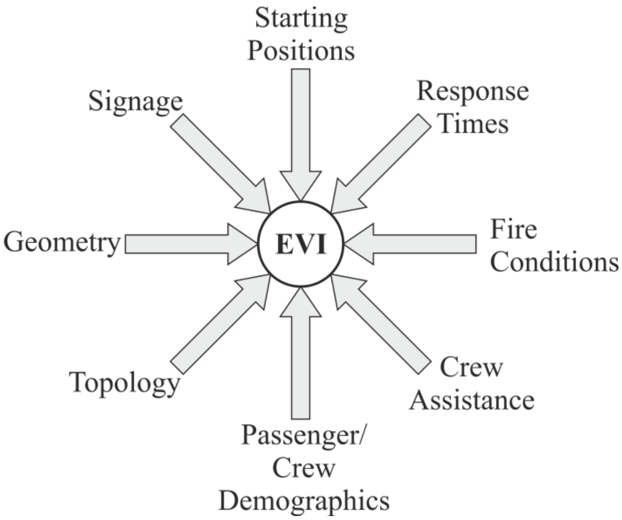

Figure 1: Many factors are influential to the evacuation outcome and these must be accounted for by simulation software.

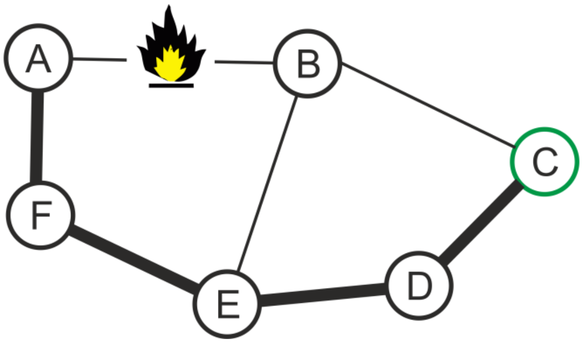

Figure 2: Representation of the ship topology in graph form is central to the evacuation modelling.

At the micro-level, agents select a vector to move closer to this waypoint whilst avoiding others, as depicted in Figure 3. The on-board areas are restricted to being convex regions, i.e. the route between any two points within a region can be represented by a straight line (macro-level).

Agents are thus governed by rules at the macro- and the micro-level. Because of this combination of macro- and microscopic behaviour EVI is a *mesoscopic* model (Vassalos et al, 2001).

A further feature of EVI is the facility to assign objectives to the people onboard. For instance, crew members can be sent to cabins to alert passengers and also provide information about the route to lost passengers. Simple objectives can also be assigned to passengers. Table 1 provides a summary of different objectives which can be used in the software.

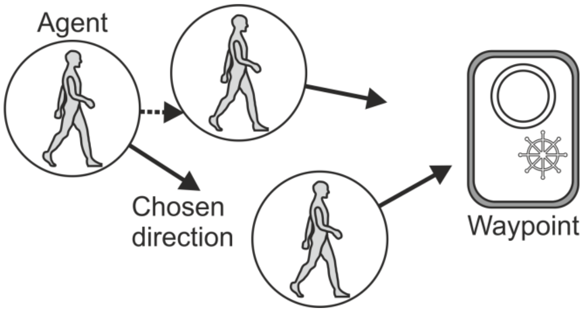

Figure 3: At the micro-level, agents try to move towards their destination while simultaneously avoiding collisions with others.

Table 1: Different types of objectives may be assigned to the passengers and crew.

Objective	**Description**	**Agent Type**
Evacuate	Default objective for all passengers/crew. Progress towards and wait at assigned muster station.	All
Return to cabin	Return to assigned cabin, e.g. to collect life jacket.	All
Go to	Go to a specific location.	All
Search cabins	Go to specified cabins and alert resident passengers.	Crew only
Re-route	Assign alternative route to passengers, e.g. in case of fire.	Crew only

Linking Fire and Evacuation Simulation

The fire simulation software produces fire data at discrete points in space which may not necessarily be organised in a regular grid structure. However, such a regularly-spaced structure is desirable in evacuation simulation. Appropriate fire data used to assess fire effects on a passenger at an arbitrary position can be located by using the position of the person in question and the spacing interval of the grid, avoiding the need to perform a search for the nearest data point which would be computationally time consuming for large data structures.

As illustrated in Figure 4, the data points from the fire simulation are used to create a regular grid structure. The fire state at each grid point is obtained by weighting the fire data from within a certain radius for each fire point inversely to its distance from the grid point in question.

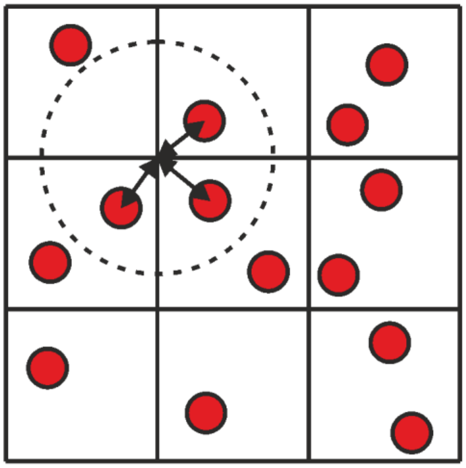

Figure 4: Data at FDS devices are used to generate a grid in EVI based on weighting using the distances between grid points and devices.

Quantification of Fire Effects in Evi

As fires produce heat in addition to smoke, exposure of humans to these fire products presents hazardous situations in the evacuation procedure. Heat and smoke can impede movement, impair visibility, block escape routes and even totally incapacitate occupants. The effects of fire and smoke on human life safety can be divided into three major parts:

- Toxicity due to inhalation of asphyxiants stimulated by the presence of other toxicants, in addition to respiratory and pulmonary irritation. Carbon monoxide, carbon dioxide and oxygen depletion are considered;

- Heat exposure due to convective and radiant heat;

- Visibility impairment due to smoke obstruction and sensory irritation. The walking speed of evacuees is reduced according to smoke concentration.

Heat and toxicity are treated by calculating the cumulative Fractional Effective Dose (FED) and assigning values to different health statues as they are presented in Table 2. Details about the formulations used in the above methods can be found in (Azzi and Vassalos, 2009).

In addition to modelling the incapacitating effects of fire, a range of other aspects should be modelled in order to appoint realism to the simulations. For instance, in a regular evacuation exercise each passenger is assigned a reaction time and will not begin moving until the simulation time has exceeded this value. However, a passenger directly exposed to noxious conditions (e.g. temperature or toxicity) will start moving immediately and any reaction lag will be ignored.

Table 2: Categories of injury at different levels of Fractional Effective Dose (FED).

FED Range	Injury Category
0 ≤ FED < 0.3	Negligible
0.3 ≤ FED < 0.7	Mild injury
0.7 ≤ FED < 1	Serious injury
1 ≤ FED	Fatality

Similarly, people may become aware of a fire just outside their cabin. For instance, passengers may be alerted from noise of people moving outside, or signals from other passengers and so on. In this case, the reaction time is again disregarded and the passenger immediately starts moving towards the muster station.

In more complex scenarios, the fire conditions will deem some regions of the ship unusable. A new graph structure can be constructed which takes into account the fire effects. Such a graph (Figure 2) is made by heavily penalising rooms where hazardous conditions are encountered. Initially, passengers do not have access to this updated map. However, it is assumed that all crew members have sufficient knowledge of and familiarity with the ship layout and they are able to re-route passengers in such a case. Therefore a lost passenger coming into contact with a crew member will be given an updated route to the muster station in the model.

APPLICATION EXAMPLE

In order to demonstrate the application of the fire and evacuation tools, an evacuation scenario in fire conditions was simulated. The geometry of the evacuated space, details of the simulated fire and the evacuation scenario are presented in the following sections.

Geometrical Arrangements

Safety regulations require that a ship should be divided into vertical zones for fire protection purposes. The layout considered in this paper consists of three main vertical zones (MVZ) spanning five decks. The geometrical arrangements are similar on all decks. The arrangement is a typical shipboard accommodation space with passenger cabins spread along two long corridors (40 meters) as illustrated in Figure 5. 26 cabins are located on each deck and within a single vertical zone. The corridors between different MVZs are separated by self-closing fire doors.

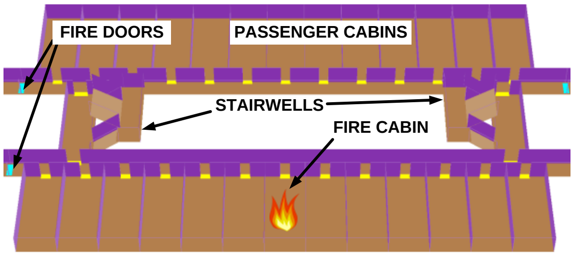

Figure 5: Layout of space accommodation in a single MVZ on the lowest deck in the domain.

Fire Simulation Settings

The fire is assumed to break out in a cabin (Figures 5 and 6) on the lowest deck on the starboard side of the ship, where the door is assumed open all the time and no fire suppression systems are activated. The combination of these two assumptions constitutes an extreme case scenario.

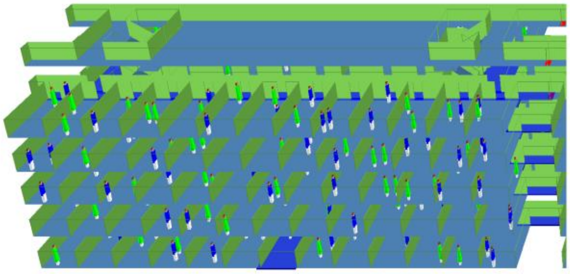

Figure 6: One MVZ of the example ship layout. Each zone is served by two main stairwells. The assigned muster station is located on the uppermost deck.

Fire Simulation

The software used for fire simulation is the Fire Dynamics Simulator, FDS (McGrattan, 2010). The heat release rate (HRR) curve was obtained from the published fire data of experimental tests on burning passenger cabins conducted by the SP technical research institute in Sweden, (Arvidson et al., 2008). An intense flashover fire is developed. The fire reaction considered in simulations is that of polyurethane with carbon monoxide and soot yields of 0.035 and 0.013 respectively.

The bulkheads (walls) of all corridors and cabins are assumed insulated with 50 mm of Rockwool while the decks (ceilings and floors) are insulated with 25 mm of Rockwool to provide a B-15 class according to (SOLAS, 2009). The doors of all cabins (except that containing the fire) are closed. The stairwells' doors are assumed open and allow smoke propagation to the four upper decks.

A uniform rectangular mesh with cubical cells was used for the computational domain. The cell side size in the fire room was 10 cm while in the rest of the domain a cell side of 20 cm was employed.

Evacuation Scenario

An IMO night case was simulated. In this scenario, passengers were initially distributed evenly in the accommodation area. Each cabin accommodated two passengers except the one with the fire where no passengers were allocated. In total 154 passengers were on the lowest deck and 156 on each of the four upper decks providing a total of 778 passengers in the domain (Figure 6). A total of 30 crew members were present.

Passengers were required to evacuate towards the muster stations on the upper decks. Those passengers initially located in the MVZ containing the fire had to move into the adjacent MVZs and then proceed to the appropriate muster stations. Evacuation modelling with EVI is normally conducted as a Monte-Carlo simulation where each run differs in terms of passenger/crew demographics (speed and response times) and initial location.

Two simulation batches were used, with 50 simulation runs performed for each. In the first batch, no crew assistance was provided. In accordance with IMO guidelines for a night simulation case, some crew members, initially located in the muster stations, were sent to the furthermost cabins from their starting positions in order to produce counter-flow in the model. In the second batch, some crew members were assigned "search cabins" objectives, where they moved from the muster stations on the upper decks to the cabins in the burning fire zone, alerting passengers as previously described.

RESULTS AND DISCUSSION

Fire Simulations

The output heat release rate in the simulations showed severe fluctuations after around 15 minutes and burning in the corridor and stairwells due to the fact that the input HRR was extracted from experimental data of a cabin afire with unlimited air supply through the door. However, in the simulations, the burning cabin is located on the lowest deck with air entrained through the stairwell openings on the fifth deck. Therefore, the authors deemed reasonable to truncate the input HRR after 15 minutes to account for oxygen deficiency and thus avoid severe fluctuations and fuel burning very remotely from the cabin. The initial HRR from experiments and final output HRR from FDS simulations are shown in Figure 7 below.

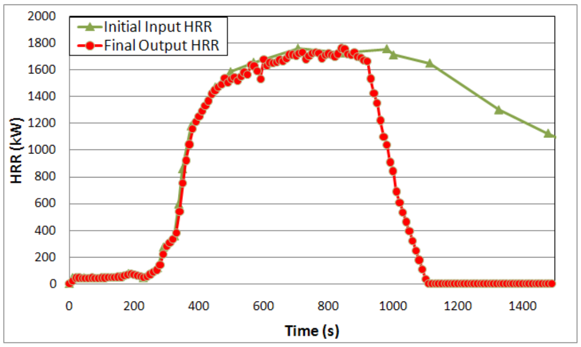

Figure 7: The initial input HRR as extracted from experiment data and the final output HRR of fire simulations.

The temperature in the burning cabin exceeded 850°C during the developed phase of the fire, whilst the temperature in the doorway inside the corridor reached 750°C (Figure 8). These figures are very comparable to those measured in the actual experiments where 800°C was exceeded in both cabin and corridor.

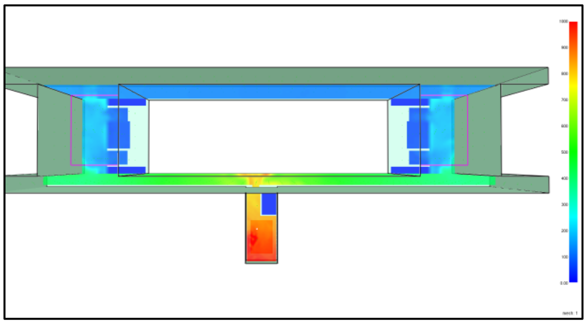

Figure 8: Plan view from Smokeview (FDS post-processor) showing the temperature in the first deck at 1.5 meters.

Evacuation Simulation

The evacuation times required for the different runs with and without crew assistance are shown in Figure 9 in a cumulative plot. For instance, the point (900, 60) indicates that 60% of the runs had an evacuation time of less than or equal to 900 seconds. The evacuation times where crew assistance was provided are lower since the passengers in the hazardous MVZ were alerted by crew members and thus began their journey to the muster stations earlier.

The number of occurrences of each category of injury for the simulation runs without crew assistance is shown in the box plot of Figure 10. Different levels of injuries with median and upper/lower quartile values are depicted. In the simulation batch with crew assistance, no injuries occurred in any of the simulation runs since the crew were able to reach passengers before the corridor area attained a hazardous state.

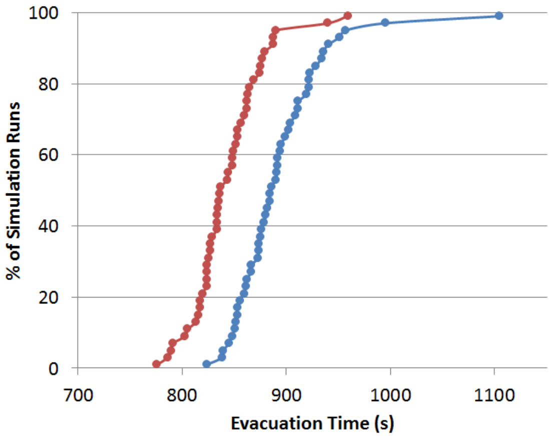

Figure 9: Cumulative plot for required evacuation times for the simulation batches without crew (blue) and with crew assistance (red). Each point represents the total time required for all passengers and crew to reach their muster stations in one simulation run.

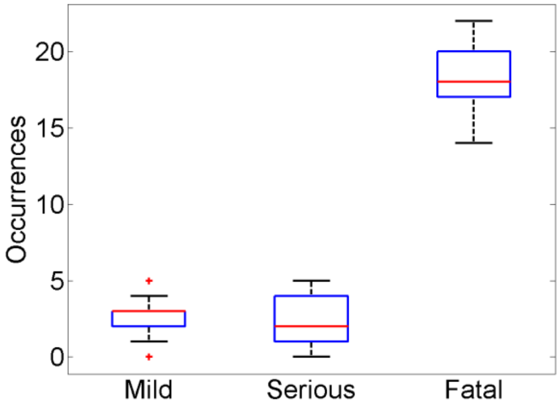

Figure 10: Boxplot of occurrences of different injury levels encountered for the 50 simulation runs without crew assistance.

As depicted in Figure 11 and as is typically observed in evacuation simulation, the greatest build-up in passenger congestion was observed within the main stairwells. Nevertheless, the congestion level was low, and the overall evacuation times were dominated by the reaction times and travel speeds of individual passengers in addition to their initial locations on the ship, as opposed to bottlenecks and congestion.

During the simulations without crew assistance, the large majority of injuries and fatalities occurred in the area immediately adjacent to the burning cabin. Hazardous conditions rapidly developed in this corridor before the passengers reacted. Consequently, rapid damage was inflicted upon these passengers when they finally did emerge from their cabins (Figure 12).

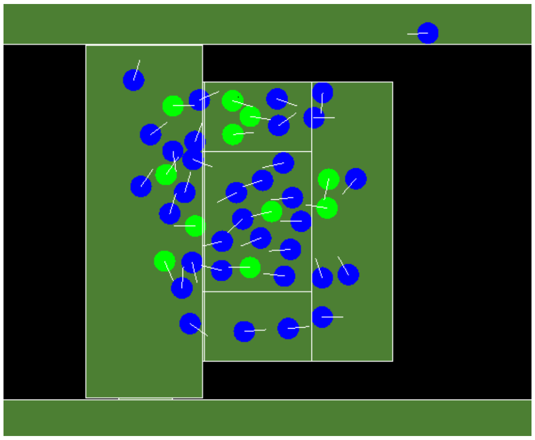

Figure 11: Congestion was highest in the main stairwells adjacent to the MVZ containing the fire. Congested passengers are shown here as green circles.

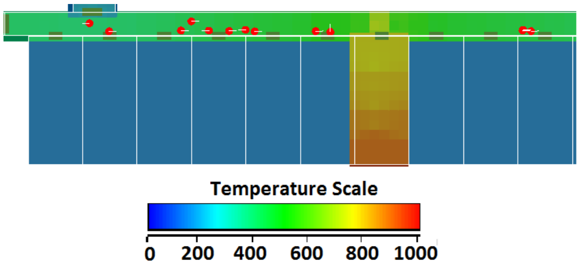

Figure 12: Most fatalities (shown as red circles) occurred in the corridor in the vicinity of the burning cabin.

Although the fire effects were the main focus of this example, the evacuation software can be useful in identifying key congestion areas for models of more complex geometry and higher passenger/crew population. Areas of high congestion can be identified, and strategies for reducing passenger congestion and bottlenecks such as changes to ship geometry and routes to the muster stations can be tested.

The congestion in the main stairwells seen in this model was caused by passengers in the burning MVZ migrating to adjacent zones, placing extra pressure on the stairwells serving those neighbouring areas. It is expected that this would be a typical feature of evacuation in fire conditions since egress from a main vertical zone is normally required.

The simulation example presented here has demonstrated how the fire simulation and evacuation modelling software can be coupled to investigate a particular fire case. Further work is required to investigate the sensitivity of the model to factors such as variation in passenger and crew demographics, passenger reaction to the fire conditions, alternative fire locations, and variation of fire types.

CONCLUSIONS

This paper has discussed the issue of evacuation at sea and the related difficulties encountered. Shipboard evacuation can be complicated due to the complex geometry of the ship and the effects induced by sea conditions. Considering evacuation in fire affected conditions further complicates the evacuation dynamics and introduces the need to account for fire effects on evacuees in evacuation models.

The demonstration case performed here highlights the problem of the long response times of the passengers in reacting to fire alarms. The delayed responses can be fatal, although these adverse outcomes can be mitigated by crew assistance.

The decisions made by the passengers and crew in response to the fire conditions are currently modelled using a simplified approach. Further additions to the software are required to model more realistically the evacuation process in a fire scenario. These could be based on observations from reports on actual evacuation from burning ships or buildings.

AKNOWLEDGMENT

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