MODELING AND SIMULATION OF THE EVACUATION PROCESS OF PASSENGER SHIPS

E. K. Boulougouris* and A. Papanikolaou**
Department of Naval Architecture & Marine Engineering
National Technical University of Athens
9 Heroon Polytechnicou Street GR-157 73 Zografou, Greece
*: Corresponding author’s email: yboulg@deslab.ntua.gr
**: Corresponding author’s email: papa@deslab.ntua.gr

ABSTRACT
The need to safely evacuate within very short time a large number of people from a confined space, such as the superstructure of large passenger ships, is a difficult task of great practical interest, as documented in recent discussions at the Marine Safety Committee of the International Maritime Organization (MSC-IMO).

This paper describes the methodology utilized by the code EVDEMON (EVacuation DEmonstration & MOdeliNg), currently under development at SDL-NTUA, for the simulation of the evacuation process onboard passenger ships and presents typical results of application to the evacuation of a modern Ro-Ro passenger ferry. The code is understood as a design tool assisting the designer in the early design stage as to the consideration of proper arrangements for enabling a timely and safe evacuation. The designer is asked to care of optimal measures in terms of internal arrangements to allow for the fast evacuation without bottlenecks, when the ship is in danger. Given the uncertainty of human behavior under stress and the restrictions of a possible mathematical modeling thereof, only multiple simulations of different evacuation scenarios may give the naval architect an indication about the potential outcome in such an event, so that bottlenecks can be identified and removed to the extent possible. At a later development stage, namely after the validation phase, simulation codes, like the presented one, might be used as evidence for the approval of evacuation plans by relevant authorities, as documented by MSC-IMO (MSC Circ. 909/ 1999).

INTRODUCTION
Significant marine disasters triggered always the maritime community to look after new concepts for addressing existing but not satisfactorily solved safety problems. The requirements for more rational arrangements that would enable a safer and easier evacuation of ships in emergencies are not an exception to the above rule. It was, among others, the tragedy of the ESTONIA ro-ro passenger vessel that stressed the necessity of these requirements (Allan, 1996). The causes of that accident remain still today a point of dispute but the likelihood that another vessel carrying thousands of people on board might find her in a similar situation is a probability that cannot be ignored. This is even more a problem of large cruisers, with planned carrying capacities of several thousands that the maritime community is called to solve by pro-active measures properly, before such disasters occur. The international maritime community has addressed until now this problem through a number of rules and regulations, based on past experience of marine disasters and state of the art know-how, covering as many aspects as considered necessary and practically feasible, particularly measures regarding the ship’s construction, fire protection-detection-extinction, life-saving equipment, helicopter landing and pick-up area, evacuation procedures, crew training etc. But one main factor that cannot be predicted sufficiently is the human behavior under stress and when in groups of large number of people. Will the passenger make it to the area assigned by the designer to enable his survival or is the time practically not enough? Here is the point where the simulation of the evacuation procedure by proper design tools is introduced.

BACKGROUND
According to Regulation II-2/28-3 of the Annex to the International Conference for the Safety of Life at Sea, 1974 (SOLAS, Consolidate Edition, 1997), it is required for ro-ro passenger ships built on or after 1st July 1999: “For ro-ro ships constructed on or after 1 July 1999 escape routes shall be evaluated by an evacuation analysis early in the design process. The analysis shall be used to identify [...] congestion which may develop [...] due to normal movement of passengers and crew along escape routes, including the possibility that crew may need to move [...] in a direction opposite the movement of passengers. In addition, the analysis shall be used to demonstrate that escape arrangements are sufficiently flexible to provide for the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may not be available as a result of a casualty”. In addition to that, several requirements, already in place, affect the evacuation of this type of ships, the most important being:

- SOLAS III/20-1.4 requiring that the maximum time allowed for embarkation and launching of survival boats is 30 minutes, from the time ‘abandon ship’ is given;
- 1995 SOLAS Conference requiring that the complete evacuation procedure of ro-ro passenger ships should be completed in 60 minutes;
- IMO ’s resolution A.757(18), prescribing the dimensioning criteria for escape routes, stairs’ and landings and corridors.

IMO has also published (interim) guidelines for a simplified evacuation analysis on ro-ro passenger ships through the MSC/Circ. 909. The critical points of these guidelines are:

- The analysis should consider at least two scenarios, as they are specified by the IMO for the design of escape ways (IMO ’s Res. A.757(18)); namely a night scenario (all passengers in cabin, a fixed % of the crew in cabin) and day scenarios (passengers in public areas, crew distributed in working spaces);
The analysis is made with 100% of passengers capacity certified (passenger load).

The total evacuation time is considered consisting of two parts, namely mustering (peoples’ movement to the muster stations after becoming aware that the ship is to be evacuated) and embarkation (passenger egress from the muster stations to the embarkation stations, up to the moment the life boat are launched);

Preceding the launch of the evacuation procedures, the guidelines assume an awareness time that is 10 and 5 minutes respectively for the night and the daylight scenarios.

Between the mustering and the embarkation phases, the procedure assumes a certain overlapping, amounting up to one third of the total embarkation and life boat launch time, as can be seen in fig. 1.

The calculation of the mustering time is based on “ideal” conditions, that are: simultaneous evacuation of passenger and crew, without hindering each other, via the primary escape routes, with people in good fit and with 100% availability of escape arrangement. This time is then multiplied by a safety factor of two and then an additional 30% is added to account for the possibility of counter flow.

The speed of people is taken from US NFPA and varies according to the density of persons and the type of escape facility (descending stairs, ascending stairs, corridors).

The evacuation time is then calculated adding to the mustering time the embarkation time. This is taken either from data provided by the manufacturer of the lifeboats and launching system, or from full-scale trials. If no such information exists then the maximum allowable value, namely 30 minutes, should be used.

It is a known fact that testing an existing evacuation arrangement of a ship by evacuation drills the assessment of the results remains has uncertainties, even if the participants are trained (Koss and Manor, 1996). On the other hand, the naval architect is called to finalize the general arrangements of the living spaces and to make provisions for proper evacuation based on existing regulations, that often prove not covering sufficiently all safety aspects, but only those identified from past experience. The only valuable solution to this appears the sufficient all safety aspects, but only those identified from past relevant know-how. Similar tools have been used, e.g., in the aircraft industry (Galea, 1996), the building industry (Owen, 1996; Shih, 2000) and the offshore industry (Ying, 1998). Note, however, that this type of tools are nowadays progressively introduced also to the assessment of ship designs (Vassalos, 2002; Meyer-König, 2002).

HUMAN EVACUATION BEHAVIOR

The human behavior under stress is very difficult to predict. With the term stress we express, “psychological stress designating unpleasant emotional states evoked by the threatening environmental events or stimuli” (Ozel, 2001). There are situations where this behavior becomes irrational. This is usually described by the term ‘panic’. This has been observed during egress situations where crowd crushes and people show an element of competitiveness. According to the UK Ministry of Works, “Panic is an assembly audience results in a crowd jamming the exits and causing injuries quite apart from the injury by the fire […] individuals as well as groups may become panic-stricken. Lives may be lost, for example, through fear of using staircases in which there is some smoke but which would actually give safe passage out of a building”. It has been also argued that this irrational behavior at the crowd level, is likely to be rational in the individual’s own terms (Sime, 1995).

From observations of Helbing et al (2002) we find that pedestrians under normal situations tend to:

- Feel strong aversion to taking detours or moving opposite to the desired walking direction, even if the direct way is crowded.
- Prefer to walk with an individual desired speed, which corresponds to the most comfortable walking speed. The desired speeds within pedestrian crowds are Gaussian distributed with a mean value of approximately 1.34m/sec and a standard deviation of about 0.26m/sec.
- Keep a certain distance to other pedestrians and borders.

From the above, the difficulty to model the human perception and decision-making is obvious. Therefore it comes to no surprise that engineers prefer to avoid the detailed modeling of the decision making process and they tend to simplify models. They include few easily distinguishable patterns recognizable in this behavior. Such a simplified approximation of the human behavior in case of an evacuation signal is illustrated in fig. 2 (Reisser-Weston, 1996). It is obvious that there is a period of situation assessment between the acoustical signal and the decision to act and evacuate. Other possible actions before the initialization of the evacuation process is the assembly of a family or the decision of the preferred exit from the particular room. Therefore the time for a crowd to escape from a situation of potential entrapment is a function of T (time to escape) = t₁ (time to start to move) + t₂ (time to move to the exit) + t₃ (time to pass through exits), rather than T = t₁ (Sime, 1995). Of course competitive behavior that affects the crowd in case of panic, as they attempt to acquire something that they believe will lead them to safety, makes them irrational and results in jamming the exits and causes injuries that all result in large time delays.

MODELING APPROACHES

At a low level, the simulation of the evacuation requires the modeling of the motion of a large number of passengers, which are essentially pedestrians. Pedestrian motion simulation itself is another quite broad topic. There are many different ways to address scientifically this topic: regression models, queuing models, route-choice models, gas-kinetic and macroscopic models, microscopic models. Regression models use statistically established relations between flow variables (e.g. flow per meter width and speed) and use these to predict pedestrian flow operations under specific circumstances. The form of these statistical relations is generally different for different kinds of infrastructure.
(hallways, stairs) and flow compositions, and need to be established explicitly for the facilities of interest. Queueing models use Markov-chain models to describe how pedestrians move from one node of the network (mostly a room) to another. Random waiting times are incurred on the network links (generally doors), due to queues building up when pedestrian demand is larger than the door capacity. These models have been used mostly to describe evacuation behavior from buildings. Route-choice models describe pedestrian wayfinding through the walking facility based on the concept of utility maximization. In this case, pedestrians choose their (intermediate) destinations in order to maximize the utility (travel time, comfort, etc.) of their trip. Macroscopic models and gas-kinetic models use the analogy with fluid or gas dynamics to describe how density ρ(t, x) and velocity v(t, x) change over time using partial differential equations (Navier-Stokes or Boltzmann like equations). The last category contains the microscopic models. These describe the time-space behavior of individual pedestrians. There are two subcategories of these models: the social force models and the Cellular Automata (CA) models.

The last category is herein considered the most attractive for studying pedestrian flows for a number of reasons. They model the interactions of the pedestrians using intuitively understandable behavioral rules. They are easily implemented on digital computers and run exceedingly fast. The difference between the two subcategories is in the discretization of space and time. Social force models describe microscopically the pedestrian behavior by means of so-called social fields (Helbing, 2002) induced by the social behavior of the individuals. This leads to (coupled) equations of motion similar to Newtonian mechanics. The adopted approach is, however, not exact, because the third law ("action=reaction") is in general not fulfilled (Schadschneider, 2002).

**BASIC PRINCIPLES OF THE MODEL.**

In the EVDEMÖN model of SDL-NTUA, as in all CA models, space, time and state variables are discrete. To keep the model simple, we aim at providing the passenger entities with as little intelligence as possible and to achieve the formation of complex structures and collective effects by means of self-organization. We do not make, at this stage of development, detailed assumptions about the human behavior. Interactions between passengers are repulsive for short distances. One likes to keep a minimal distance to others in order to avoid bumping into them. This is achieved by preventing multiple occupation of a space 'cell'. For longer distances the interaction is often attractive, e.g. when passengers belong to the same group, such as a family.

The area available to passengers is divided into cells of approximately 40 × 40 cm². This is the typical space occupied by a pedestrian in a dense crowd (Schadschneider, 2002). Each cell is either empty or occupied by an entity (passenger). An example of the spatial modeling is shown in fig.3.

At each time step the condition of the system is updated through the allocation of the passengers at different space locations. There are generally two types of procedures used for such simulations: the random sequential update and the parallel update. The first moves the passengers in a random order but every passenger only once in a time step. After the move of a passenger the next reacts to the new distribution. Because of this there is no problem with multiple occupations of a single cell. On the other hand the parallel update moves the pedestrians in the first step only virtually. Due to this there is the possibility for a multiple occupation of a single cell because the moving passenger does not know if the cell he has chosen is still empty or occupied by a virtually moved pedestrian. Because of this, after the virtual move of all pedestrians, a conflict solution is performed to resolve the problem with more than one passenger per cell. A cell, which is claimed by more than one passenger, is drawn under the concerned pedestrians. The winner gets the cell while the losers move back to their original positions.

**Wayfinding**

Another important aspect of any evacuation simulation, strongly linked with the decision process, is the wayfinding algorithm. The problem of path finding is primarily studied in Robotics and Artificial Intelligence (AI) literature. Several approaches have been proposed (Lewińska, 1998; Hoogendoorn, 2001). In CA models it is common practice to use 'floor fields'. These differentiate into the dynamic and the static floor field. The first is just the virtual trace left by the previous passengers that used the particular cell. It is subject to diffusion and decay, which eventually leads to a dilution and finally the vanishing of the trace after some time steps. The static floor field is used to specify regions of space that are more attractive, e.g. an emergency exit.

In our model we decided to adopt a methodology popular in computer games, namely the A* algorithm or 'A star'. The idea behind A* is to look for the shortest possible route to the destination not through exploring exhaustively all the possible combination but utilizing all the possible directions at any given point (Bandi and Thalman 2000; Kawick, 1999). An example of an application of the algorithm is shown in fig.4.

The underlying assumption is that at any given time step each passenger plans its path to his target point, which is to reach the preferred exit (fig. 5). Obviously, at each room there are only a limited number of potential targets for the passengers, which are the exits. The selection of a target point is made initially as the entity enters the room and it may change if it remains stationary more than a certain number of time steps dependent on the individual’s parameters.

**Characteristics of the population**

The human entities assumed in our model can move in eight different directions as shown in fig. 6. They belong to two main categories: the passengers and the crew. Each of these categories has different characteristics e.g. crew entities are not characterized by their age and they have reporting posts which makes them to move sometimes against the evacuating passengers. On the other hand the passengers belong to different age groups, they may be children, adults and elderly people. The age is a factor in the determination of the mobility characteristics of a passenger e.g. its maximum speed and his time delay with respect to the alarm signal. The maximum speed is defined by the maximum number of cells per time step that an entity may change; e.g. if the fastest passenger can change 3 cells per time step and this is set to be 1 sec, then the maximum speed is 1.2m/sec or 4.32 km/h which is consistent with the IMO MSC/Circ.909. Due to the dynamics of the human movement, each entity may accelerate between two sequential time steps from standstill to maximum speed or decelerate from maximum speed to standstill (Schadschneider, 2002). The maximum speed property of each individual is distributed, at the initialization stage, using a random number generator in order to achieve certain distributions.

**Graphics**

In the planning of the software tool development it was considered essential that inexperienced users should be able to easily apply the developed tool, with modest hardware requirements. Therefore the Graphics User Interface (GUI) should be in such a form that the state of the system could be easily controlled and the characteristics of the environment (space arrangements) easily identified. It is true that many different approaches have been introduced, until now, for the
development of related computer simulation codes. Programs such as SIMULEX (Thompson, 1995) use 2D representation of the human movement, while others prefer the Virtual Reality (VR) models in their simulations (Shih, 2000).

The adoption of herein a CA modeling approach required a consistent modeling of the graphical space. The development platform was decided to be simply a standard PC Pentium. Therefore the graphic environment has been modeled with the use of Microsoft® DirectX® 8. DirectX® , which is a set of low-level application programming interfaces (APIs) for creating games and other high-performance multimedia applications. It includes the support for two-dimensional (2-D) and three-dimensional (3-D) graphics, sound effects and music, various input devices, and enables a variety of networked applications such as multiplayer games. EVDEMON uses a tile-based environment, which is usually described as 2½D space model (fig.7).

From the procedural point of view and at present stage of development, the EVDEMON code is able to control, for a specific general arrangement, various scenarios of different populations and distributions thereof, and to conclude on the required time for the evacuation of the specified space.

FURTHER DEVELOPMENT

The further development of the EVDEMON code of SDL-NTUA will consider the incorporation of a model for the effects on the individual’s decision process by the presence of significant heeling angles, due to an assumed damage of the ship, the presence of smoke and fire in rooms and also the impact to the kinetic characteristics of passengers due to ship motions. The validation of the simulation results by relevant physical model experiments (to the extent available for restricted space scenarios) and the comparison with results of other similar simulation codes is another significant task prior to the finalization of the code development.

CONCLUSIONS

Evacuation models based on computer simulations of individual human’s egress movements start to play an important role in the early design and operation of large, passenger carrying ships. The present paper outlined the basic principles of such a model under development at the Ship Design Laboratory of NTUA. After validation, simulation codes, like the presented one, will be an invaluable tool for designers of passenger ships and might be eventually used as evidence for the approval of evacuation plans by relevant authorities, as discussed at the MSC Committee of the International Maritime Organization (MSC Circ. 909/1999).
REFERENCES


