INTEGRATION OF AN AGENT BASED EVACUATION SIMULATION AND THE STATE-OF-THE-ART FIRE SIMULATION

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ABSTRACT

The most important objective of a fire safety design is to ensure that humans can safely escape from a building in the case of fire. Fire regulations are adequate for normal buildings but may not take into account the special issues of large and complicated buildings, like shopping centres, assembly facilities, etc. Numerical simulation of fire and evacuation processes can be used to improve fire safety in such buildings. However, the usability of many current evacuation models is limited, because they do not take into account the individual properties and decision making processes of humans, the dynamics of large crowds and the interaction between fire and people. In this article, a recently presented evacuation programme is developed further. The code allows the modelling of 'panic' situations and the interaction between evacuation simulation and the state-of-the-art fire simulation. The major features of the human movement algorithm are described. A reaction function model for exit route selection and some social interactions among agents are introduced into the computer programme. This computational tool for evacuation modelling is implemented as a part of the state-of-the-art fire simulation tool Fire Dynamics Simulator (FDS). Like the current version of FDS, the evacuation module, FDS+Evac, presented in this article is made publicly and freely available.

KEYWORDS: Escape Modelling, Fire Modelling, Crowd Movement, Fire Dynamics Simulator

INTRODUCTION

The ever increasing risk caused by the quick growth of unit sizes in buildings, ships, and human crowds needs to be controlled, because large accidents, like major fires, do occur in the built environment. The most important objective of a fire safety design is to ensure that humans can safely escape from a building in case of fire. Modelling and numerical simulations are one of the few means to manage this objective in a rational way. The usability of many current evacuation models is limited, because they do not take into account the individual properties and decision making processes of humans, the dynamics of large crowds and the interaction between fire and people. This article describes, how one adds to Fire Dynamics Simulator[1, 2] (FDS), originally developed at the National Institute of Standards and Technology (NIST), an egress calculation module FDS+Evac, whose preliminary version was recently presented.[3] In FDS+Evac, each human is followed by an equation of motion. This approach allows each human to have its own personal properties and escape strategies, i.e., persons are treated as autonomous agents. The model behind the movement algorithm is the social force model introduced by Helbing's group[4, 5, 6, 7] and modified by Langston *et al.*[8] to include a better description of the shape of the human body and to include the rotational degrees of freedom.

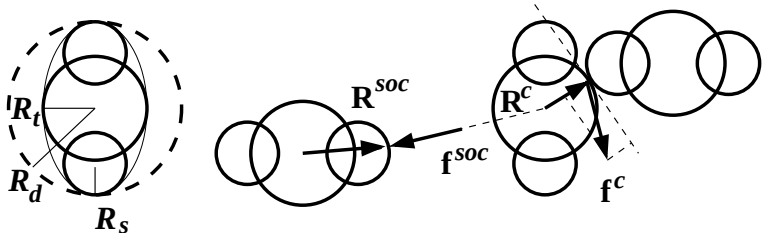

FIGURE 1: Definitions of the human dimensions and the radial vectors $\mathbf{R}^c$ and $\mathbf{R}^{soc}$.

The existing fire simulation environment of FDS is used to minimise the programming effort to write an egress programme. For visualisation, the existing Smokeview programme[9] developed at NIST is used. Additional benefit of using FDS as the platform of an egress model is the direct and easy access to the fire related properties, like gas temperatures, smoke and gas densities, and radiation levels at each point in the computational grid. These quantities can be used to model the behaviour of evacuating humans. The doses of lethal and/or harmful fire products which evacuating humans inhale during the egress can be calculated. Third benefit is that the fire and egress parts are easily coupled, e.g., evacuating humans may open doors, which would affect the fire development etc. Fourth benefit is that the flow and pressure solver of FDS can be used to generate the preferred movement direction field which is needed in the social force model. Fifth benefit is that FDS and, thus, FDS+Evac is freely obtainable from a web page including the source code, so the models could be freely developed and improved by the fire engineering community. This article presents the theoretical basis of the egress module. First, the movement model, the fire-human interaction models, the exit route selection and the social interactions among the agents are presented. Next, the results of test calculations are summarised. Finally, the main features of FDS+Evac and the results of the test calculations are summarised. This section contains also information on the ongoing development work of the FDS+Evac model.

THEORETICAL BASIS FOR THE EVACUATION MODEL

As said, the method of Helbing's group is used as the starting point of the human movement algorithm of FDS+Evac. This model is shortly described below. For a longer description, see the papers by Helbing's group[4, 5, 6, 7] and references therein. For the modification of the one-circle representation of a human to a three-circle one, see the paper by Langston *et al.*[8]

Human Movement Model

FDS+Evac uses the laws of mechanics to follow the trajectories of the humans during the calculation. Each human follows his/her own equation of motion:

$$m_i \frac{d^2\mathbf{x}_i(t)}{dt^2} = \mathbf{f}_i(t) + \boldsymbol{\xi}_i(t) \ , \qquad [1]$$

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 the surroundings, m_i is the mass, and the last term, $\boldsymbol{\xi}_i(t)$, is a small random fluctuation force. The velocity of the human, $\mathbf{v}_i(t)$, is given by $d\mathbf{x}_i/dt$. FDS+Evac treats humans as combination of three elastic circles moving on a two-dimensional plane.[8] These circles are approximating the elliptical shape of the human body similarly as in the Simulex model[10] and in the MASSEgress model,[11] see Fig. 1. The default body dimensions and the unimpeded walking speeds of different predefined human types of FDS+Evac are listed in Table 1.

The force on human i has many components:

$$\mathbf{f}_i = \frac{m_i}{\tau_i}\left(\mathbf{v}_i^0 - \mathbf{v}_i\right) + \sum_{j\neq i}\left(\mathbf{f}_{ij}^{soc} + \mathbf{f}_{ij}^{att} + \mathbf{f}_{ij}^{c}\right) + \sum_{w}\left(\mathbf{f}_{iw}^{soc} + \mathbf{f}_{iw}^{c}\right) + \sum_{k}\mathbf{f}_{ik}^{att} \ , \qquad [2]$$

TABLE 1: Unimpeded walking velocities and body dimensions in FDS+Evac. The offset of shoulder circles is given by $d_s = R_d - R_s$, for the definition of the other body size variables, R_d, R_t, R_s, see Fig. 1.

Body type	R_d (m)	R_t/R_d (-)	R_s/R_d (-)	d_s/R_d (-)	Speed (m/s)
Adult	0.255±0.035	0.5882	0.3725	0.6275	1.25±0.30
Male	0.270±0.020	0.5926	0.3704	0.6296	1.35±0.20
Female	0.240±0.020	0.5833	0.3750	0.6250	1.15±0.20
Child	0.210±0.015	0.5714	0.3333	0.6667	0.90±0.30
Elderly	0.250±0.020	0.6000	0.3600	0.6400	0.80±0.30

where the first sum describes human–human interactions, the sum over w describes human–wall interactions, and the last term, $\mathbf{f}_{ik}^{att}$, may be used for other human–environment interactions, like the fire–human repulsion. The first term on the right hand side describes the motive force on the evacuating human. Each human tries to walk with his/her own specific walking speed, $v_i^0 = |\mathbf{v}_i^0|$, towards an exit or some other target, whose direction is given by the direction of the field $\mathbf{v}_i^0$. The relaxation time parameter τ_i sets the strength of the motive force, which makes a human to accelerate towards the preferred walking speed.

The human–human interaction force in Eq. [2] has three parts. For the social force term, $\mathbf{f}_{ij}^{soc}$, the anisotropic formula proposed by Helbing *et al.*[6] is used

$$\mathbf{f}_{ij}^{soc} = A_i e^{-(r_{ij}-d_{ij})/B_i} \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\varphi_{ij}}{2} \right) \mathbf{n}_{ij} \ , \qquad [3]$$

where r_{ij} is the distance between the centres of the circles describing the humans, d_{ij} is the sum of the radii of the circles, and the vector $\mathbf{n}_{ij}$ is the unit vector pointing from human j to i. For a three circle representation of humans, the circles used in Eq. [3] are those circles of the two humans, which are closest to each other. The angle φ_{ij} is the angle between the direction of the motion of human i feeling the force and the direction to the human j, which is exerting the repulsive force on human i. The parameters A_i, B_i, and λ_i could be different for each human but in the present version of FDS+Evac they have same values for each human. The psychological wall–human interaction, $\mathbf{f}_{ij}^{soc}$, is treated similarly, but values A_w, B_w, and λ_w are used for the force constants. The physical contact force between humans, $\mathbf{f}_{ij}^{c}$, is given by

$$\mathbf{f}_{ij}^{c} = \left(k(d_{ij}-r_{ij}) + c_d \Delta v_{ij}^n \right) \mathbf{n}_{ij} + \kappa(d_{ij}-r_{ij})\Delta v_{ij}^t \, \mathbf{t}_{ij} \ , \qquad [4]$$

where Δv_{ij}^t is the difference of the tangential velocities of the circles in contact, Δv_{ij}^n is the difference of their normal velocities, and vector $\mathbf{t}_{ij}$ is the unit tangential vector of the contacting circles. This force applies only when the circles are in contact, i.e., $d_{ij} - r_{ij} \geq 0$. Note, that Eq. [4] contains also a physical damping force[8] with a damping parameter c_d, which the original model by Helbing *et al.* does not have. This parameter reflects the fact that the collision of two humans is not an elastic one. The physical wall–human interaction, $\mathbf{f}_{iw}^{c}$, is treated similarly and same force constants are used. The term $\mathbf{f}_{ij}^{att}$ can be used to describe attraction (or repulsion) between humans, like a herding behaviour or an adult–children interaction. It could also be used to form pairs of humans, e.g., describing a fire fighter pair entering the building. All of the force terms in Eq. [2] are relatively short ranged and they need a line-of-sight connection. Longer ranged forces could be taken in to account by changing the preferred walking velocity field $\mathbf{v}_i^0$.

Equations [1]–[4] describe the translational degrees of freedom of the evacuating humans. The rotational degrees of freedom are treated similarly, i.e., each human has his/her own rotational equation of motion:

$$I_i^z \frac{d^2\varphi_i(t)}{dt^2} = M_i^z(t) + \eta_i^z(t) \ , \qquad [5]$$

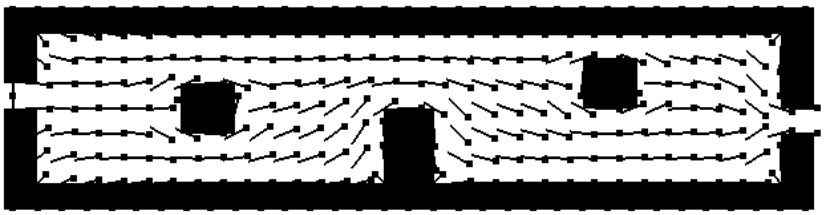

FIGURE 2: A simple example case showing how the flow solver of FDS is used to calculate the human movement field $\mathbf{v}_i^0$. There is an outflow boundary condition at the right door, whereas there is an inert boundary condition at the left door.

where $\varphi_i(t)$ is the angle of the human i at time t, I_i^z is the moment of inertia, $\eta_i^z(t)$, is a small random fluctuation torque and $M_i^z(t)$ is the total torque exerted on the human by its surroundings

$$M_i^z = M_i^c + M_i^{soc} + M_i^\tau \ , \qquad [6]$$

where M_i^c, M_i^{soc}, and M_i^τ are the torques of the contact, social and motive forces, respectively.

The torque of the contact forces is calculated as

$$\mathbf{M}_i^c = \mathbf{R}_i^c \times \mathbf{f}_{ij}^c \ , \qquad [7]$$

where $\mathbf{R}_i^c$ is the radial vector which points from the centre of human i to the point of contact. In FDS+Evac, also the social forces exert torques on humans and these are given by the formula

$$\mathbf{M}_i^{soc} = \mathbf{R}_i^{soc} \times \mathbf{f}_{ij}^{soc} \ , \qquad [8]$$

where only the circles, which are closest to each other, are considered. The vector $\mathbf{R}_i^{soc}$ points from the centre of human i to the fictitious contact point of the social force, see Fig. 1.

Analogous to the motive force, the first term on the right hand side of Eq. [2], a motive torque is defined as

$$M_i^\tau = \frac{I_i^z}{\tau_i^z}\left((\varphi_i(t) - \varphi_i^0)\omega_i^0 - \omega(t)\right) = \frac{I_i^z}{\tau_i^z}\left(\tilde{\omega}_i^0 - \omega(t)\right) \ , \qquad [9]$$

where ω_i^0 is the maximum target angular speed of a turning human, $\omega(t)$ the current angular velocity, $\varphi_i(t)$ the current body angle, and φ_i^0 is the target angle, i.e., where the vector $\mathbf{v}_i^0$ is pointing. The target angular speed, $\tilde{\omega}_i^0$, defined in Eq. [9] is larger when the body angle differs much from the desired movement direction. Langston *et al.*[8] used a different formula for the motive torque, which had a form of a spring force. During this work, it was noticed that a force like that will make humans to rotate around their axis like harmonic oscillators and, thus, some angular velocity dependent torque should be used.

In FDS+Evac method, humans are guided to exit doors by the preferred walking direction vector field, $\mathbf{v}_i^0$, and this field is obtained using FDS and its flow solver. This vector field is obtained as an approximate solution to a potential flow problem of a two-dimensional incompressible fluid to the given boundary conditions, where all walls are inert and the chosen exit door acts as a fan, which extracts fluid out of the domain. This method, or rather a trick, produces a nice directional field for egress towards the chosen exit door, see Fig. 2. A field of this kind will always guide humans to the chosen exit door. This route will not be the shortest one, but usually it is quite close to it. This field will guide more humans to the wider escape routes than on the narrower ones due to the fact that the field is a solution to an incompressible flow. Note, that in the present version of FDS+Evac, escaping agents have a rule for the exit door selection. Thus, the above sentence applies when there are many routes to the chosen exit door. The analogy to an incompressible fluid flow is not a bad starting point to find the movement directions of

large human crowds. For example, when humans are leaving a large sports or entertainment event, they usually just follow the human flow to the outside of the building without much control on the process.

Parameters of the Human Movement Model

The human movement method presented in Eqs. [1]–[9] has many parameters. Some of these parameters are related to physical dimensions of humans, like m_i and I_i^z, but many are parameters related to the chosen model. Some of these parameters are chosen to be the same as found in the literature[5, 8] and some were estimated from test calculations. The parameters of the social force were chosen such that the specific human flows through doors and corridors were appropriate. The parameters for the three circle representation of human contact forces and the rotational degrees of freedom were selected mainly by trial and error in order to obtain reasonably realistic human movement. Monte Carlo simulations were done to see, which are the most important model parameters and further analysis was focused on those parameters.

The first choice for the social force parameters of human-human interaction was $A_i = 2000$ N, $B_i = 0.08$ m, and $\lambda_i = 0.5$. For the human–wall interaction values $A_w = 2000$ N, $B_w = 0.08$ m, and $\lambda_w = 0.2$ were used. It was noticed that these values are not good for congested situations when three circles are used to describe a human body. These parameters were modified such that the interaction strength parameter A was made velocity dependent, $A(v_i) = 2000\,\mathrm{Max}(0.5, v_i/v_i^0)$ N.

For the contact force parameters, values $k = 12 \times 10^4$ kg m^{-2}, $\kappa = 4 \times 10^4$ kg s^{-1}m^{-1}, and $c_d = 500$ kg s^{-1} are used both for the human–human and for the human–wall interactions. The mass of a default male is $m_i = 80$ kg and his moment of inertia was chosen to be $I_i^z = 4.0$ kg m^2. For other humans, the mass and the moment of inertia are obtained by scaling. For the relaxation time parameters, τ_i and τ_z, values 1.0 s and 0.2 s are used, respectively. The body sizes and unimpeded walking velocities, v_i^0, are shown in Table 1. The angular velocity parameter ω_i^0 has a value of 4π s^{-1}, i.e., two rounds per second, in FDS+Evac.

In principle, all the above parameters may be dependent on the person in question. But in FDS+Evac, only the body sizes, walking velocities, and the motive force parameter τ_i are personalised by choosing them from a random distribution. A uniform distribution ranging from 0.8 s to 1.2 s is used for τ_i and the used uniform distributions for the body dimensions and for the walking speeds are shown in Table 1.

Fire and Human Interaction

By using FDS as the platform of the evacuation calculation we have direct and easy access to all local fire related properties, like gas temperature, smoke and gas densities, and radiation levels. Fire influences evacuation conditions; it may incapacitate humans and in extreme cases block major exit routes. On the other hand, humans may influence the fire by opening doors or actuating various fire protection devices. For now, the effect of smoke on the movement speeds of humans and the toxic influence of the smoke are implemented in movement algorithm of FDS+Evac. The exit selection algorithm of the agents uses smoke density to calculate the visibility of the exit doors.

Smoke reduces the walking speed of humans due to the reduced visibility, its irritating and asphyxiant effects. Recently, Frantzich and Nilsson[12] made experiments on the effect of smoke concentration on the walking speeds of humans. They used larger smoke concentrations than Jin[13] and they fitted the following formula to the experimental values

$$v_i^0(K_s) = \frac{v_i^0}{\alpha}(\alpha + \beta K_s) \ , \qquad [10]$$

TABLE 2: Preference order used in the exit selection algorithm. The last two rows have no preference. This is because the evacuees are unaware of the exits that are unfamiliar and invisible and, thus, can not select these exits.

preference	visible	familiar	disturbing conditions
1	yes	yes	no
2	no	yes	no
3	yes	no	no
4	yes	yes	yes
5	no	yes	yes
6	yes	no	yes
No preference	no	no	no
No preference	no	no	yes

where K_s is the extinction coefficient ($[K_s] = \mathrm{m}^{-1}$) and the values of the coefficients α and β are 0.706 m s^{-1} and -0.057 m^{2}s^{-1}, respectively.

The toxic effects of gaseous fire products are treated by using Purser's Fractional Effective Dose (FED) concept.[14] Human is considered to be incapacitated when the FED value exceeds unity. An incapacitated human is modelled as an agent, who does not experience any social forces from the other humans and whose target movement speed, v_i^0, is set to zero. The size of an incapacitated human is not changed, i.e., he/she remains on his/her feet. This is a very crude model and it needs to be modified in later versions of FDS+Evac.

Exit Selection

Game theoretic reaction functions and best response dynamics are applied to model the exit route selection of evacuees. In the model, each evacuee observes the locations and actions of the other evacuees and selects the exit through which the evacuation is estimated to be the fastest. Thus, the exit selection is modelled as an optimisation problem, where each evacuee tries to select the exit that minimises the evacuation time. The estimated evacuation time consists of the estimated time of walking and the estimated time of queueing. The walking time is estimated by dividing the distance to the exit by the walking speed. The estimated time of queueing is a function of the actions and locations of the other evacuees. It is also assumed that people change their course of action only if there is an alternative that is clearly better than the current choice. This behaviour is taken into account by subtracting a parameter from the estimated evacuation time of the exit currently chosen.

Apart from the locations of exits and the actions of other people, there are also other factors that influence the evacuees' decision making. These factors are the conditions related to the fire, the evacuees' familiarity with the exits and the visibility of the exits. The effect of these factors is taken into account by adding constraints to the evacuation time minimisation problem. According to the three factors mentioned, the exits are divided to seven groups so that each exits will belong to one group. The groups are given an order of preference.

The familiarity of each exit for each agent can be determined by user in the input-file of FDS+Evac. It is also possible to give a probability for the familiarity of an exit, and FDS+Evac will randomly set the familiarity of the exit. FDS+Evac determines the visibility of an exit to an agent by taking into account the blocking effect of smoke and obstacles. The possible blocking effect of other agents is not considered in the current version of the programme. The existence of disturbing conditions is estimated from the fire-related data of FDS on the visible part of the route to the exit. By disturbing conditions we mean

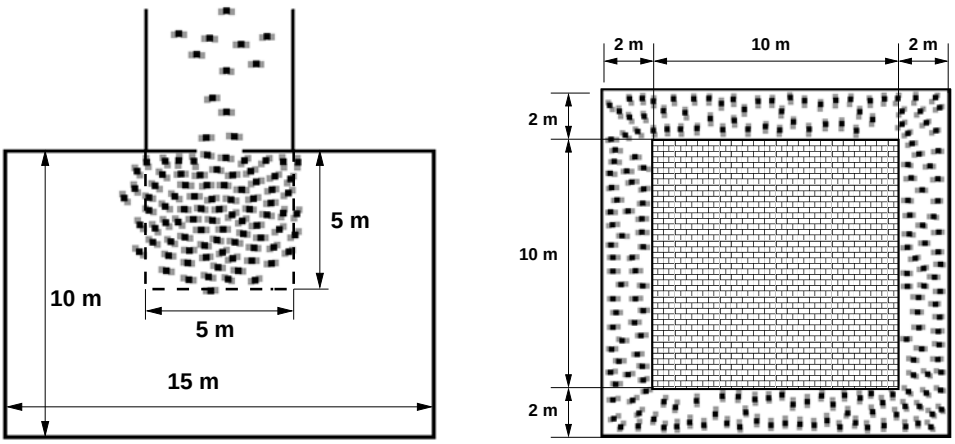

FIGURE 3: Test geometries used to calculate the specific flows through doors and corridors.

conditions, like temperature and smoke, that disturb an evacuee but are not lethal. If there are lethal conditions on an exit route, the exit has no preference.

The exit selection algorithm consists of the above described two phases. First the exits are divided to the preference groups according to Table 2. Then, an exit is selected from the most preferred nonempty preference group by minimising the estimated evacuation time.

According to socio-psychological literature,[11, 15] the familiarity of exit routes is an essential factor influencing decision making. This is because the unknown factors related to unknown routes are considered to increase the threat. As a result, evacuees prefer familiar exit routes even if there are faster unfamiliar routes available. For this reason, emergency exits are used rarely in evacuations and fire drills.

Groups

According to socio-psychological literature, a crowd consists of small groups, like families, that tend to act together.[11] This behaviour should be taken into account when building evacuation models. A method for modelling this grouping behaviour with the equations of Helbing was developed. In the model, the actions of a group are divided into two stages:

1. In the gathering stage the group members walk towards each other to gather the group.
2. In the egress stage the group moves together along the selected exit route.

These two stages are modelled by altering the preferred walking direction field of Helbing's equation of motion. In the gathering stage the pedestrians are trying to move towards the centre of the group. When the distances from the centre to each pedestrian are under a threshold value, the group is considered to be complete. When a group is complete, it starts to move towards an exit. This means that each group member is set to follow the same flow field. While moving towards an exit, the group members also try to keep the group together. This is modelled by adjusting the walking speeds and by adding an additional force that points to the centre of the group. This force is called as the group force. The magnitude of the group force describes how eagerly the group members try to keep the group together. It can be given different values for different kinds of groups. For example, a group consisting of a mother and a child should have a larger group force than a group of work mates.

The group-model is not yet available in FDS5, but it will be added to later versions of the program. The model has been programmed to a test-version and the results are promising, but quantitative effects of the model are yet to be analysed. The results of these analyses will be presented in a separate paper.

RESULTS

The human movement algorithm of FDS+Evac has many parameters. Some of these are related to the physical description of a humans, like the body size, the mass, the walking speed and the moment of inertia. The others are the parameters of the chosen movement model, τ, τ^z, ω^0, the parameters of the social force, A, B, λ, and the parameters of the contact force, k, κ, c_d. To test the relative importance of these parameters, Monte Carlo simulations were performed to find the parameters which have the greatest effect on human flows. Two different geometries were used in the simulations, see Fig. 3. One of the geometries was used to study the flow of humans through a narrow door and through a wide door and the other geometry was used to study human flows in a corridor using densities 1.0 and 2.0 persons per square metre. There were 100 humans randomly located at the 5×5 m^2 square in the door flow calculations. Corridor flow calculations had 96 or 192 humans inside the corridor depending on the density. Thousand egress simulation with different random initial human properties were performed for each of these four different cases. In total eleven model parameters, A_i, B_i, λ_i, v_i^0, τ_i, A_w, B_w, λ_w, ω_i^0, τ^z, and I_i^z, were varied in the simulations. The monitored output quantity was the specific human flow in all cases and the Spearman's rank correlation coefficients (RCC) were calculated for these four cases and they are shown in Fig. 4.

It is seen from Fig. 4 that the parameters A_i, B_i, λ_i, v_i^0, τ_i, and B_w have the largest impact on the specific flows through doors and corridors. Thus, further simulations were done to quantify these effects. Each of these six parameters were varied separately and 100 simulations were done for each discretely chosen value of the parameters. Two different door widths, 1.0 m and 2.0 m, were chosen to represent a narrow and a wide door. Corridor flow was calculated using a density of 2.0 persons per square metre, because it is known that around this density the specific flow has its maximum value. The results of these, in total almost 20000 simulations, are shown in Fig. 5, where the markers represent the average of 100 simulations and standard deviation is shown as error bars. Note that in FDS+Evac the initial properties and positions of humans are not deterministic, because the humans are randomly positioned, the parameters R_d, v^0, and τ_i, are sampled from a random distribution and there are small random forces in Eqs. [1] and [5]. Increasing the values of A_i and B_i increases the social force which tries to keep humans apart from each other and, thus, the specific flow for door geometry will decrease. The corridor case has a constant human density. Thus, these two parameters can not have an effect through the density. Larger social force, i.e., larger A and/or B, will make a forward walking person to reduce his/her speed in order not to step on someone's heels, when the anisotropy parameter, λ_i, is less than unity. Increasing the walking velocity will of course increase the specific flow. Decreasing τ_i, i.e., increasing the motive force to go forward, increases specific flows quite rapidly for the door flow. This effect is not as pronounced in the corridor case, because there is no free space in front of humans to accelerate and also the humans are already moving with some velocity whereas they are almost standing and waiting their turn in front

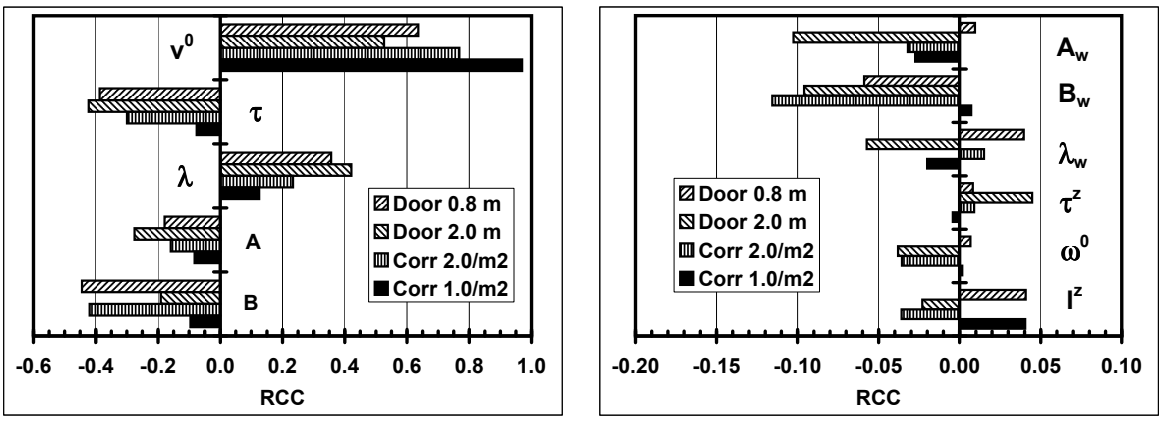

FIGURE 4: Rank correlation coefficients (RCC) for specific flows through doors and corridors. Widths 0.8 m and 2.0 m were used for doors and human densities 1.0 m^{-2} and 2.0 m^{-2} were used for corridors.

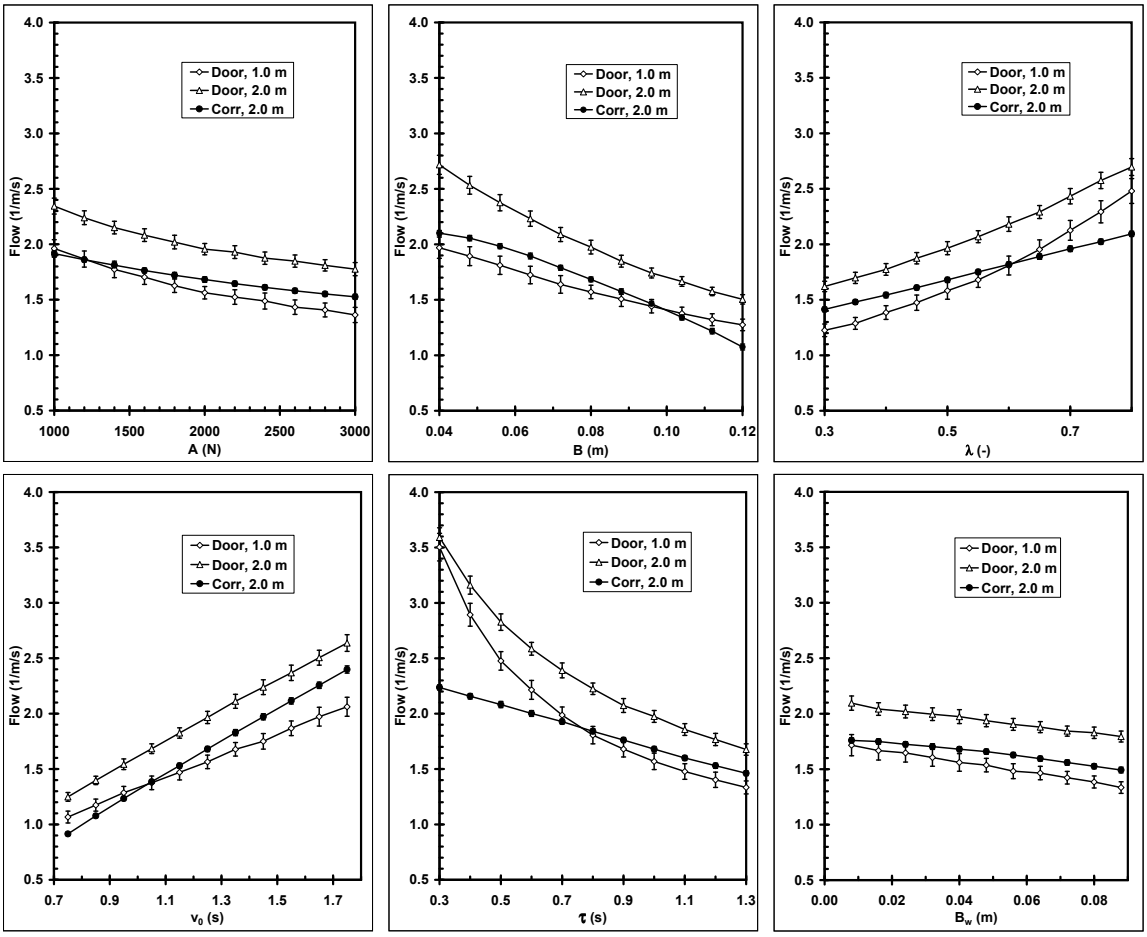

FIGURE 5: Effects of different model parameters, A_i, B_i, λ_i, v^0, τ_i, and B_w on the specific flows through doors and corridors. The corridor has 2.0 m^2 human density and two doors widths, 1.0 m and 2.0 m, are used.

of the door. The anisotropy parameter of the social force, λ_i, controls how eager humans are to push those who are in front of them. When λ_i is large then humans are 'pushy'. The effect of the wall related parameter B_w is to modify the effective width of doors and corridors, thus, increasing its value will make the effective width smaller and this will decrease human flows.

In Figure 6, the results of FDS+Evac simulations are compared with other simulation programmes and hand calculation formulas. On the left, the specific flows through doors are compared. Shown are the values calculated by FDS+Evac with the parameters reported on the previous section. The results of the programmes MASSEgress and Simulex are extracted from Pan's thesis.[11] On the right, specific corridor flows are compared. Shown are the results of FDS+Evac simulations, Nelson's engineering formula from the SFPE Handbook,[14] and the four different experimental results fitted to the analytical forms by Fang *et al.*[16] Note, that each FDS+Evac data point is an average of 100 simulations and standard deviations are shown as error bars. For corridor flow the error bars are hardly visible behind the markers.

It is seen that the present version of FDS+Evac is able to produce reasonable flows through doors and corridors. For some applications these flows may by considered to be too large, e.g., maritime applications,[17] but it is quite straightforward to modify the parameters of FDS+Evac such that specific flows do not exceed 1.3 persons/s per metre as is easily seen from Fig. 5.

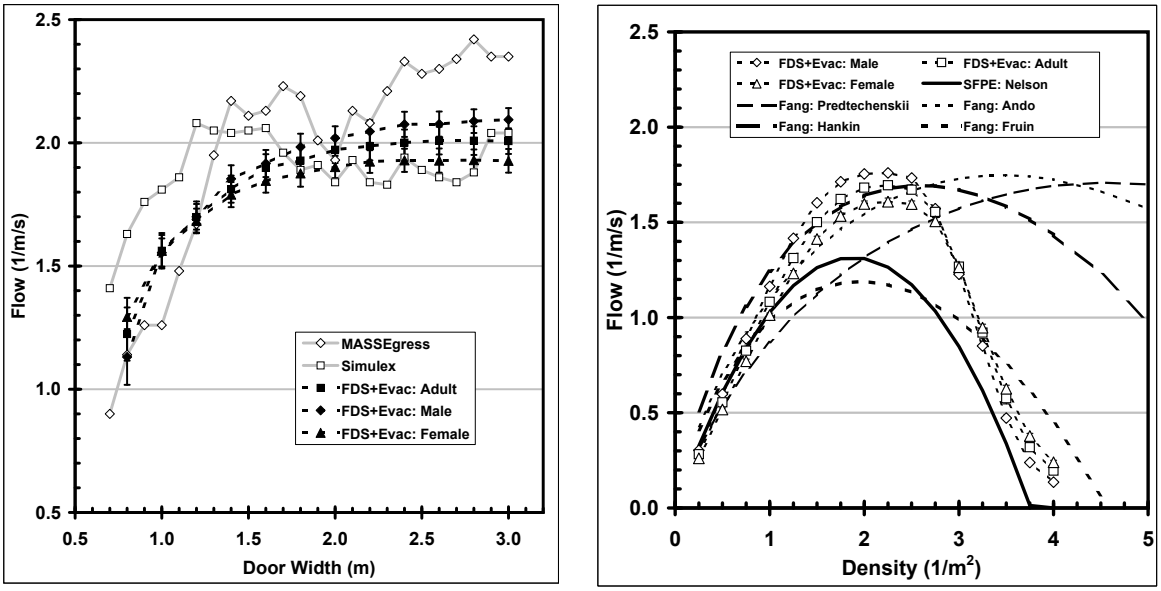

FIGURE 6: Specific flow through a door as a function of the door width and specific flow in a corridor as a function of the human density.

DISCUSSION AND CONCLUSIONS

This article describes how an egress calculation module is added to FDS. The preliminary version of this egress program, FDS+Evac, was recently presented,[3] but in this article it is generalised to a more realistic treatment of the shape of the human body. The effect of the many parameters of the method are studied and a set of 'default' parameters is introduced in the computer programme. Using these parameters, the results for door and corridor flows are good, i.e., similar to other evacuation programmes and standard hand calculation formulas. Some modifications are needed to satisfy IMO and some country specific requirements, which can be done quite easily by changing slightly some of the model parameters.

A reaction function model for the exit route selection is introduced and a group-model for the social interactions is presented. To model the exit selection of evacuees realistically, more factors need to be considered. For example, the current model does not take into account evacuees' tendency to follow each other. This "herding behaviour" will be considered in future versions of the computer programme.

FDS+Evac can be applied to buildings where the floors are mainly horizontal. Floors may be also inclined but the user should be careful when giving the walking velocities along inclines because this feature is not fully tested yet. FDS+Evac was found to run satisfactorily, and fast enough for practical purposes: It has been applied to simulate the egress process of a large two-storey shopping mall, where there were 4000 agents in the simulations. FDS+Evac will be made public, when the version 5 of FDS is released during spring 2007, on the web page: *http://www.vtt.fi/fdsevac/*.

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