Simulating mustering and evacuation processes onboard passenger vessels: model and applications

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Keywords: evacuation simulation, safety assessment, SOLAS

Abstract
The analysis of evacuation processes onboard passenger ships has attracted increasing interest over the last years. Especially the introduction of so called performance based requirements as stated in SOLAS II-2/28-1.3 leads towards a more comprehensive assessment. However, for a thorough investigation of the evacuation performance it is not sufficient to look only at the geometry, like hydraulic or flow models do. Behavioural and procedural aspects have also to be taken into account, although one will never be able to predict exactly what will happen. Since knowledge of the initial conditions, influencing factors, and laws of human behaviour is limited, it does not make sense to include factors that cannot be quantified. Therefore, a compromise has to be found: to get as close to reality as necessary and to provide a method as flexible, straightforward, and comprehensible as possible. This, of course, is a crucial question in evacuation assessment and modelling of real world processes in general. We present a microscopic simulation model that is capable of representing every individual person and his/her characteristic abilities as well as all necessary details of the floor plan and at the same time allows for a fast and efficient simulation. The behavioural and procedural aspects of mustering and evacuation are also included: waypoints, mustering stations, and embarkation stations define the sequence of events for different groups of persons. This accounts for social influences like group formation. The general philosophy with respect to the individual motion is to focus on the measurable quantities like walking speed and orientation frequency and to represent the remaining psychological factors via stochastic parameters. The implementation of the model is outlined and simulation results for passenger ships and High Speed Passenger Craft (HSC) are shown. However, the validity of the assumptions and the scope of the applications will have to be further scrutinized by comparison with detailed empirical data from actual drills or evacuations, as far as available.

1 Introduction

Tragic ferry disasters in the past have shown the need for improved safety-standards in the shipping industry. Because of the large number of passengers carried on ships, and the unforgivable environment they mostly sail in accidents can result in high casualty

numbers. An effective evacuation-procedure must therefore be mandatory. But what will happen, if two thousand or even more people move through a ship, try to gather their belongings or related persons and to get out? Where do the bottlenecks occur? How can congestions be prevented? There are many questions that arise, when the evacuation-concept of a ship has to be evaluated and descriptive calculation methods are not able to handle the complexity of the problem in a holistic approach.
This paper gives an overview of the simulation of mustering and evacuation processes. Therefore, some general remarks about the various influences and their representation within the model are made. The basic aim is to further develop the Cellular Automaton model providing the basis for the simulation and to support the IMO (International Maritime Organization) in establishing guidelines for the use of simulations for the safety-assessment of passenger ships [1]. The goal is to establish a simulation model to quickly and effectively assess the design of a passenger ship.

2 Different evacuation procedures for different vessels

For classification passenger vessels are divided into the following three main groups: High Speed Passenger Craft (HSC), RoPax- and cruise ships. The exact definition for each type can be found in the appropriate IMO regulations (cf. [3] and references therein).

Figure 1: Pictures of a typical HSC, a RoPax-Ferry and a cruise liner (pictures: author, Jos. L. Meyer shipyard).

The evacuation procedures for those different types of vessels differ greatly. This is due to several reasons: the geometrical layout, the length of the journey, the typical passenger population onboard, etc. Because the general layout of a HSC is fairly simple and the passengers are seated in rows (just like in an airplane), it is unlikely that they will be spread all over the vessel in an emergency situation. The evacuation strategy is therefore very straightforward: After the life rafts have been deployed, the passengers will take their life vests from beneath their seats and leave the ship via the slides.
The procedure is totally different with RoPax- and cruise ships, since people can have cabins and are able to linger on many public places all over the ship. In case of an evacuation, they have to retrieve their vests in the cabins or at central distribution points, gather at muster stations and walk on to the embarkation stations were they finally leave the ship. Everybody can imagine what will happen on a cruise liner where one half of the passengers is seated in the restaurant while the other half sits in the theatre and the mustering signal is given.

3 Model assumptions

3.1 Physical aspects of human motion

In this section, we describe a model that is capable of simulating the various evacuation procedures that can occur onboard ships. One basic principle is to use a microscopic method: the behaviour and movement of every single person is simulated. This is quite a challenge regarding effort in time and computer memory. To restrict the requirements, a Cellular Automaton (CA) model is used with a minimum set of parameters per person to characterise her behaviour. We argue that those parameters are sufficient to describe the relevant aspects of human motion onboard ships:

- the maximum walking speed,
- the patience before she chooses an alternative goal, if her way is blocked by congestions,
- a factor that characterizes the visual perception of her environment,
- the delay time, during which she will wait before starting to evacuate,
- a dawdle probability with which she will stop for one time step, to take into account breaks for regeneration or orientation, and
- a factor that characterises the inertia of the persons movement.

The reduction of the various influences to this list of parameters is possible, because these are the factors that finally characterize the movement from a physical point of view. Other authors distinguish between defining attributes and progress variables [7]. The majority of those are connected to the influence of narcotic gases and heat, which is not yet included in our model. The remaining attributes determine the motion abilities. Taking this into account the approach is similar to the one presented here. Attributes like age, gender and stamina eventually take effect on, e.g., the walking speed. As a result of these simplifications, the simulations can be done on standard computers with very high calculation speeds (about 10.000 persons in real-time on a 500 MHz PC with 128 MB RAM). It is therefore possible to predict evacuations in a very short time which will allow online-simulations for big crowds in near future. By varying the parameters, any population can be represented.

3.2 Representation of the floor plan

The floor plan of the structure to be assessed is transformed into a grid of quadratic cells with an edge-length of 0.4 meters. One person thereby occupies one cell. This derives from the maximum density in crowds, when the movement reaches a stop [4].

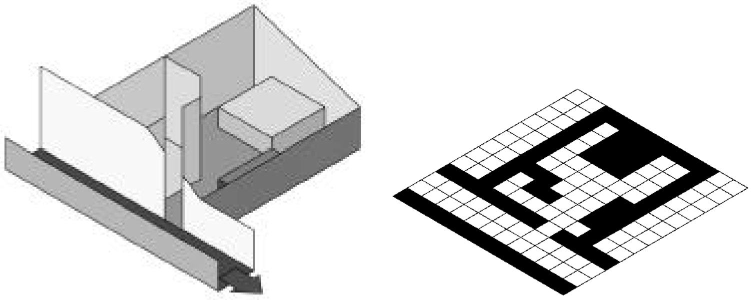

Figure 2: Example for a discrete floor plan.

Each cell contains different pieces of information, depending on the way it influences the person standing on it. If it is not accessible, it represents an obstacle like a wall or furniture. Others influence the speed of the persons walking over them, so stairs and doors can be considered. To change the decks (e.g., at stairs), cells are implemented, that cause the person standing on them, to jump to the next upper or lower level. In this manner, the floor plan of complex structures can be modelled in a very simple way.
Another point of discussion is the discrete cell size. The main argument against the usage of cells are small variations in the width of corridors or doors. On the other hand, a person has a discrete size, so it seems very unlikely, that the functional relation between corridor width and flow is linear. We are currently conducting research on this topic.

3.3 Inclusion of ship motion

An additional remark is in place concerning ship motion: Since the parameters are not time dependent, dynamic ship motion is not explicitly included. It might be represented by a higher dawdling probability or decreased walking speed. Actually, in the literature, the approaches used for solving this problem are based on a speed reduction factor. Brumley [8] has obtained the following empirical result for the speed reduction factor

$$\bar{r}_v = 1 \qquad \text{for } \Theta < 15°$$

$$\bar{r}_v = 1 - 0.25\left(\frac{M_1}{M_2} - 1\right) \qquad \text{for } 15° \le \Theta \le 25°$$

$$\bar{r}_v = 1 \qquad \text{for } 25° < \Theta$$

where T is the angle of list and roll motion, respectively. M_1 and M_2 are the environmental moment and the (measured) resisting moment of the person. Unfortunately, it is not completely clear, how M_2 (the resisting moment) and T are connected.
Another empirical formula is given in Vassalos et.al. [9], cited from [10]:

$$r_v(q) = \begin{cases} \dfrac{e^{1-|q/q_{\max}|} - 1}{e - 1} & \text{for } 0 \le q \le q_{\max} \\ 0 & \text{for } q > q_{\max} \end{cases}$$

T(t) is the angle of the roll motion and T_{max} is set to 20° is the roll amplitude. So the general approach towards including roll motion in the simulation seems to be clear.
Some discussion is necessary, however, on the type of formula to use and the values of the parameters (especially T_{max}).

3.4 The movement algorithm

Depending on her maximum walking speed and the surrounding obstacles, a person will move from one cell to the next adjacent (via the corners or the edges). She thereby tries to avoid others and to maintain her maximum walking speed. Because the persons can move through more than one cell per time-step (one second), a parallel update was rejected, and an improved random-sequential-update was chosen. Hereby, the simplicity of a sequential-update was maintained, while the dynamics of the pedestrians is similar to a parallel update for speeds of more than one cell per time step. Jam waves can therefore clearly bee seen in corridors with periodic boundary conditions. The basic procedure is shown in Figure 3.

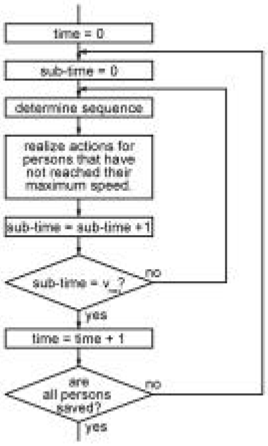

Figure 3: The basic update-algorithm.

4 Orientation and route-choice

The orientation is a fundamental challenge. It is rather easy to make a person in the simulation evade obstacles and other pedestrians, but the way she chooses where to go and how to get there is the decisive problem. In a first step, the information of which way a person had to walk to reach the exit was implemented by arrows in the cells that pointed into the direction a person had to walk. In the currently developed new approach, the route-information is given by a potential and only the goal-cells have to be marked. The potential then automatically spreads from one accessible cell to the following and by this throughout the whole structure. By a smoothening algorithm it adapts to the architectural circumstances, so persons following it will not stick to one side of a corridor, just because they want to bend off at the end of it (Figure 4). Next to these route-potentials, wall-potentials can be added, which influence the distance people keep to walls. They can either "push" people away or "pull" them towards obstacles. The last would be the case in e.g. bad visibility, when people tend to walk along walls and do not step into wide spaces.

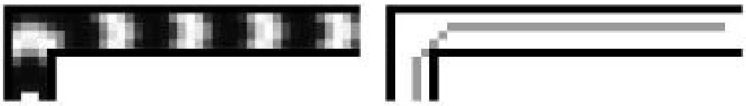

Figure 4: Iso-potential-lines in a hooked corridor, spreading from the bottom-left (left) and a resulting possible path (right).

Because the evacuation-route of a person in a RoPax- or cruise ship can contain many different waypoints (e.g. cabins, muster stations, lifeboats), three different kinds of potentials where developed.
Cabin-potentials are used for marking corridors. A person reaching these kind of cells will stay on them for a given individual time, before choosing a new goal out of the list. This resembles the behaviour of passengers reaching their cabins and getting their life vest. On the other hand, cabin-potentials can be used as simple waypoints, when the duration of stay is set to zero, thus defining evacuation routes.
At the assembly station persons will wait and gather into groups. After a certain time has passed, the people at the assembly stations are led to the embarkation stations, while the new arrivals have wait. This process is repeated in given interval times, after the first blocking-time has passed. The result of this behaviour in the simulation is equal to the mustering process in reality: As long as the lifeboats are being prepared, the passengers will be assembled and afterwards led on towards the embarkation stations.
The procedure of embarking into the lifeboats is simulated by the rescue potentials. They are blocked for a given time (preparing the lifeboats) and after that, the people reaching them have to wait for a certain egress time before they get rescued. This takes into account the egress time, the delay for entering a lifeboat or sliding on a marine evacuation system (MES). Throughout the simulation, the people which have been rescued per exit are counted and if the maximum capacity is reached, the belonging potential is switched of and the remaining passengers have to be directed towards the other exits.
By dividing passengers into groups (e.g., having cabins on the same corridor) and using various of the mentioned potentials to mark their possible goals, various route choices become possible, and thereby the situation of a big RoPax- or cruise ship getting evacuated can be matched (Figure 5).

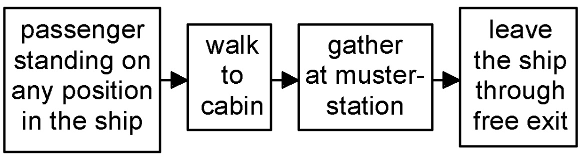

Figure 5: The possible actions of one arbitrary passenger.

5 Characteristics of the model

The characteristics and validity of a simulation for crowd motion can be seen from the flow-density-relations. These relations are not provided beforehand but are a simulation result. The geometry is a corridor (200x20 cells) with different densities of people walking in the same direction and periodic boundary conditions. Three cases where investigated: a person occupies all the cells she passes in one time step, half the cells and finally only the cell she currently stands on. In the last case, the occurring jam-waves where most remarkable, moving against the flow and growing more and more stable with the density growing (Figure 6).

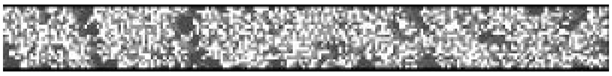

Figure 6: Corridor with periodic boundary conditions and a density of 4,4 P/m². People move from the left to the right and occupy only one cell. Jam-waves are clearly visible (dark areas).

The resulting flow-density-relations were compared with empirical data (from [5]) and the results meet reality very well, if one person occupies all the cells she passes in one time step (Figure 7).

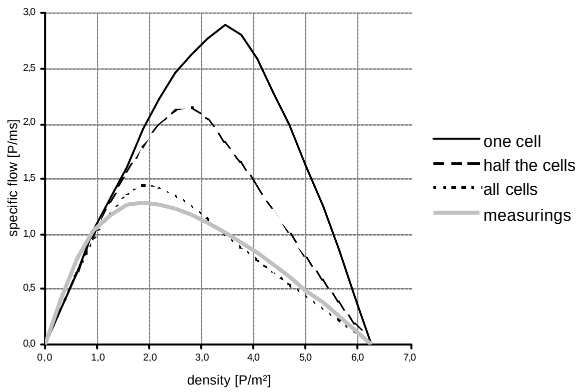

Figure 7: Flow-density-relations of the model.

Counter flow is investigated to see the effect of small numbers of people (one to ten) moving against the main stream. This happens, when crew members have to move in another direction than the evacuating passengers. Because the influence of this effect is bigger in narrow spaces, the width of the corridor was set to five cells. For small densities, the disturbance by the person moving against the stream becomes clearly visible (Figure 8).

Figure 8: The effect of counter flow in a narrow corridor.

The effect on the flow-density-relation is obvious (Figure 9). At low or very high densities, the counter flow had no remarkable influence on the flow. In the middle section however, this changed dramatically. The occurring fluctuations thereby emerge from deadlock like situations. Although all persons are distributed randomly at the start of each run, the counter flowing individuals sometimes gather and thereby jam the corridor. By implementing a method for lane formation, this problem could be solved.

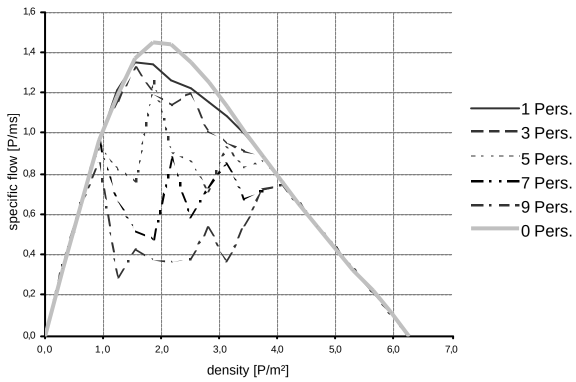

Figure 9: The effect of counter flow on the flow-density-relation.

6 Application

In order to verify the simulation-model, the results are compared with practical tests. Several evacuation trials with high speed passenger craft were carried out which give similar results as the simulation. Because the period that the exits are blocked while the life rafts are launched has the major impact on the evacuation time (Figure 10), these results give only little information about the motion properties. It was therefore necessary, to perform a well documented evacuation trial with the main focus on the flow-density-relations.

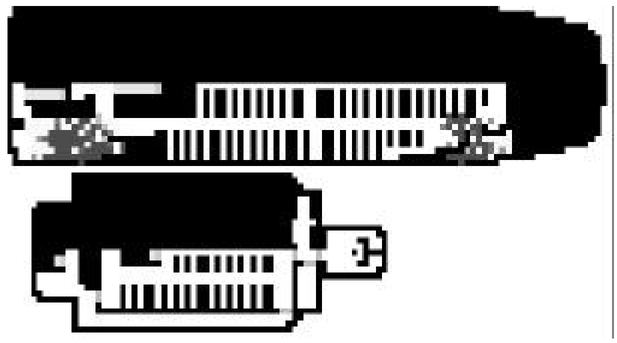

Figure 10: Queues in front of the exits during a high speed craft evacuation.

7 Summary and Conclusion

It is possible to simulate complex scenarios and behaviour with elementary models. As a result of these simplifications, calculation speeds are very high and allow the investigation of large moving crowds in a short time. For the use of such models in the design-process the conversion of technical drawings into a format suitable as input for the simulation software is crucial. The orientation by automatic spreading potentials already improves conversion-speeds. Next to this, a CAD-import will be developed which allows quick transformation of *dxf*-files into the internal file format.
Further verifications have to be done by comparison with practical trials. An evacuation of a cruise ship together with the strategic partners is planned as part of the BYPASS

project in near future. Additionally, fundamental research will be done to gather more detailed information about crowd-movement and behaviour.

8 References

[1] International Maritime Organization , *FP44/19, Report to the Maritime Safety Committee*, Sub-Committee on Fire Protection. http://www.imo.org.

[2] Hubert Klüpfel, Tim Meyer-König, Joachim Wahle, Michael Schreckenberg, *Microscopic simulation of evacuation processes on passenger ships*, in: *Proceedings of the Fourth International Conference on Cellular Automata for Research and Industry*, Springer, Berlin, 2000.

[3] International Maritime Organization, *SOLAS (Safety of Life at Sea)*, (Bath Press, London, 2000).

[4] D. Helbing, *Verkehrsdynamik, Neue physikalische Modellierungskonzepte*, Springer Verlag, 1996.

[5] U. Weidmann, *Transporttechnik der Fußgänger, Transporttechnische Eigenschaften des Fußgängerverkehrs Literaturauswertung*, Schriftenreihe des IVT Nr. 90, Januar 1992, ETH Zürich (in German).

[6] H. Klüpfel, T. Meyer-König, M. Schreckenberg, *Empirical Data on an Evacuation Exercise in a Movie Theatre*, submitted to *Fire Safety Journal* (2001).

[7] S. Gwynne, E.R. Galea, M. Owen, P.J. Lawrence, and L. Filippidis, *A review of the methodologies used in the computer simulation of evacuation from the built environment*, Building and Environment **34**, 741—749 (1999).

[8] A. Brumley, *The influence of human factors on the motor ability of passengers during the evacuation of ferries and cruise ships.* In: *Conference on human factors in ship design and operation* (Institute of Naval Architects, Ed.) (2000).

[9] D. Vassalos, H. Kim, G. Christiansen, and J. Majunder, *A mesoscopic model for passenger evacuation in a virtual ship-sea environment and performance-based evaluation.* To appear in: *Proceedings of the International Conference on Pedestrian and Evacuation Dynamics (PED)* (M. Schreckenberg and S.D. Sharma, Eds.) (Springer, Berlin, 2001).

[10] E. Tsychkova, *Influence of Waves and Ship Motions on Safe Evacuation of Passenger Ships*, Licentiate Thesis, Kungliga Tekniska Högskolan (KTH), (June 2000).