A Proposal for the Goals and New Techniques of Modelling Pedestrian Evacuation in Fires

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ABSTRACT

In this article, we propose the goals for evacuation simulations in the context of the fire safety engineering. It is proposed that the safety of a building design should be measured using F-N plots that are based on the fire statistics. A new evacuation code is developed that allows the modelling of 'panic' situations and interaction between evacuation simulation and the state-of-the-art fire simulation. The major features of the new code are described and first preliminary results are shown. The method presented was found to run satisfactorily, and fast enough for practical purposes. When the results were compared against the results obtained using Simulex and buildingExodus codes, a good agreement was found in two of the three cases but for a case with congested corridor considerable differences occurred.

KEYWORDS: escape modelling, fire modelling, crowd movement, Monte Carlo simulation

INTRODUCTION

Despite many precautions, large accidents like major fires could occur in the built environment. Powerful countermeasures are needed to balance the increased risk caused by the quick growth of unit sizes in buildings, industrial installations or human crowds. Modelling and numerical simulation are one of the few means to manage these problems in a rational way. In high-risk industry, formal risk analysis has been the tool to quantify potential risks by comparing risks of a planned new object with risks already prevailing in the society. The early spearhead of such technology was the 'Rasmussen report' [1]. It was a study assessing the increased risks to the public from 100 operating nuclear power reactors in the U.S.A. The probability from such accidents was compared with probabilities from already existing man made and natural risks. An F-N plot is the tool that presents such risks: frequency F of an event as a function of the number of fatalities N [2]. An F-N plot is the only logical way to assess the life risk also in fires.

F-N plots have been developed for fires for a long time (see, e.g., [3]), but have hardly been used in real fire safety designs of buildings even though the simulation of fires is widely used for large targets like shopping centres and industrial facilities. The major reason has been costs, but the situation is quickly changing. In the fire safety engineering of large buildings, zone models have already been replaced by Computational Fluid Dynamics (CFD) tools. Introducing an evacuation simulation to the same platform would allow the interaction of fire and escaping people in the computation. The next step should be the computation of escape probabilities using Monte Carlo, which is now technically possible.

In Fig. 1 an F-N plot is presented based on a collection of statistical data from multiple fatality fires [4]. Conditional data, normalized by the number of fires, were first collected from Nordic countries (Finland, Norway, and Denmark). Since the populations were small, U.S. data were added allowing multiple fatalities to reach up to 12. Direct systematic data do not exist beyond that, but U.S. estimates were used [1]. To obtain an analytical function for the probability, attenuated Pareto functions were used:

$$f(N) = A\exp\left(-(N/N_c)^2\right)/(N/N_c)^n, \quad N \geq 1, \tag{1}$$

where N is the number of fatalities. Good fit was obtained in the range $1 \leq N \leq 12$ using $N_{c1} = 11$, and $n_1 = 3.5$. For $N > 12$ another fit with $N_{c2} = 600$, and $n_2 = 0.85$ gave reasonable agreement with data. The cut-off value of fatalities N_c is related to the number of people exposed to hazard. Under ‘residential’ and ‘common mode’ events, the values are of different magnitude, and the latter might still increase as unit sizes grow. Taking the sum of the fitted curves and plotting curves ten times higher and smaller yields a first estimate on the clearly tolerable and intolerable probabilities, within which observations fall. When evaluating evacuation from large buildings, an F-N plot has to be made using Monte Carlo simulation. If that curve falls below the ‘Tolerable’ in Fig. 1, the design is clearly good, if it lies above ‘Intolerable’, it must be rejected. If it falls between these curves, some additional consideration is needed. New international efforts are needed to provide up to date, reliable data for Fig. 1.

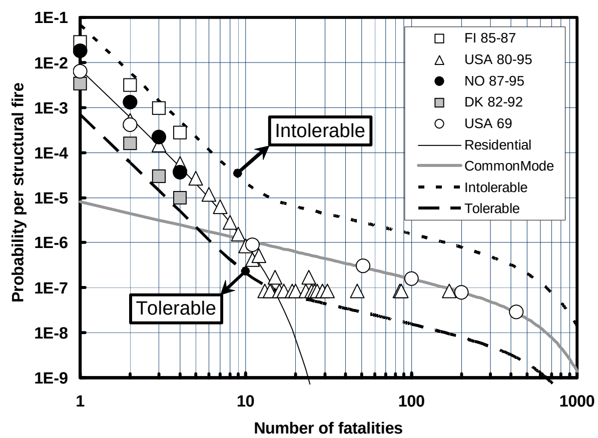


Fig. 1. Conditional probability per fire of multiple fatalities based on statistics from some countries shown in the inset [4].

Monte Carlo Simulations

Monte Carlo is a general technique to estimate the influence of various inputs to the target function like life risk. Calculating the Spearman's rank-order correlation coefficients gives quantitative measures on the sensitivity of the targets. We have earlier presented a Monte Carlo calculation platform called Probabilistic Fire Simulator (PFS) [5], which is suitable for assessing realistic fire scenarios using zone fire models. An extension for the use of CFD codes like Fire Dynamics Simulator (FDS) [6] has been developed just recently [7]. Our next goal is to conduct a fire driven interactive evacuation problem as Monte Carlo to determine: (i) the most important human related input variables to guide experimental work and (ii) a quantitative F-N plot for a total building object to compare with data from fire statistics.

In this paper, which is a work-in-progress-report, we describe the major features of the new code, demonstrate first preliminary results, make comparisons with the results obtained using other existing codes, and finally show a situation where the outcome might be different from the existing codes. Fire-people interactions, Monte Carlo, and F-N plots will be dealt with at the later phases of the project.

Review of Earlier Work

The history of simulation of human evacuation from fires is extensive, but has been summarised in several articles in a special issue of Safety Science (Vol. 18, no. 4, 1995), especially Smith [8] and Thompson and Marchant [9], which describe the status at that time. Shortly later Sime [10] stressed that 'a comprehensive approach to crowd safety design, management and risk assessment needs to integrate psychology and engineering frames of reference'. The latest state of the art in escape simulation has been described in two recent proceedings from the International Conference on Pedestrian and Evacuation Dynamics [11,12].

Selection of Modelling Principles

The most common basis of evacuation models is the people-fluid analogy: it is considered satisfactory for smooth flow and a viable basis for many other approaches. It has, however, drawbacks in critical situations because it does not create local pressure peaks or congestions. These are situations where large losses might be expected. The flow of granular particles as compared with fluids gave a fruitful comparison, which was borrowed from a theory of many-particle physics [13,14,15]. Helbing's group [16,17] presented a new escape model, which is applicable also in 'panic' situations. In this model, people were presented as single particles moving on a plane, and interacting with boundaries and with each other if coming in close contact. This behaviour is determined by laws of mechanics. People use their eyes to coordinate movements, and for that purpose they added a social force [18,19]. There the psychological effects advocated by [10] come into play, but now in a pseudo-mechanistic way.

In the present work, the method of Helbing's group was chosen as the starting point for the evacuation simulations by carefully assessing the alternatives found in literature. In so doing, we do not claim that it is superior to other available models or even correct in all major details, but that it could handle some of the situations we felt important. There are several other factors, especially in the early phase of evacuation, where much new research is needed [20,21,22]. As we understand, validation of evacuation models is still in its early phase as compared, for example, with smoke spreading models. Detailed experimental data is only starting to emerge. For this reason, the present model is compared to two other evacuation models by using three different test cases.

DESCRIPTION OF THE HUMAN MOVEMENT ALGORITHM

As stated earlier, we chose to use the method of Helbing's group as the starting point for the new evacuation model. The model is briefly described below. For a more detailed description, see the papers by the Helbing's group [16,17,18,19] and references therein.

The model uses the laws of mechanics to follow the trajectories of people during the calculation. Each human follows its own equation of motion:

$$m_i \frac{d^2\mathbf{x}_i(t)}{dt^2} = \mathbf{f}_i(t) + \xi_i(t) \ , \tag{2}$$

where $\mathbf{x}_i(t)$ is the position of the human i at time t, $\mathbf{f}_i(t)$ is the force exerted on the human by its surroundings, m_i is the mass, and the last term, $\xi_i(t)$, is a small random fluctuation force. The velocity of the human, $\mathbf{v}_i(t)$, is given by $d\mathbf{x}_i/dt$.

The force on people has many components:

$$\mathbf{f}_i = \frac{m_i}{\tau_i}\left(\mathbf{v}_i^0 - \mathbf{v}_i\right) + \sum_{i \neq j}\left(\mathbf{f}_{ij}^{soc} + \mathbf{f}_{ij}^{att} + \mathbf{f}_{ij}^{ph}\right) + \sum_b \mathbf{f}_{ib} + \sum_k \mathbf{f}_{ik}^{att} \ , \tag{3}$$

where $\mathbf{f}_{ib}$ describes the human–wall interactions, $\mathbf{f}_{ik}^{att}$ some other human–environment interactions, e.g., fire–human repulsion. The human–human interaction has three parts. For the social force term $\mathbf{f}_{ij}^{soc}$ we have used the anisotropic formula proposed by Helbing *et al.* [17].

$$\mathbf{f}_{ij}^{soc} = A_i e^{-\left(r_{ij} - d_{ij}\right)/B_i}\left(\lambda_i + \left(1 - \lambda_i\right)\frac{1 + \cos\varphi_{ij}}{2}\right)\mathbf{n}_{ij} \ , \tag{4}$$

where r_{ij} is the distance between the centres of the circles describing the humans, d_{ij} is the sum of the diameters, and the vector $\mathbf{n}_{ij}$ is the unit vector pointing from j to i. The angle φ_{ij} is the angle between the direction of the motion of person feeling the force and the direction to the body, which is exerting the repulsive force.

The term $\mathbf{f}_{ij}^{ph}$ in Eq. 3 describes the physical contact force between humans and it is given by:

$$\mathbf{f}_{ij}^{ph} = k\left(d_{ij} - r_{ij}\right)\mathbf{n}_{ij} + \kappa\left(d_{ij} - r_{ij}\right)\Delta v_{ij}^t \mathbf{t}_{ij} \ , \tag{5}$$

where Δv_{ij}^t is the difference of the tangential velocities of the humans in contact and vector $\mathbf{t}_{ij}$ is the unit tangential vector of the contacting circles. This force applies only when the humans are in contact, i.e., $d_{ij} - r_{ij} \geq 0$. The term $\mathbf{f}_{ij}^{att}$ in Eq. 3 can be used to describe attraction (or repulsion) between humans, like a herding behaviour or adult–children interaction. It could also be used to form pairs of humans, e.g., describing a fire-fighter pair entering the building.

The first term on the right hand side of Eq. 3 describes the self-driving force on the evacuating human. Each person tries to walk at his/her own specific walking speed $|\mathbf{v}_i^0|$ towards an exit or some other target. τ_i is the relaxation time parameter, for which a value of about 0.5 s is used in this work. The trajectory to the exit is given by the direction of the preferred walking velocity $\mathbf{v}_i^0$ field. The novelty of present method lies in the way that this preferred walking direction vector field is obtained using FDS and its flow solver.

By using FDS as the platform for the evacuation calculation we have direct (and easy) access to all the local fire related properties, like gas temperature, smoke and gas densities, radiation levels, and one can use these to change the behaviour of the humans. Fire influences evacuation conditions, may incapacitate people and in extreme cases can block major exit routes. On the other hand, humans may influence fire by opening doors or activating various fire protection devices.

In our method, each person finds the exit door by following the potential flow solution of a two-dimensional incompressible fluid to the given boundary conditions, i.e., which exits may be used by this human. The FDS flow solver is used to calculate an approximation to this potential flow field by using large viscosity and low flow speeds, so that there are no vortices in the solution. The necessary boundary conditions can be given two different way: 1) all walls are pushing fluid in the computational domain at a constant flux (and velocity) and the fluid flows away from the open doors, 2) all walls are 'inert' and the doors act as fans, which suck fluid out of the domain (thus generating a pressure drop in the building). Both methods (rather tricks) produce a nice directional field for egress (see Fig. 2). The methods must be tested later against measured data.

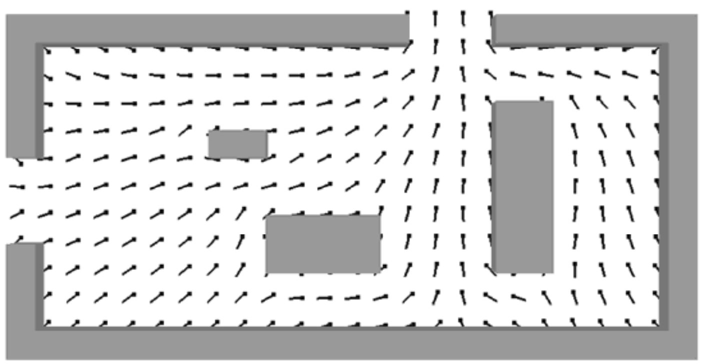


Fig. 2. A simple example case showing the idea how the flow field calculated by FDS is used to guide human movement.

RESULTS AND DISCUSSION

The implementation of the code was tested using three different scenarios: (A) a typical open floor office, (B) a large space like a sports hall, and (C) a fictitious assembly space. Three different scenarios were chosen to demonstrate both the major features that are different from existing evacuation codes and reveal possible errors in the implementation.

Case A: Open Floor Office

Case A considers one floor of a multi-storey office building, whose layout is shown in Fig. 3. The floor has dimensions of 40×40 m^2 and there are initially 216 persons on this floor. The properties of these humans were assumed to be as the ‘Office Staff’ category in the Simulex model [23,24] and the reaction times of the humans were assumed to follow a normal distribution with mean of 90 s and standard deviation of 11 s.

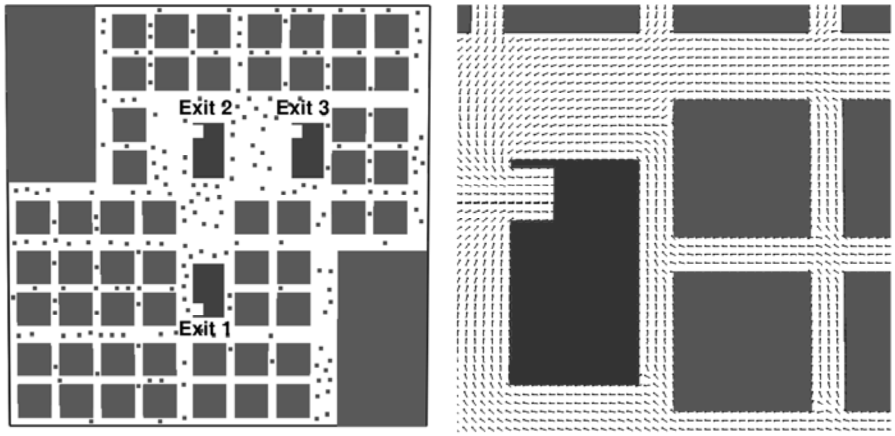


Fig. 3. The geometry and initial random positions of humans in Case A open floor office (left) and some details of the flow field (right).

The results of the present model and Simulex simulation are shown in Fig. 4. Simulations were conducted for each possible door combination, i.e., it was assumed that some of the exit doors may not be operational during the evacuation. Only when two exit doors were blocked, did queues form at the door. For two or three operational doors the main form of the evacuation curves arise from the reaction time distribution. It is seen that the present model and Simulex results agree very well.

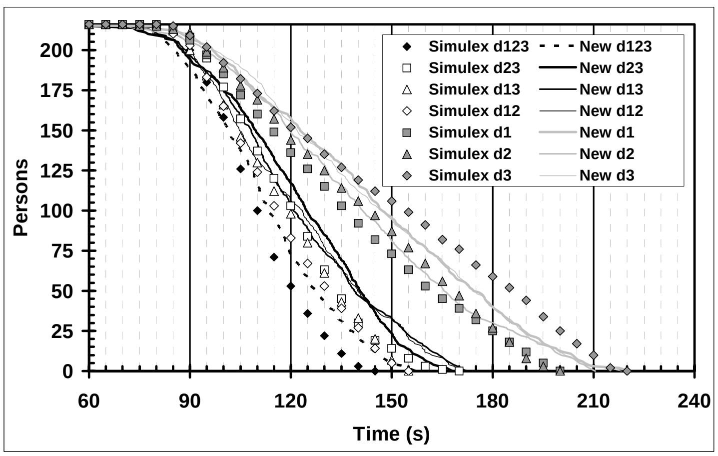


Fig. 4. Comparison of the present model and Simulex runs for Case A. The labels refer to the exit door combinations used in the simulations.

Case B: Sports Hall

Case B, a sports hall [25] is used to practice different kind of sports, including track and field and football (soccer). There are no spectator stands in the hall and neither are there any social spaces (like showers). People enter the hall through the main entrance (‘Door 1’ in Fig. 5). Doors 2 and 3 are 4.0 m wide two leaf doors and doors 4 and 5 are 0.9 m wide single leaf doors.

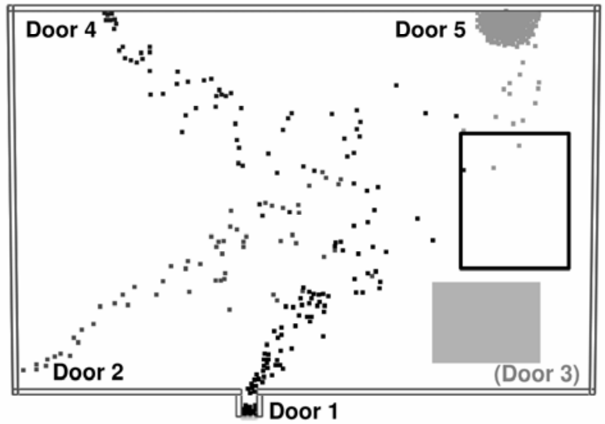


Fig. 5. Snapshot of the simulation using the present model in Case B sports hall.

In this simulation, it is assumed that a fire starts close to door 3 (the shaded rectangle in Fig. 5) so that this door cannot be used for egress. It is assumed that 235 persons use the closest door ('Door 5'), 130 persons use the main entrance ('Door 1'), 60 persons door 2, and 75 persons use door 4. Persons are initially located at the east end of the hall in an area of 20×25 m^2 (the open rectangle in Fig. 5). Three different reaction time scenarios were considered, two having a normal distribution with a standard deviation of 15 s but different means (60 s and 180 s), and one having a log-normal distribution (median 75 s, standard deviation of the logarithm of reaction time was 0.7). Actually, the log-normal distribution was approximated by two uniform distributions, because the version of the Simulex, which was used, does not support log-normal distributions for the reaction time.

The results are plotted in Fig. 6 showing, that the present simulations agree well with the Simulex results. For the cases, where the average reaction time is peaked (standard deviation is 15 s), there are some differences between the calculations. These differences can be traced back to the 'Door 5', which is only 0.9 m wide, but through which 235 persons escape.

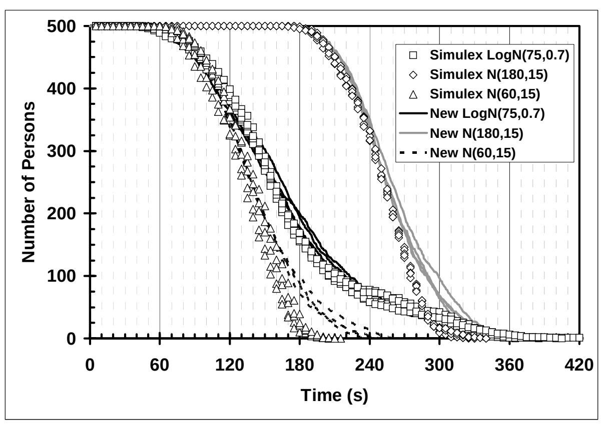
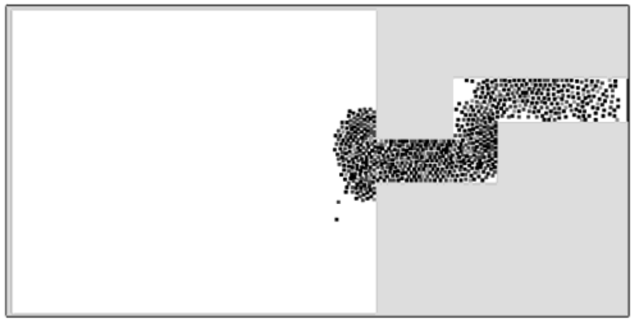
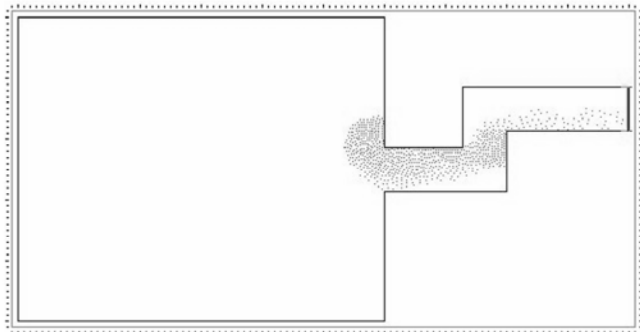


Fig. 6. Comparison of the present model and Simulex runs for Case B sports hall.



(a)



(b)

Fig. 7. Snapshot of the (a) present simulation, (b) Simulex calculation in Case C assembly space.

Case C: Fictitious Assembly Space

Case C is a large fictitious public space having dimensions of 50×60 m^2. There is only one 7.2 m wide corridor leading to the exit. The geometry is shown in Fig. 7, where snapshots of the present model and Simulex calculations are shown. There are 1000 persons initially in the building. For the present model, the simulation time was about 700 CPU seconds using a PC with 2.2 GHz P4 processor and 2 GB memory. For Simulex the simulation time was about 5400 CPU seconds using a PC with 800 MHz PIII processor and 384 MB memory.

The results of the present method are compared with Simulex and buildingExodus calculation in Fig. 8. Considerable difference is shown between the present results and the results of Simulex and buildingExodus codes. This difference can be traced back to the human motion in the corridor, see Fig. 7. Simulex and buildingExodus are not using the whole width of the bended corridor efficiently, when the simulations are done using default values and standard input. Both the Simulex and the buildingExodus model are trying to move humans to the exit(s) using shortest walking paths, whereas the humans in the present method are trying to follow the artificial flow lines, which determine the preferred walking velocity field in the Eq. 3. (An advanced user of these codes might be able to get different results by using some additional features.) The results of the present model are considered to be more realistic. Figure 8 also shows the results for a case, where there is no corridor at all, i.e., there is just one 7.2 m wide exit door located at the wall of the room. In this case, the three different codes agree much better. The same would be true for a straight corridor case.

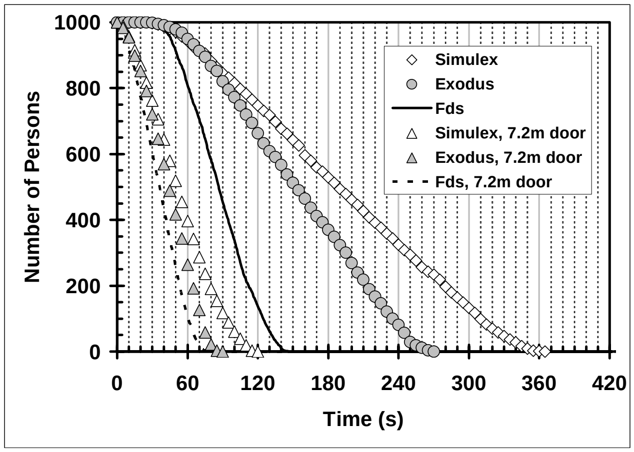


Fig. 8. Comparison of the present model, Simulex, and buildingExodus runs for Case C assembly space.

CONCLUSIONS

The method presented was found to run satisfactorily, and fast enough for practical purposes. Comparison of the results obtained with Simulex and buildingExodus, indicated good agreement in two of the cases (A and B). However, for a congested corridor (case C) considerable differences occurred. Since we do not have experimental data available, the comparison is only between models, indicating technical performance. These differences are, however, so big that further research is well motivated.

Since this is work-in-progress the first next step is to include fire to human influences to be able to estimate incapacitation and fatalities in case of egress delays. The second addition will be cues to start and direct escape (individual vs. herding, visibility of exit signs, and interaction with related people and belongings). Because no clear models are available on these effects, some crude on-off guesses are made, numerical experiments will be carried out and sensitivity analysis by short Monte Carlo will be made to guide the selection of relevant variables for modelling as well as observations from experiments.

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